TRIAC Dimmer Circuit Project Report

“Simplicity is the ultimate sophistication” – Leonardo da Vinci

"I have made this longer than usual because I have not had time to make it shorter." - Blaise Pascal

Introduction

The key to understanding applied electronics lies in mastering one’s understanding of fundamental principles. This is because designers create practical electrical systems by combining, layering, or otherwise collaging fundamental principles together, effectively hiding them behind a veil of abstraction; as a result, trying to educate oneself about applied electronics as a starting point rather than the fundamental principles they are built on is often a difficult and unrewarding endeavor. At best, after much laborious practice, one can achieve expert competency in one application with little or no ability to transfer or apply that knowledge to any other problem. At worst, one receives a vague impression about how a truly remarkable system works, and mistaking that vague impression for expertise, effectively arrests any possibility for deeper learning. This low return on a high investment of study often becomes a deterrent to people who would otherwise be interested in expanding their knowledge; yet, it also seems that many people are hesitant to return to fundamental principles for fear that doing so reflects poorly on their intelligence or education, as though spending all their time on understanding complex applications is somehow more meritorious. This way of thinking is simply backwards, and may in fact be the primary impetus preventing people from truly growing in their knowledge and understanding of applied electronics.

In this project, I will seek to illustrate the value of mastering fundamental principles through the design, implementation, and testing of a simple TRIAC (triode for alternating current) dimmer circuit. TRIAC dimmers are a common and delightfully straightforward technology used for controlling the duty cycle of a load connected to an AC (alternating current) power source. I will not spend time here discussing the theory of operation of a TRIAC dimmer or the RC (resistor-capacitor) network that drives it, as there are bountiful resources available on the internet explaining these concepts more concisely than I ever could. Neither will I spend time in this project discussing the fundamental principles that students should learn in their undergraduate electrical engineering courses, as the intention here is to demonstrate the value of designing from these principles, not teaching them for the first time. If the reader is unfamiliar with TRIAC technology, I highly recommend finding a [video](https://youtu.be/jS9ANqJf-ZY?feature=shared) that illustrates a TRIAC dimmer in operation with shots from an oscilloscope, as a good picture is worth a thousand words. Because of the abundance of educational resources such as these already on the internet, this project will instead focus on illustrating how the implementation of a very simple circuit can in fact be an occasion to master fundamental principles, and how this mastery can be carried forward to understand other applied electronics.

I will break this project down into four main phases. The first phase will deal with the analytical “paper and pencil” design of a TRIAC dimmer from scratch without the help of prototyping, simulation, or reference designs. I will approach the problem as though I were the first engineer encountering it, which is a powerful way to ensure that no knowledge of the design is taken for granted. The second phase of the project will complement the analytical design conducted in the first phase with the power of simulation. Simulation provides a great sanity check in design work, but it is not infallible. Once simulation has convinced me that my design is reasonable, I will finally “cheat” and compare it to several reference designs. In the third phase, I will actually move forward with a physical prototype based on my design that I can use to collect real-world data to compare with my analysis and simulations. Once I collect this data, the fourth and final phase will provide a detailed comparison and study of the data gathered in the previous three phases. At the end of all four phases, I will provide a conclusion discussing whether the project was successful in its objective to illustrate the importance of mastering fundamental principles in the quest to understand applied electronics.

TO DO: Insert images of TRIAC dimmers here

Requirements

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Analytical Design Process

With the prevalence of highly capable circuit simulation softwares such as SPICE that leverage numerical techniques to solve complex circuit problems, or the abundance of reference designs available on the internet that are ready to be prototyped and quickly tweaked to meet specific requirements, analytical circuit design is oft brushed aside as something antiquated or reserved for the classroom. And indeed, simulation tools and reference designs save engineers a tremendous amount of time and effort in the design process so that it would be unreasonable to ignore them. Re-inventing the wheel is a waste of time in such cases. So then, is analytical circuit design still relevant in real-world circuit design? Except for a few basic “back of the hand” calculations, perhaps not. But supposing an electrical design engineer has no tools at their disposal except a pencil and paper (or worse, a napkin), can they still design? An engineer who skips the analytical design portion because they *shouldn’t* do it is much distinguished from an engineer who skips the analytical design portion because they *can’t* do it. Therefore, far from being antiquated, analytical circuit design still exists as a key factor in determining which category an engineer belongs to, even if its application rarely extends beyond the classroom.

But even the classroom exists for a reason. Electrical engineers who are willing to apply a little elbow grease every now and again and attempt an analytical circuit design with pencil and paper can reap enormous benefits. How so? Designing with pencil and paper forces one to return to the fundamental principles of electronics. No shortcuts and no pre-supposed familiarity with applied electronics. As outlined in the introduction, the objective of this project is to illustrate how mastering fundamental principles rather than applications maximizes the return on an individual’s investment in education; therefore, this project shall embrace analytical circuit design as the first step in the design process.

Before developing an analytical model of the TRIAC dimmer circuit, it is important to establish my goals for the model. In this case, I really have one particular goal in mind: to deduce the appropriate passive component values for my circuit. This is the crucial design step that in most cases will be relegated to simulation, prototyping from reference designs, or some combination of the two. The component values must be selected so that rotating the potentiometer knob causes the duty cycle of the load to range from 0% to 100% (or as close as possible). As long as my model allows me to deduce these component values, I can ignore additional complexities (for now).

As it turns out, an appropriate model that will allow me to accomplish this goal is simply an RC circuit driven by an AC voltage source. This is because the RC ladder acts as a trigger circuit for the TRIAC. When the capacitor voltage exceeds the breakover voltage of the DIAC, the TRIAC is triggered and the load is turned on. On the other hand, when the capacitor voltage subceeds the breakover voltage of the DIAC, the TRIAC is *not* triggered and the load is turned off. Controlling the values of and , then, controls the duty cycle of the load. I have already selected a DIAC and TRIAC from STMicroelectronics which are both recommended for dimmer circuit designs, and knowing these component ratings I can calculate the required passive component values with an analytical model of an RC circuit driven by an AC voltage source.

To begin developing the model, I will define some known values. First among these are the parameters for my AC voltage source, which being a 120VRMS @60Hz mains supply should be easy to derive. I will choose to use a sine function for modeling it, since the sine function is 0 at time equal to 0, and that will make the math a little easier further down the road. Expressing my AC mains supply as a sine function gives the following:

Here, is the peak voltage and is the angular frequency of the sinusoid. Given that the source is a 120VRM @60Hz mains supply, calculating these values is trivial:

To further develop the circuit model, I will identify any constants or variables that need solving for. The goal of my model is to calculate the required values of the passive components and . The value of will be allowed to vary while will be selected to remain constant. This is because it is much simpler and cheaper to find a variable resistor (e.g., a potentiometer) than it is a variable capacitor, and only one degree of freedom is required to control the load duty cycle. Therefore, can be classified as an unknown variable while should be classified as an unknown constant.

One last part of the circuit model that deserves careful scrutiny is the load. A unique feature of the TRIAC dimmer architecture is how the load is placed in series with the dimmer circuit itself, meaning the behavior of the load has a direct impact on the performance of the dimmer. TRIAC dimmers were originally designed to control simple resistive loads such as incandescent light bulbs, typically exhibiting around 150Ω. Modern lighting systems, however, almost exclusively use LED technology, which at the very least requires AC rectification, and, depending on the design, may also involve dropping the voltage with a buck controller. In this scenario, there is no guarantee the load will look like a simple resistor. Fortunately, many LED drivers such as the LM3445 from Texas Instruments advertise themselves for retro fitting TRIAC dimmer circuits. The application circuit for the LM3445 shows a full wave rectifier followed by a valley fill and a bleeder circuit. The valley fill circuit smooths the rectified AC voltage and will introduce some capacitance at the load on startup, but following that the bleeder circuit is responsible for providing a load resistance of 230Ω to ensure proper firing of the TRIAC. Therefore, although a far cry from the simplicity of an incandescent light bulb, the LM3445 will present a similar load to the TRIAC dimmer and I can move ahead with my model using a 150Ω resistor.

A schematic representation of the complete analytical circuit model is presented below.

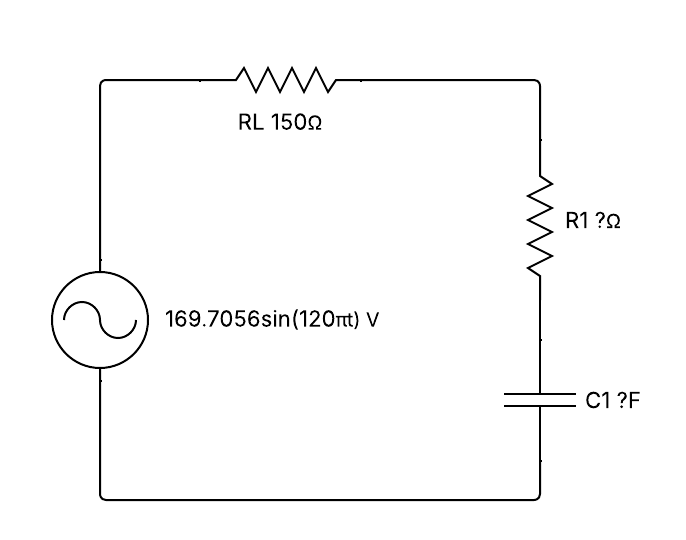


Figure : Initial Analytical Circuit Model

With my analytical circuit model being clearly defined, it is time to begin the heavier lifting. Again, the goal of my model is to deduce the appropriate passive component values for my circuit; specifically, to deduce the values of and that provide a voltage waveform that triggers the TRIAC appropriately. Therefore, I am primarily interested in deriving the transfer function between the input voltage waveform, , and the capacitor voltage waveform, which I will call the output voltage waveform . In the interest of avoiding a cluttered page, I will omit most of the algebraic maneuvers between each step in the derivation, but will provide enough milestones for the reader to follow along. To start, apply Kirchoff’s voltage law to the circuit model:

Next, apply the Laplace transform to convert this problem from the time domain into the frequency domain (it can be verified that this circuit is in fact a linear, time-invariant system, so the Laplace transform can be applied with no hitches). As will be seen later, the reason I favor the Laplace method for solving this problem is that it provides both the homogenous and the particular solution (i.e., the general solution) in one shot.

Notice also that my Laplace transform of the capacitor voltage includes the initial voltage of the capacitor. This is another reason I prefer the Laplace method: it can be generalized to include initial conditions in the final solution. To help save space in the rest of the derivation, define the time constant of the circuit:

Now, with a little algebra, solve for the transfer function between in the input voltage and the output voltage.

This solution holds for any input (a.k.a, forcing) function . In this particular case, of course, I know exactly what the input function is going to be and I already have its time domain expression in (1). It is easy enough to take the Laplace transform of (1) or find it in a Laplace transform table.

Now, substitute (6) into (5) and rearrange to solve for the output voltage.

All that remains in order to find the time domain expression for the output voltage is to inverse Laplace transform (7). To do this, start by applying partial fraction expansion.

Then, solve for the unknown constants.

Now, simply apply the inverse Laplace transform to each of the terms in (8).

Finally, substitute (8a) – (8c) for the constants in (10) and simplify.

Equation (11) is the complete, time domain solution for the output voltage of the analytical circuit model in figure 1! There are in fact three distinct terms to this solution. The first term represents the transient response of the system, as indicated by the fact that it is a decaying exponential. When the input voltage is first applied to the system, the capacitor experiences in-rush current resulting in a transient component of the output voltage that will die out and can only be ignored after approximately five time constants. The second term represents the steady state response of the system, as indicated by the fact that it is an undamped sinusoid. This portion of the output voltage will remain consistent for as long as the input voltage is applied to the system. The third and final term represents the initial condition response of the system, which taken by itself would show how the output voltage waveform behaves in the absence of any input voltage. Like the transient response, it is a decaying exponential with the same time constant, and any contributions from this term to the total output voltage of the system will die out after five times that constant. Together, these three terms describe the entire behavior of the system, ignoring any external influences (i.e., EMI, electromagnetic interference) that may excite additional responses in the circuit. It may be advantageous at times to analyze the system solely from the perspective of steady state; therefore, the second term of the general solution is isolated and provided below for reference.

Admittedly, even with such detailed equations as (11) and (12), my analytical design of the TRIAC dimmer would likely grind to a halt without the help of computers. Without the ability to begin plugging in and churning out real numbers quickly, the utility of long equations is somewhat limited. Therefore, to proceed with my analytical design, I will program equations (11) and (12) into an excel spreadsheet with the goal of using them to tune the values of and until the circuit provides the required signal to trigger the TRIAC.

To begin, consider the case where the load is running at 100% duty cycle. This means the TRIAC must be triggered continually (or as close as possible). In this case, maximum duty cycle will be achieved when the output voltage is in phase with the input voltage. There is no way in the existing circuit to force the output voltage to remain above the DIAC breakover voltage for a complete line cycle, therefore the “off” time of the TRIAC will be minimized when the input and the output are in phase. Examining equation (12) (or perhaps, drawing on one’s knowledge of applied electronics), this condition is accomplished when the time constant of the circuit is zero. There are two ways to achieve this, but only one of them is practical since the capacitor cannot be removed entirely from the circuit. Therefore, to achieve maximum load duty cycle with our TRIAC dimmer circuit, consider the case where is set to zero.

Given that the breakover voltage of the DIAC is 32V and a line frequency of 60Hz corresponds to a period of 16.6667 milliseconds, the maximum duty cycle can be calculated as follows:

Notice that the line period is divided in two for this calculation because the positive and negative halves of the line cycle mirror each other. Thus, ignoring polarity, a complete period can be replaced with just one half period to make the duty cycle calculation more straightforward. For the rest of this report, I will refer to this time as a half-line period.

While this design may look OK on paper, however, a purely capacitive circuit has some practical design concerns such as uncontrolled inrush current and unpredictable behavior due to parasitic resistance (including the equivalent series resistance of the capacitor itself). Therefore, a more practical design should include a non-zero value of that reduces inrush current and makes any parasitic resistance negligible, leading to more predictable behavior. As equation (12) dictates, however, one can only “purchase” this non-zero resistance with at least a little phase shift between the input and output voltage, which will result in a smaller maximum duty cycle. As per the design requirements, I will target 92%, which buys 2% to play with.

Run a similar calculation as before, but in this case solve for time given the target duty cycle.

Now I can use the excel spreadsheet programmed with equations (11) and (12) to determine the time constant required for the output voltage to reach 32V at 0.6667 milliseconds. But which equation to use? Equation (11) gives the full response of an RC circuit driven by an AC source including transients and initial conditions, while equation (12) gives just the steady state response. In the case of maximum duty cycle, the TRIAC activates at 0.6667 ms and effectively shorts out the RC ladder, discharging the capacitor through . This means that the RC circuit never reaches steady state, and hence, I cannot use equation (12) to solve this problem! Rather, I must use equation (11), treating each half-line cycle as a new time zero and taking into account the transient and initial condition responses of the circuit. For now I will assume that is small enough that the capacitor discharges entirely before the next half-line cycle, that way I can ignore the third term in (11) (I will check this assumption later). It is significant that I must use equation (11) to solve this problem, because one could in fact derive the steady state response given in equation (12) using the phasor analysis shortcut. Supposing one was familiar with this shortcut but ignorant as to where it came from, however, it would be impossible to address a problem of this complexity analytically. Therefore, it has already been shown that returning to fundamental principles opens up more design avenues that can be applied to a wider range of problems.

Returning to the design question at hand, it is possible using equation (11) to toy with the values of and until I discover the time constant required to make the output voltage reach 32V at 0.6667 ms. This time constant is in fact (and one can plug this back into equation (11) to verify):

Comparing five times this value (5τ = 0.8080 ms) with the time required to reach the breakover voltage (0.6667 ms) re-emphasizes the fact that one cannot ignore the transient portion of the response here. Additionally, I can use this time constant to justify my earlier assumption that the capacitor will fully discharge after the TRIAC is triggered and before the next half-line cycle. If the TRIAC fires at 0.6667 ms, and according to the third term in equation (11) the capacitor will fully discharge after 0.8080 ms, then the capacitor will be fully discharged at 1.4747 ms. Given that a half line cycle is 8.3334 ms long, my assumption is justified.

With a time constant calculated and my design assumptions justified, I can finally set about selecting concrete values for and . Keeping design for manufacture in mind, I will pick a readily available capacitor value of 0.1uF and a resistor value of 1.62kΩ (both values landing in the e-series), which gives a time constant of:

My excel spreadsheet also conveniently allows me to plot time series data generated using equation (11), so I can plot the response of the RC circuit. Of course, my excel spreadsheet does not take into account the behavior of the circuit once the TRIAC turns on, which would discharge the capacitor until the next half-line cycle. Therefore, I have plotted just the first half-line cycle to compare against the output voltage, and it remains to the reader to envision what the output curve would look like once it hits the breakover voltage of 32V at 0.6667 ms.

Figure : RC AC Response for τ=0.1620ms

Having solved for practical values of and that result in the maximum duty cycle of the TRIAC dimmer, it is time to consider the case of the minimum duty cycle. Theoretically, there should be nothing preventing me from achieving a duty cycle of 0% or fully “off”, which is good news from a power conservation standpoint. According to equation (11), while keeping the capacitor value constant I should be able to slowly increase the value of until the peak value of the output voltage never exceeds the breakover voltage of 32V. For a practical design, I should also include a bit of margin to ensure that small fluctuations in the line voltage do not trigger the TRIAC. The fact that the TRIAC does not fire in this situation should also provide a hint as to which equation to use when calculating the value of . Because the TRIAC never shorts out the RC ladder, the circuit will eventually reach steady state. Therefore, I will use equation (12) to calculate a reasonable value of . As it turns out, a resistance of 150kΩ (in series with the 1.62kΩ from before) will result in a peak output voltage of 29.2964V at steady state, and this happens to be a common resistance value among potentiometers. Less than 3V of margin, however, may be cutting it close. The time constant of this RC circuit is:

As before, I can plot time series data generated using equation (12) to show the response of the RC circuit. This time, because the system is at steady state, I will plot multiple line cycles.

Figure : RC AC Response for τ=15.1620ms

With the value of selected, as well as values of for both 92% and 0% duty cycle, my analytical design process is complete. A schematic representation of the analytic circuit model with component values filled in is provided below.

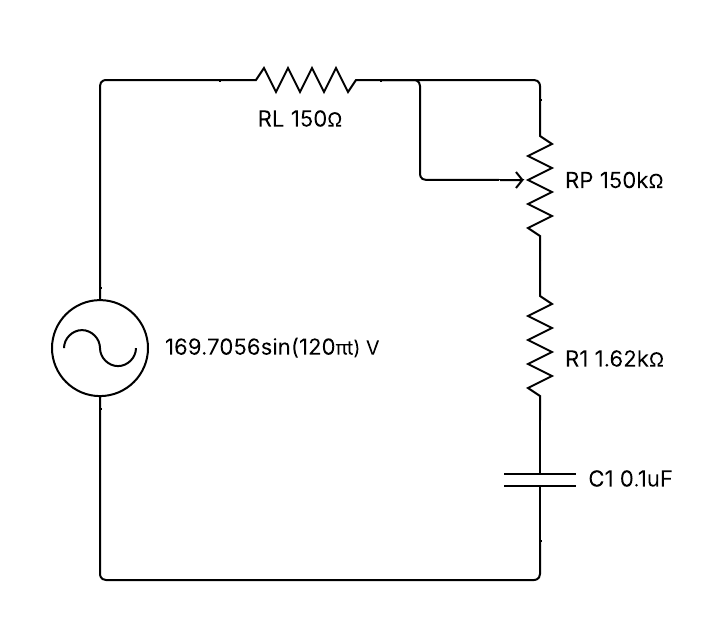


Figure : Updated Analytical Circuit Model with Component Values

It is worth stepping back here for a moment to appreciate the level of design work that a humble pencil and paper (OK, and an excel spreadsheet) can accomplish. Rather than a vague, qualitative discussion about RC circuit behavior, equation (11) allows for a precise, quantitative analysis. There is a big difference between describing the functionality of an RC circuit in words or images and actually putting numbers to it. Additionally, as noted when examining the results of equation (11), this analytical approach opens up new design avenues only available when designing from fundamental principles. Finally, it is worth noting that equation (5) is the generalized transfer function for *any* RC circuit. As long as the Laplace transform of the input voltage source can be found, it is possible to find the analytical solution for an entire host of signals. Thus, the analytical approach has not only familiarized me with the application of RC networks in TRIAC dimmers, but has also provided me with a solid foundation that I can extend to analyze the application of RC networks in other electronics. So far, a strong argument can be made that mastery of fundamental principles does indeed better equip one to understand a wider variety of applied electronics.

Simulation Design

We now run a simulation with these component values, with the added complexity of the DIAC/TRIAC attached to the output of the capacitor. Calculation assumed the DIAC and TRIAC perform ideally, but of course reality is more complicated. For instance, there is a non-zero voltage drop across the TRIAC, even when it is activated. There is also non-zero current required to trigger the TRIAC through the DIAC, which will have a small loading effect on the RC network. Ultimately, only a physical prototype can put our minds at ease on this point, but simulation at least provides a sanity check.

The first simulation is of the potentiometer set to 0k, giving the first time constant of 0.1620 ms. All transients die out within one half-line cycle, but each half-line cycle must be treated as the start of a new response with transients. As can be seen in the graph, the capacitor does in fact fully discharge, meaning the third term in equation (11) is zero and can be ignored. Unlike the excel spreadsheet, simulation includes the effect of the TRIAC.

Figure : TRIAC Dimmer Simulation for RP=0kΩ

The second simluation is of the potentiometer set at 150k, giving the time constant of 15.1620 ms. In this case, the transients will last a few line cycles 5t=75.8100ms. Therefore, run simulation until 80ms. In simulation, however, we discover a bit of a problem. Because we calculated the resistance value based on steady state peak value, the first peak is actually significantly higher than 32V due to the transient response of the circuit. This causes the TRIAC to fire and prevents the circuit from reaching steady state. Hence, our calculated peak value is actually invalid, since it depends on the ability of the circuit to reach steady state first.

Figure : TRIAC Dimmer Simulation for RP=150kΩ

To solve this problem, instead solve the for the minimum resistance required to make the first peak of the transient response less than 32V, so that the TRIAC never fires and the circuit can reach steady state. Our excel calculations indicate that a reasonable value of resistance that can make this happen is 250k. At 250k, the time constant of the circuit is:

Therefore, we should run simulation until 5t=125ms.

Figure :

Figure :

The only issue with 250k is that as long as the TRIAC is off (i.e., the circuit is in steady state), the output peak voltage is so low that a lot of the range of the potentiometer is wasted. What if we could find an in between value, such that if the circuit is in steady state it will remain in steady state, but even the transient response will eventually converge to steady state?

Try a resistance of 200k, right between 150k and 250k, and see what happens. According to our calculations, it should trigger the TRIAC with its transient response, which is confirmed by the simulation, but the simulation also shows it converging to steady state afterwards. This is because the capacitor cannot discharge completely, and the existing charge on the capacitor prevents the next swing of the line from recharging the capacitor to the point where it fires the TRIAC. Thus, the voltage on the capacitor is allowed to reach steady state. The time constant in this case is:

Data Comparison

RP=0k

Table comparing calculation, simulation, and experimentation results for the time it takes the output voltage to reach the trigger voltage for maximum duty cycle (RP = 0k)

|  |  |  |  |
| --- | --- | --- | --- |
|  | Time | Vin | Vout |
| Calculation | 0.6600 ms | 41.8633 | 31.8585 |
| Simulation | 0.6765 ms | 42.8865 | 31.9249 |
| Experimentation |  |  |  |

RP=150k

At 150k, the circuit never actually reaches steady state and each charge/discharge cycle of the capacitor must be treated as a problem involving transients and non-zero initial conditions. This is why it was helpful to generalize our formula to include non-zero initial conditions! Let’s demonstrate the power of our equations by comparing what they predict at 150k vs what the simulation shows.

Simulation indicates for 150k that at each new line cycle, the capacitor has an initial voltage of -11.951 V. We will plug this initial condition into our excel equation and compare how long it takes the output voltage to reach 32V in simulation and in our calculations.

Table comparing calculation and simulation results for the time it takes the output voltage to reach the trigger voltage when RP=150k. Consider both the intial peak “1” with 0 initial voltage and the subsequent peaks “N” with an initial voltage of 11.9510V

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Peak 1 | | | Peak N | | |
|  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |

RP=250k

Table comparing calculation and simulation results for peak times when RP=250k.

|  |  |  |
| --- | --- | --- |
|  |  |  |
|  |  |  |

RP=200k

Given these parameters, here is a table that compares the time of the first TRIAC activation between simulation and calculation.

|  |  |  |  |
| --- | --- | --- | --- |
|  | Time | Vin | Vout |
| Calculation | 6.0000ms | 130.9873V | 32.5690V |
| Simulation | 6.0320ms | 129.6720V | 32.5980V |
| Experimentation |  |  |  |

Similarly, what is the next expected peak value of the capacitor voltage given the existing charge from the previous swing? According to simulation, the existing charge is 12.035V. Compare simulation and calculations.

|  |  |  |  |
| --- | --- | --- | --- |
|  | Time | Vin | Vout |
| Calculation | 7.8800ms | 28.9122 | 28.8881V |
| Simulation | 7.5178ms | 26.3530V | 28.3980V |
| Experimentation |  |  |  |

Finally, the steady state analysis at 200k.

|  |  |  |  |
| --- | --- | --- | --- |
|  | Time | Vin | Vout |
| Calculation | 7.9900ms | 21.9423V | 22.1747V |
| Simulation | 7.9841ms | 22.6810V | 22.0920V |
| Experimentation |  |  |  |

Steady state peak is still at least 10V below the trigger voltage of the TRIAC, but pushing the potentiometer value much lower prevents the circuit from every reaching steady state. To achieve a value of approximately 200k, a 500k potentiometer is connected in parallel with a 332k resistor (closest value to 333k on the e-series).

Insert graphs here of the simulation at 200k, plus the relevant excel graphs.

Current Analysis (Input 120V AC @ 60Hz)

Potentiometer at 0k

* Peak Load Current: 1.1288 A
* Peak RC Current: 17.3980 mA

Potentiometer at 200k

* Peak Load Current: 3.2433 mA
* Peak RC Current: 829.2910 uA

Insert simulation graphs here

|  |  |
| --- | --- |
| Resistor | Power Req. |
| 1.62k | 0.4904 W |
| 332k | 0.0829 W |
| 500k Pot | 0.0550 W |

Reasons for errors:

* The simulation takes discrete samples, I was going with the closest to the desired value in each case.
* Same with calculations, it is too much to do by hand, so the excel spreadsheet calculates a series of discrete values with limited granularity.

Other things to discuss:

* Why is it necessary to put the load in series with the RC circuit rather than in parallel? Show the current through the TRIAC gate.

Next Steps:

1. Run some worst-case scenario simulations to determine the necessary current/power ratings of traces and components on a PCB.
2. Now you should be ready to move on to the next step: building the PCB!

Placing the load in series or parallel with the trigger circuit:

* Placing it in parallel, the voltage on the capacitor never discharges and significant current flows through the TRIAC (at least according to simulation)
* Placing it in series, the capacitor discharges through the filter resistor

Conclusion

During the analytical design, it was shown that returning to fundamental principles opens up more design avenues