Summary

In today's society, when people are traveling or picnicking outdoors, they often experience "low battery anxiety". To solve this problem, our team designed a circuit based on a two-phase hybrid stepper motor as a wind turbine generator. It can convert the two AC currents generated by the motor into a 5V, 164mA DC current. This technical report details the composition and principles of each part of the circuit. The two AC currents are first rectified separately through a transformer and a diode bridge to obtain pulsed DC current. Then, the two DC currents are combined and converted into smooth DC current using a filter capacitor. The LM8705 voltage regulator module is used to convert the voltage into a 5V DC current. In addition, the output is reliable and safe, with a light-emitting diode used to indicate the operating status of the circuit. We tested the input voltage multiple times and the average output voltage was 5.0002V, meeting the power supply requirements of USB ports. The circuit design is simple, and the components used are inexpensive, making it very easy to produce.

目录

1. Introduction

A two-phase hybrid stepper motor can generate electricity by converting external rotational force into electrical energy, which is commonly referred to as a stepper motor generator. As the two-phase hybrid stepper motor contains two coils, it can output two AC electrical signals. Specifically, when an external force rotates the stepper motor, the magnetic field of the rotor and stator in the stepper motor changes, leading to the generation of electrical potential in the two coils of the stator. Since the phase difference between these two coils is 90 degrees, the electrical potential they generate is also two AC electrical signals with a phase difference of 90 degrees.

When using wind to drive the motor, we need to understand the concept of holding torque. Holding torque refers to the maximum torque that the motor can withstand when it is stationary. Therefore, if the wind force exerted on the motor is less than the holding torque, the motor will not start. Only when the wind force is greater than the holding torque will the motor generate sufficient torque to start rotating. Wind force can be calculated by wind speed. Usually, wind speed is measured by a meteorological station or other wind speed measuring equipment, and the unit is usually m/s. Then, the following formula can be used to convert wind speed to wind force:

$$F = 0.5 \times \rho \times A * V^\wedge 2$$

Where F represents wind force (N), ρ represents air density (kg/m^3), A represents the area of the wind turbine blade (m^2), and V represents wind speed (m/s).

Based on the parameter table of the 17HS4401 motor, we know that the holding torque of this motor is 4N/cm. Combined with actual measurements, we can determine the minimum wind speed required to drive the motor to rotate.

The relationship between motor speed and wind speed is very complex. Through extensive research and derivation, we have obtained a formula for calculating the relationship between wind speed and motor speed:

$$N = (V \times \pi \times D \times eff) / (60 \times p)$$

Where ω is the motor speed (RPM), V is the wind speed (m/s), π is the mathematical constant pi, D is the diameter of the wind turbine blade(m), eff is the efficiency of the wind power generator, and p is the number of poles of the motor.

For a two-phase hybrid stepper motor, the output voltage at a given motor speed can be calculated using the following formula:

$$V = K \times \omega$$

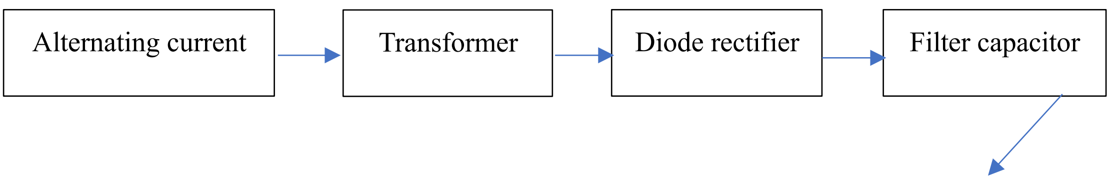
where V is the output voltage (in volts), K is the output constant of the motor (which is dependent on the motor's design and construction), and ω is the motor speed (in radians per second).

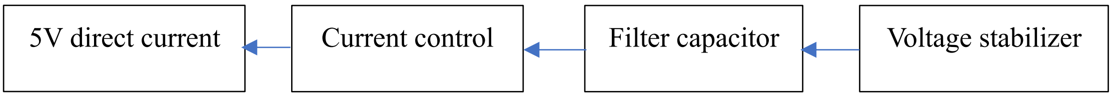
According to our research and calculations, the output voltage at different wind speeds can be roughly estimated using this series of complex formulas we provided. From this we can know that the greater the wind speed, the greater the AC voltage generated by the motor. However, since the project is focused on circuit simulation and not physical construction, we have discussed with the professor and know that in ideal laboratory conditions, the maximum voltage produced by the motor should be around 30V.

2. Design overview

Based on the previous analysis of the motor, we know that this two-phase hybrid stepping motor will generate two equally sized and frequency alternating currents, which are 90 degrees out of phase, or one-fourth of a cycle. According to ideal measurements in the laboratory under strong winds, the maximum voltage generated by using this motor as a wind power generator is 30V. In other words, when the root mean square voltage of the input alternating current is 30V, we need convert it to a 5V direct current output.

Our group design a circuit that includes components such as a transformer, diode rectifier bridge, filtering capacitor, and three-stage voltage regulator to convert AC to DC. First, the two AC sources are respectively passed through the transformer to reduce the voltage to within the maximum input voltage of the three-stage voltage regulator, which is 35V (although the root mean square voltage of the AC generated by the motor is only 30V, its peak voltage will exceed 40V, which will damage the three-stage voltage regulator). Then, the AC is rectified into DC by the diode rectifier bridge. At this time, the DC is pulsating, which is equivalent to flipping the negative current along the x-axis to positive, but its magnitude changes with time, and the waveform is still a sine wave. Normal DC current refers to a current whose direction and voltage are constant and do not change with time. We first combine the two converted DC power supplies to increase the current in the circuit while keeping the voltage constant. Then, we use capacitors for filtering in the circuit to make the voltage signal that varies with time stable, while filtering out some unstable signals of high and low frequency. At this point, we have obtained a stable DC, but its voltage is much higher than 5V. At this point, we use a three-stage voltage regulator to reduce the voltage to 5V. Finally, we filter the voltage again with a capacitor. We add a resistor to control the output current within the maximum current of the USB interface (500mA), and then add a light-emitting diode. If the LED is lit, it indicates that the circuit is working properly.





P1 The process of converting alternating current into 5V direct current

2.1 Transformer

In our project, under ideal laboratory conditions, the theoretical voltage generated by the maximum wind speed can reach 30V. Therefore, we chose it to ensure the normal operation of our circuit. As the theoretical voltage of 30V is the root mean square (RMS) voltage of the input AC voltage, we calculated that the peak voltage of the AC voltage is Peak Voltage=√2× RMS Voltage, which is √2×30V=42.43V. It exceeds the LM7805's maximum input voltage of 35v So after getting the two AC power sources generated by the two-phase hybrid stepper motor, first of all, two transformers are used to step-down each of them.

A transformer consists of a magnetic core and two coils, one called the primary coil and the other called the secondary coil. When alternating current passes through the primary coil, it produces an alternating magnetic field inside the core. This alternating magnetic field induces a current in the secondary coil. The faster the rate of change of the magnetic field, the larger the current induced in the secondary coil. When the two coils of a transformer are electrically connected, electrical energy is transferred between them in the form of a magnetic field. This is based on Faraday's law of electromagnetic induction, which states that when a conductor is placed in a changing magnetic field, it experiences an electromotive force (EMF).

According to the law of conservation of magnetic flux, the total magnetic flux in a transformer must remain constant, therefore the input power of a transformer is equal to its output power. As a result, the relationship between the input voltage, output voltage, and current in a transformer can be expressed as:

$$\frac{Vp}{Vs} = \frac{Np}{Ns}$$

where Vp and Vs represent the voltage of the primary and secondary coils, and Np and Ns represent the number of turns in the primary and secondary coils, respectively.

Using this formula, the output voltage of a step-down transformer can be calculated as follows:

$$Vs = Vp \times (Ns / Np)$$

In the step-down transformer that we are using, the number of turns in the secondary coil is less than that of the primary coil, resulting in a lower output voltage.

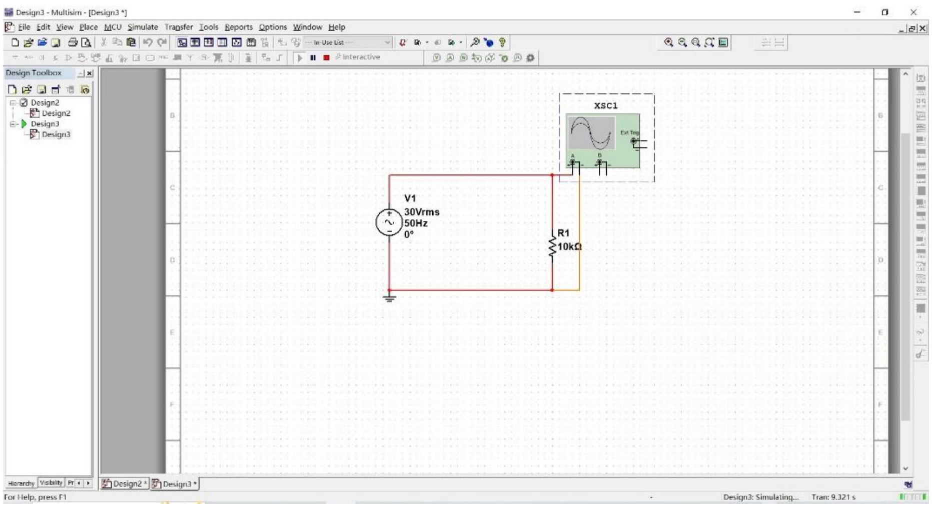
So, when the voltage of the primary coil is 42.43 volts, the number of turns in the primary coil is 1.5, and the number of turns in the secondary coil is 1, then the voltage of the secondary coil is:

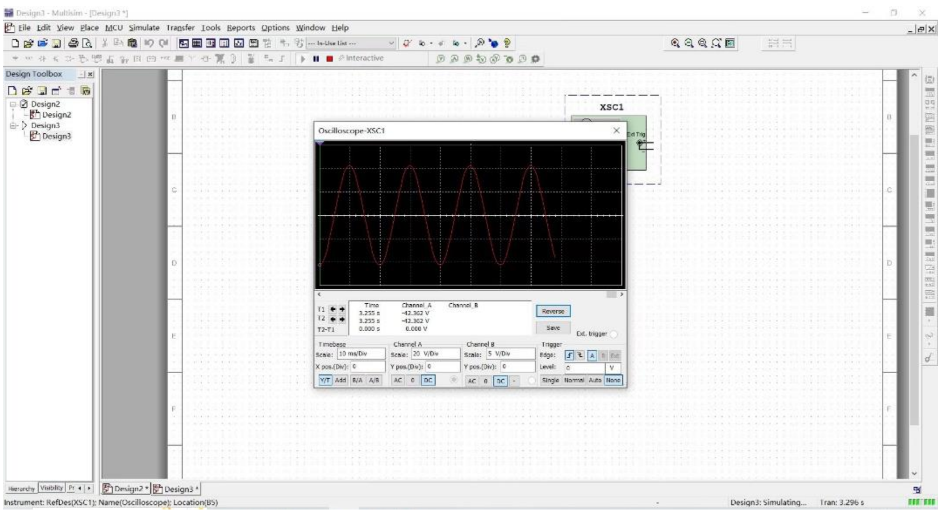
$$Vs = 42.43 \times (2/3) = 28.29\, volts$$

Now the Vs is within the safe operating range of the LM7805.

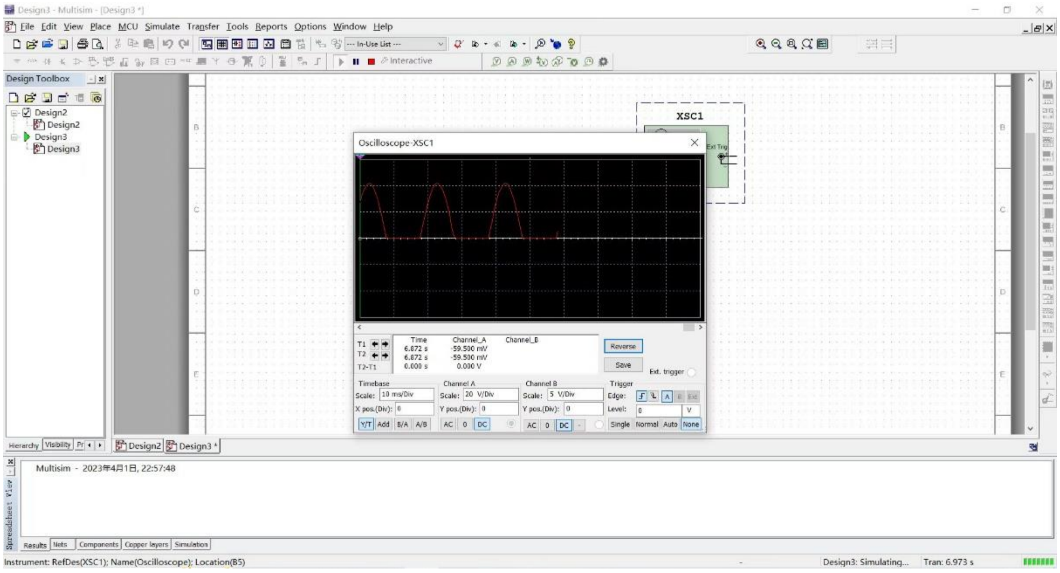
2.2 Diode rectifier

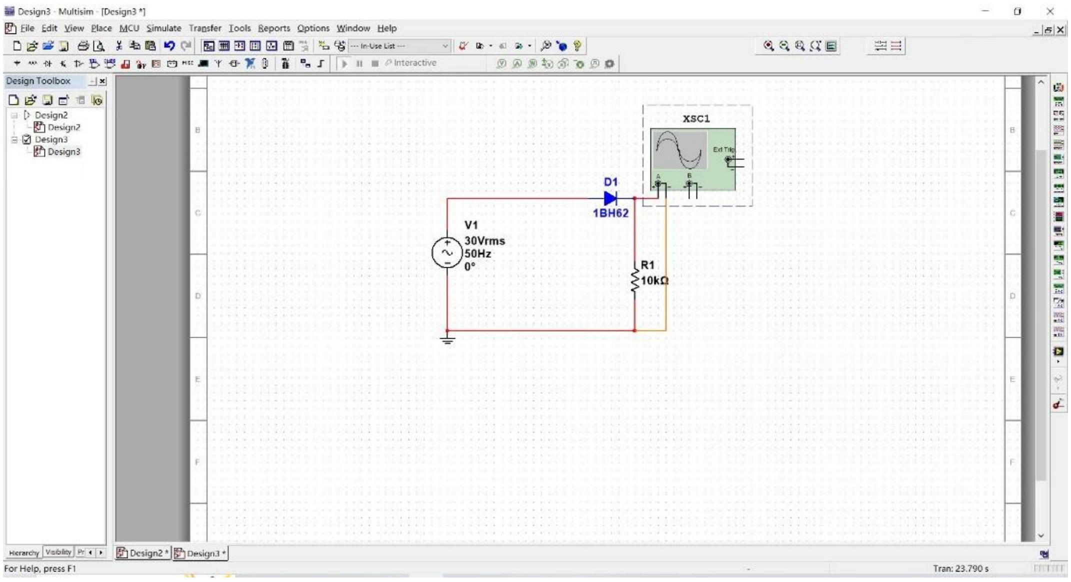
The voltage produced by a two-phase hybrid stepper motor is an alternating current (AC) signal. Through simulation software, we can clearly observe the sine wave signal generated as the current change direction.

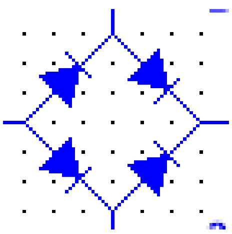




And what we need is direct current. Through simulation, it can be seen that adding a diode to the circuit will block the waveform below the x-axis. This is because of the diode's unidirectional conductivity, which only allows current to flow in one direction. However, the resulting direct current is discontinuous, consisting only of half a cycle. The output only obtains the positive half of the sine wave, and the negative half is lost, resulting in significant waste.

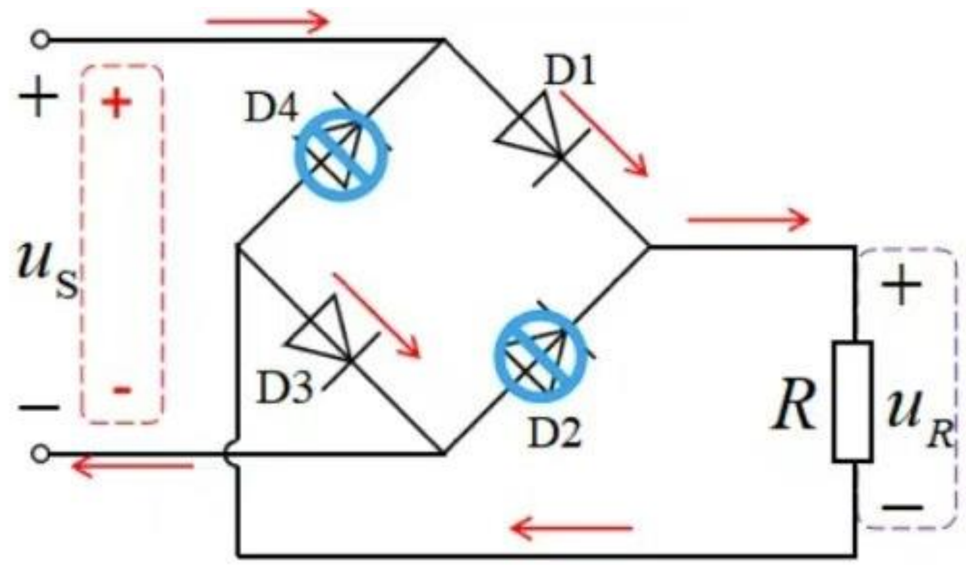




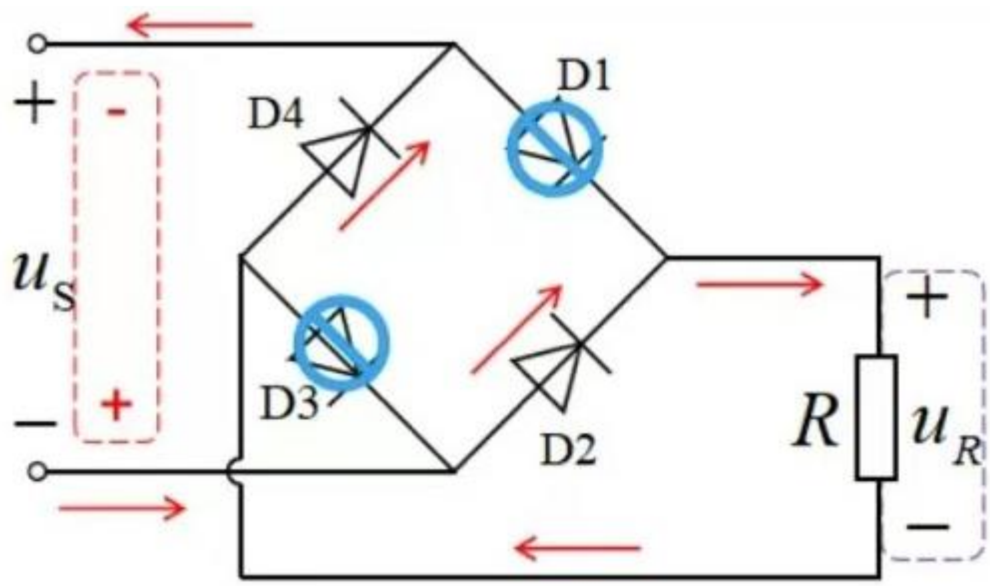


Therefore, single diode rectification is not a good solution. We need to use four diodes to construct a full bridge circuit to convert AC voltage into pulse DC voltage. A bridge rectifier utilizes four diodes, paired in pairs. When the positive half of the input sine wave is applied, two diodes are conducting, resulting in a positive output. When the negative half of the input sine wave is applied, the other two diodes conduct. Because these diodes are reversed, the output is still the positive half of the sine wave.

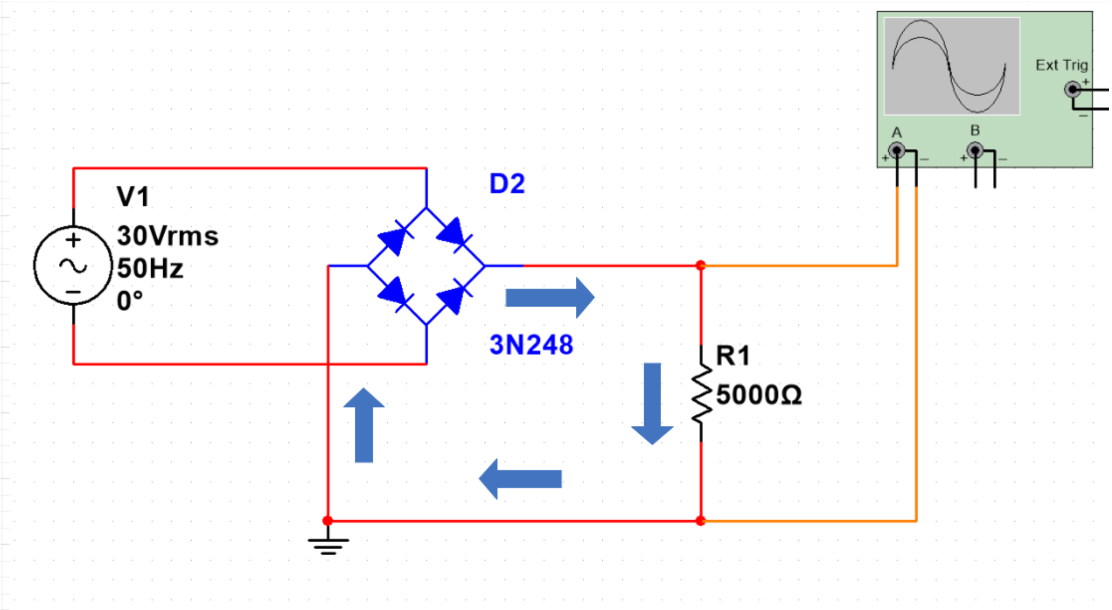
When the positive pole is at the top, the input voltage applies a forward voltage to D1 and D3, causing them to conduct, while applying a reverse voltage to D2 and D4, causing them to cut off. This forms a circuit consisting of the power supply, D1, R, and D3, generating a half-wave rectified voltage with positive polarity at the top and negative polarity at the bottom of R.



When the negative pole is at the top, the input voltage applies a forward voltage to D4 and D2, causing them to conduct, while applying a reverse voltage to D3 and D1, causing them to cut off. This forms a circuit consisting of the power supply, D4, R, and D2, generating a half-wave rectified voltage with positive polarity at the top and negative polarity at the bottom of R.

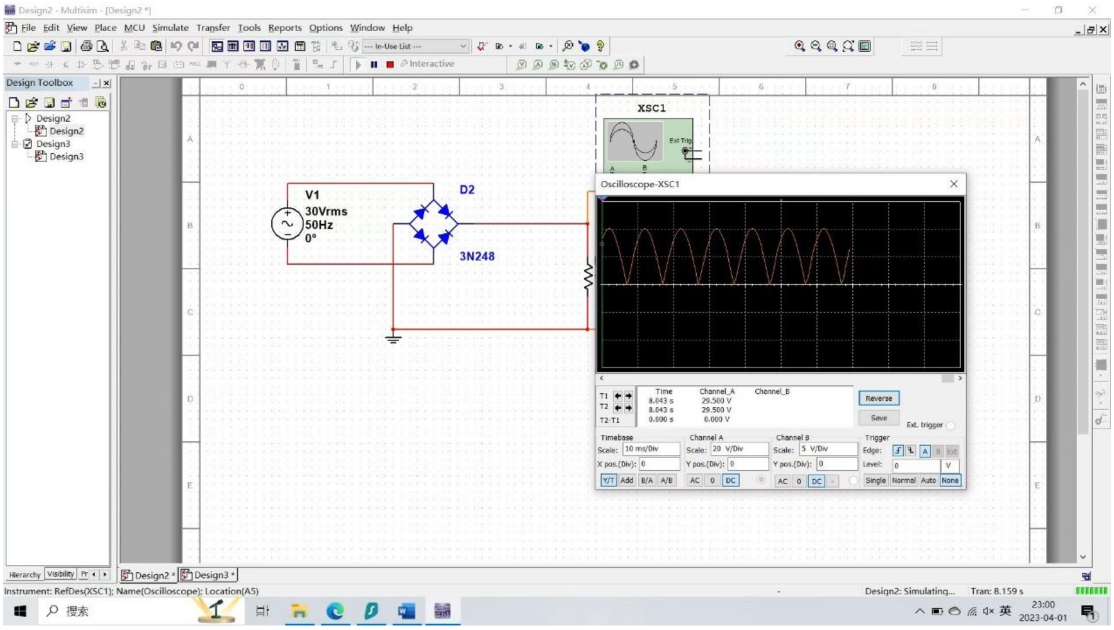


When the currents in both directions are combined, regardless of the direction of the positive pole of the power supply, the direction of the current through resistor R is always from top to



bottom, remaining the same. This makes the current flowing through the left and right sides of the rectifier bridge in the circuit direct current.

After adding the full bridge circuit, it can be seen through simulation that the output is a pulsed direct current, which means that the negative current is folded along the x-axis and becomes positive. The utilization efficiency of the input sine wave is doubled by the bridge rectifier compared to the half-wave rectifier. Bridge rectification is the first step in converting alternating current into direct current.



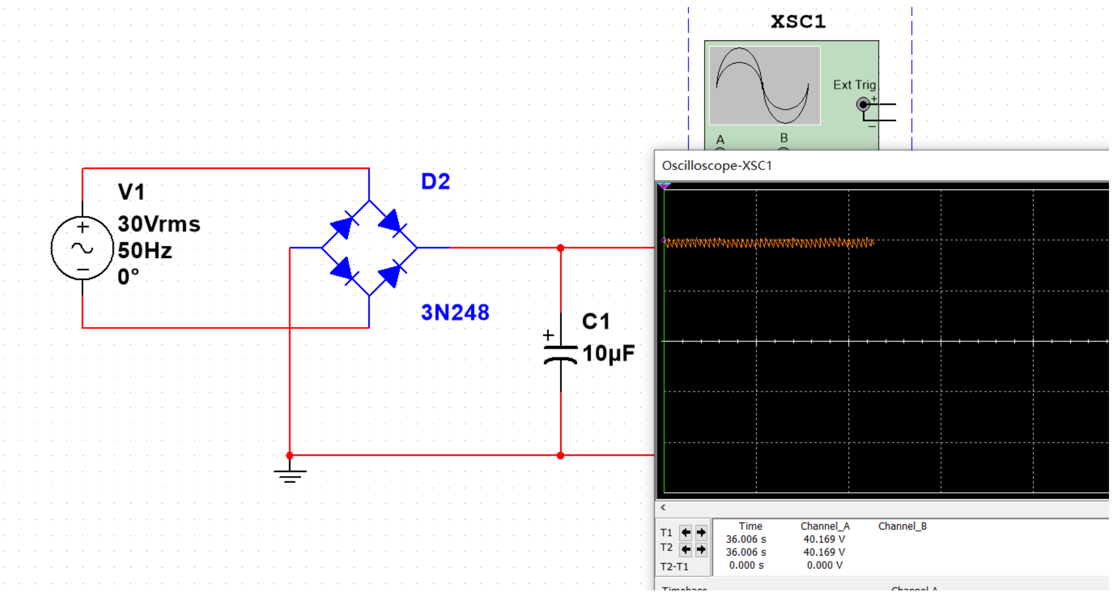
Notice that, when using two-phase mixed stepping motors to generate two AC power sources, they must be converted to DC power before they can be combined. This is because the two AC voltages differ by 90 degrees due to the nature of the motor. However, the necessary conditions for combining AC power are that the voltage level, waveform, frequency, and phase are all identical. If these conditions are not met, the combined power source may lead to voltage instability, current imbalance, power loss, and other issues.

2.3 Filter capacitor

Next, to convert the pulsating DC into a steady, constant voltage DC that is common in our daily lives (the value of voltage dose not change with the time goes by), we need to use capacitors for filtering.

Capacitor filtering involves using the charging and discharging characteristics of capacitors to smooth out power signals, eliminating high-frequency noise and transient changes in the power source. This is accomplished through the use of an RC low-pass filter, which consists of a resistor and capacitor.

When an input voltage (Vin) enters the capacitor through the resistor, the capacitor begins to charge until its voltage equals Vin. During this process, the circuit formed by the resistor and capacitor produces a filtering effect that only allows low-frequency signals to pass through while blocking high-frequency signals. The effectiveness of capacitor filtering is affected by the size of the capacitor, the resistance value of the resistor, and the frequency of the input signal.

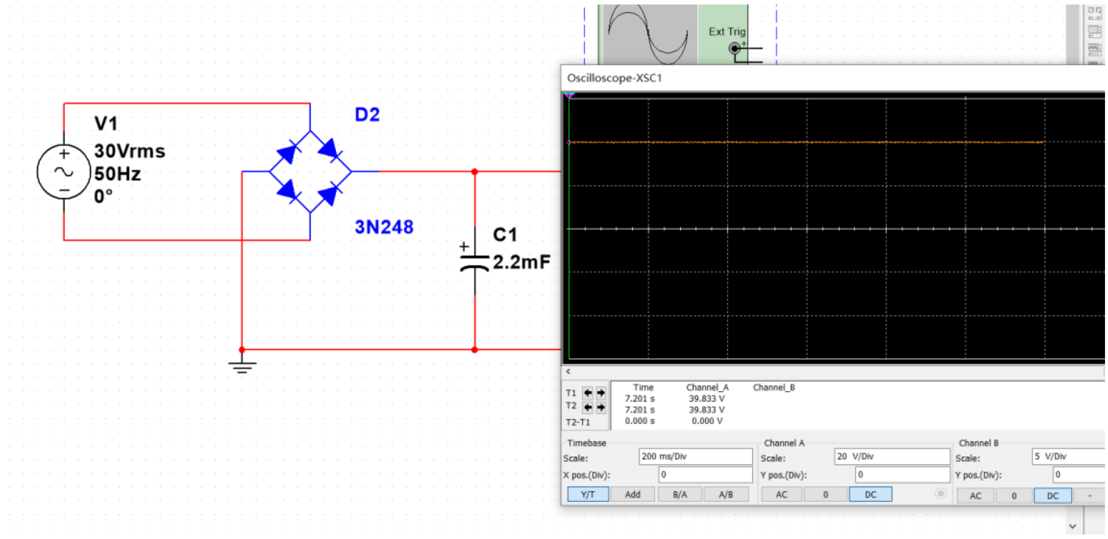


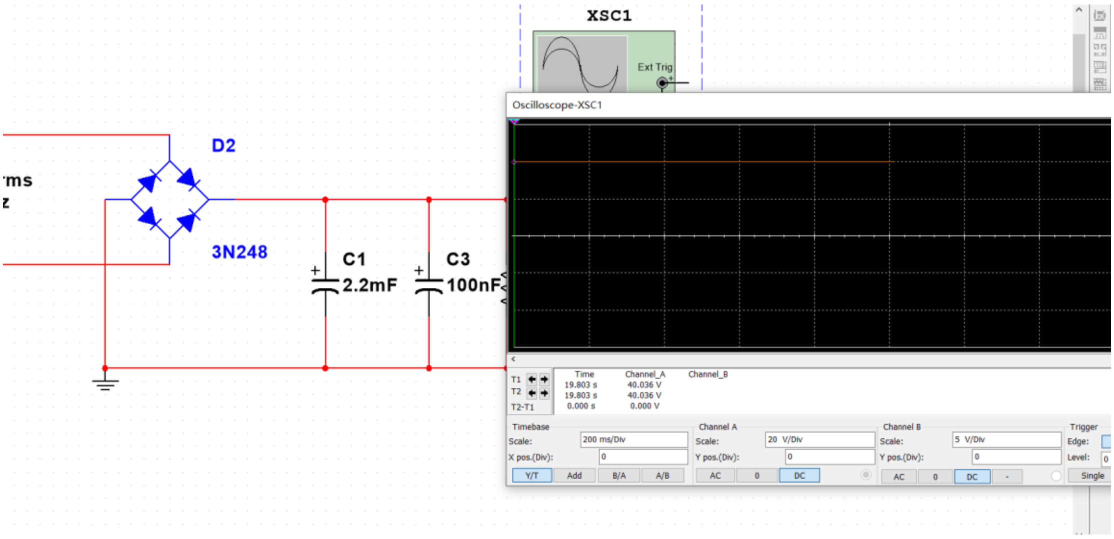
Choosing an appropriate capacitor size and resistance value can achieve the required cutoff frequency of the filter, thus achieving effective filtering of high-frequency signals. A larger capacitor size results in a lower cutoff frequency and better filtering performance, while a higher resistance value also lowers the cutoff frequency but increases power consumption.

In practical applications, it is important to select the appropriate capacitor and resistor values based on specific requirements. For filtering out higher frequency signals, a smaller capacitor value and a larger resistor value should be selected, while filtering out lower frequency signals requires a larger capacitor value and a smaller resistor value. However, if the filter capacitor's capacitance is chosen to be too large, it can increase the cost of the voltage regulator and result in a large surge current during power supply turn-on. Similarly, if the capacitance is chosen to be too small, it can result in larger power supply output voltage ripple.

It is important to note that the experiments have shown that the filtering ability of capacitors does not increase linearly with increasing capacitance, and there exists an optimal capacitance value beyond which further increases in capacitance provide negligible improvement in filtering ability. When choosing capacitors, other parameters such as rated voltage and operating temperature must also be considered to ensure the stability and safe operation of the circuit.

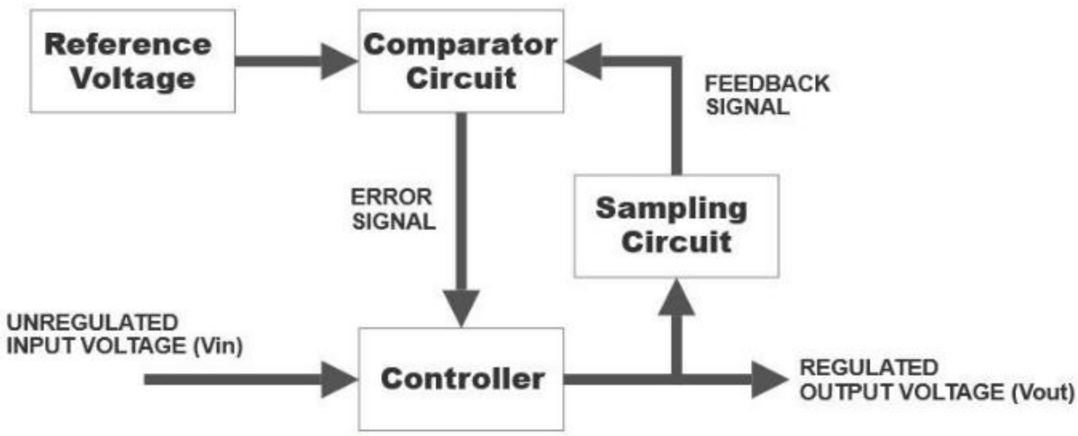
After the current passes through the rectifier bridge, through multiple rounds of testing, we place a relatively large capacitor C1 = 2.2mF, which is also called the rectifier capacitor. It can filter out a large amount of low-frequency output ripple in the waveform, quickly making the current smooth, and only containing occasional high-frequency output ripple. Next, a 100nf capacitor C3 is connected after C1, which is called the dielectric capacitor. Its main function is to filter out subtle high-frequency output ripple and protect the circuit.





2.4 Voltage stabilizer

Voltage stabilizer is an important component to regulate voltage. Voltage regulation refers to the ability to supply a stable voltage without noise or interference. The output of a voltage regulator is not affected by changes in load current, temperature, or AC power lines. It can provide the required output voltage regardless of how the input voltage or load conditions change. Electronic circuits rely on voltage regulators because they require a stable voltage supply to avoid damage. Voltage regulators are present in almost all electronic products or household appliances (such as TVs, refrigerators, computers, etc.) to stabilize the power supply voltage. In general, voltage regulators can minimize voltage fluctuations to protect equipment. In the distribution system, voltage regulators are either in the feeder or in the substation. There are two types of voltage regulators used in this series. One is a step voltage regulator, which uses switch regulation to adjust the current supply. The other is an induction regulator, which is an AC motor similar to an induction motor and provides power as an auxiliary power source to minimize voltage fluctuations and provide stable output. Voltage regulators use the principle of feedback control system, relying on a negative feedback control loop.



As shown in the above diagram, the reference voltage signal and feedback signal from the controller are provided to the comparator circuit. The comparator circuit compares the two values and sends an error signal to the controller, which uses the error signal from the comparator to adjust the output voltage.

Currently, voltage regulator circuits are mainly divided into three types, including linear voltage regulator circuits, Zener voltage regulator circuits, and switching voltage regulator circuits. Linear voltage regulator circuits are the most common voltage regulators used to maintain stable output voltage in electronic products. The linear voltage regulator is like a voltage divider circuit, in which the resistance varies with changes in the load and provides a constant output voltage.

The following are the advantages and disadvantages of linear voltage regulators:

	Advantage	Disadvantage
1	Low output voltage ripple	Low efficiency
2	Fast response speed	High power dissipation and heat generation
3	Low noise	Limited maximum output current capacity

For the selection of the voltage stabilizer, we chose the LM7805CT. The LM78 series three-terminal voltage stabilizer IC requires very few peripheral components to form a voltage stabilizer power supply, and the circuit has built-in protection circuits for over-current, over-temperature, and adjustment tubes. It is reliable, convenient to use, and inexpensive. The digits after LM78 in the integrated voltage stabilizer IC represent the output voltage of the three-terminal integrated voltage regulator circuit. For example, the LM7805 we selected represents an output voltage of +5V.

The LM7805CT chip is a type of linear voltage stabilizer used to stabilize input voltage and output a fixed voltage. Its minimum input voltage is 7V, maximum input voltage is 35V; minimum operating temperature is 0°C and maximum operating temperature is +70°C; load regulation and line regulation are both 100mV. Specifically, its main functions include:

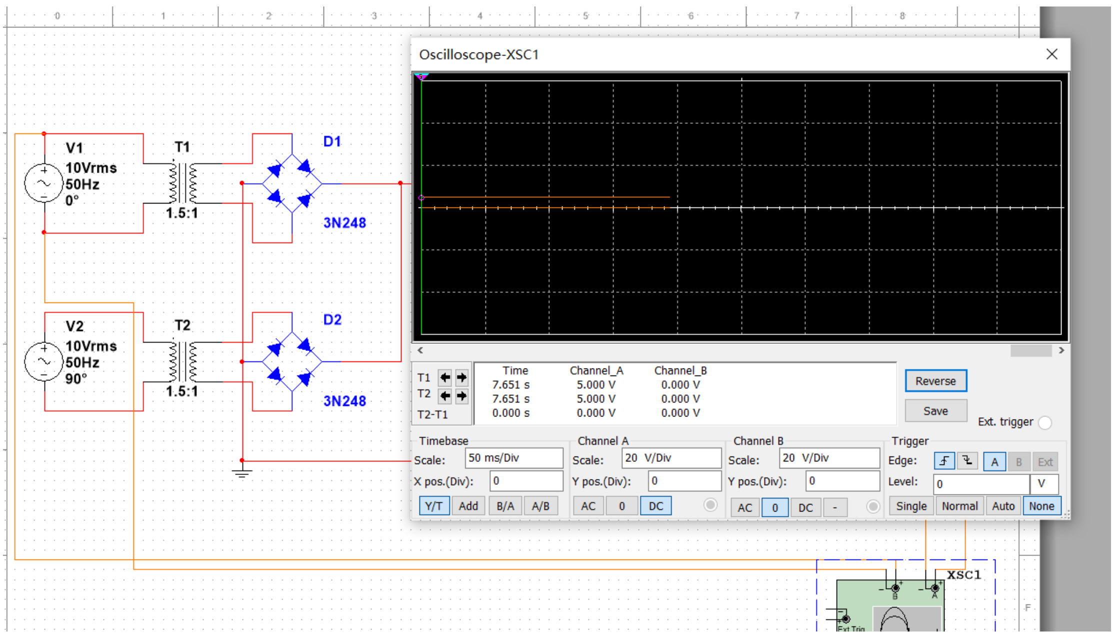
1. Voltage regulation: The main function of the LM7805CT chip is to adjust the input voltage to a stable output voltage. It can stabilize input voltage within the range of 7V-35V and fix the output voltage at 5V. When the input voltage changes, it can keep the output voltage constant through its internal circuit.
2. Current limiting: To ensure the stability of the chip, current limiting is automatically performed at the output port. The maximum current that the LM7805CT chip can output is 1A. If it exceeds this range, the chip will protect itself, meaning the output circuit will not be damaged.
3. Thermal protection: Since voltage regulator components generate a large amount of heat during operation, exceeding the range that the chip can withstand can result in burning out. The LM7805CT chip has a built-in thermal protection circuit that automatically cuts off the output

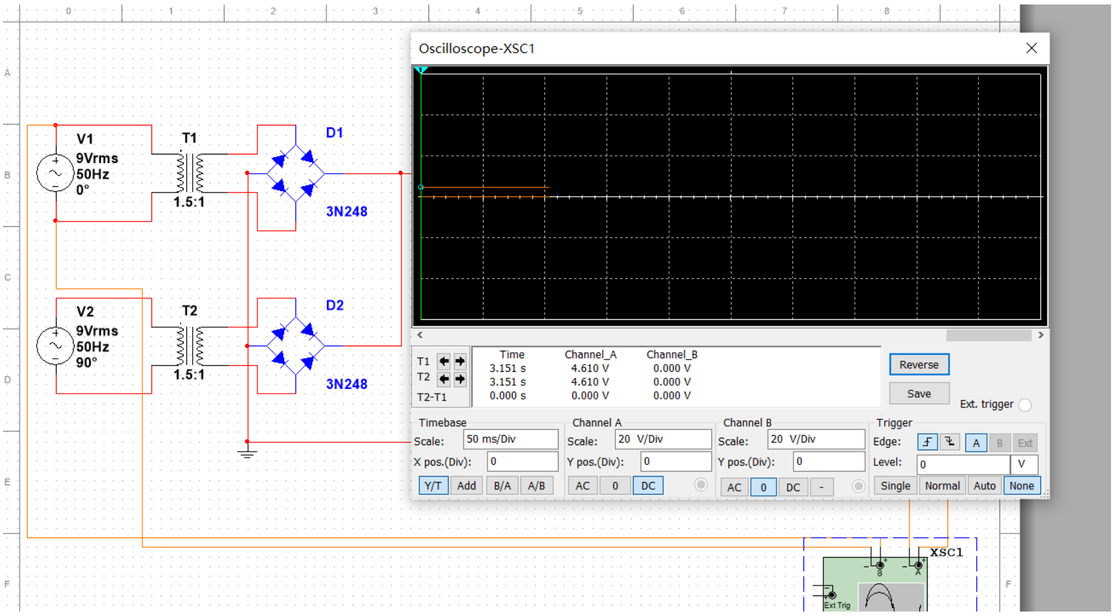
circuit when the temperature reaches a certain level, thereby protecting the voltage regulator component.

In addition, the LM7805CT chip has the following advantages:

1. High stability: The chip can keep the output voltage constant, ensuring circuit stability.
2. Easy to use: The wiring for the LM7805CT chip is relatively simple. Only the input voltage needs to be connected to the IN port, and the output port needs to be connected to the controlled device.
3. Low cost: The LM7805CT chip is relatively inexpensive and widely used in various electronic devices.

In summary, the LM7805CT chip is a voltage regulator used for voltage adjustment in circuits, outputting stable voltage values, and ensuring circuit stability and safety. Using the LM7805CT chip can stabilize the circuit's operation, and because the LM7805CT is relatively inexpensive, it is well-suited for our project's use case. After completing the circuit connections, we began testing the circuit's operation. When measuring the minimum input voltage, we obtained the following experimental data:



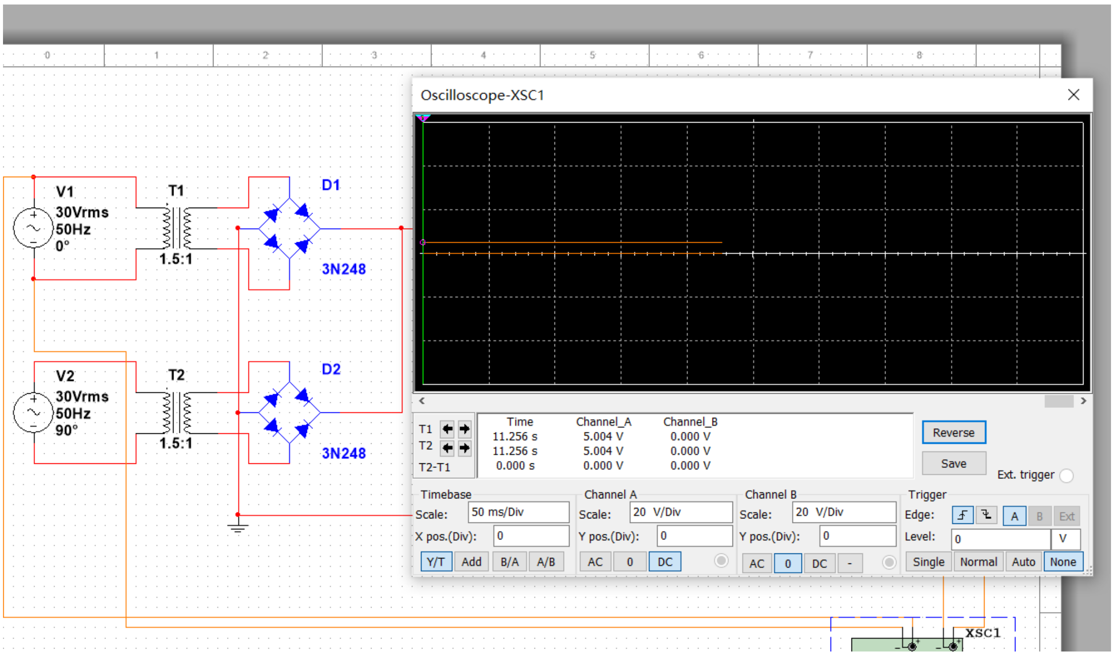


As shown in the figure, the DC output voltage of the circuit is 5.000V at a input voltage of 10V, indicating that the circuit is operating normally. However, at a input voltage of 9V, the output voltage is only 4.610V, which is too low to meet the output requirement of around 5V. Therefore, we conclude that the minimum input voltage is between 9V and 10V. We then continued to change the input voltage and obtained the following table:

In	Out
9.1V	4.705V
9.2V	4.826V
9.3V	4.917V
9.4V	4.995V
9.5V	5.000V
9.6V	5.000V
9.7V	5.000V

According to our measurement, the output DC voltage is very close to 5V when the input voltage is above 9.3V, and it stabilizes at 5.000V when the input voltage is above 9.5V. Therefore, we conclude that our circuit can operate normally when the wind speed reaches 9.3V or higher, and the minimum input voltage is 9.3V.

In our scenario, the theoretical maximum voltage that the wind speed produced can reach 30V, which means the input voltage is 30V. We substituted 30V into the simulation and obtained the following result:



Based on the simulation results, we can see that the designed circuit can output a voltage of 5.004V under the input voltage of 30V, which can operate successfully in this scenario.

2.5 Filter again

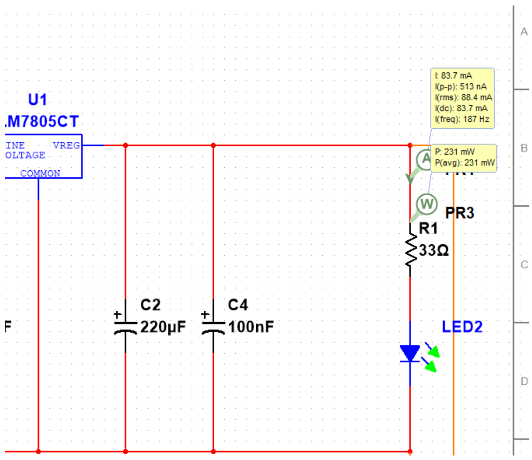
After the current passes through LM7805, we need to filter the current again. When the load is connected, the power consumption of the load is not stable, and the size of the load power consumption will change. The response speed of LM7805 is slower than the speed of the signal change, which means that the supply speed of LM7805 cannot keep up with the speed of the load power consumption change. This can cause unstable or rapidly fluctuating 5V DC voltage (interference from the load). The frequency of this fluctuation is the same as the frequency of the load signal.

To reduce this fluctuation, a filter capacitor can be added to this circuit. Compared with a regular power supply, the response speed of the filter capacitor is faster, meaning that its charging and discharging speed are relatively fast, similar to a fast-changing small power supply. This allows the fluctuation to be reduced. As long as LM7805 keeps charging this filter capacitor, the filter capacitor can quickly supply power to the load.

To further improve the performance of the filter capacitor, a large capacitor can be connected in parallel with a small capacitor. The frequency flowing through the capacitor is related to the size of the capacitor. The smaller the capacitor, the shorter the charging time, and the higher the frequency that can pass through it. On the other hand, small capacitors have good high-frequency performance because of their small size, which reduces the ESL and shortens the lead wires. However, due to their small capacity, small capacitors have a large impedance to low-frequency signals. To allow both low-frequency and high-frequency signals to pass through smoothly, a large capacitor is combined with a small capacitor. Additionally, because small capacitors can respond quickly to instantaneous current, the small capacitor is connected near the load so that it can supply power to the load quickly. Therefore, adding a filter capacitor after LM7805 can help to stabilize the output voltage and reduce the ripple caused by load fluctuations.

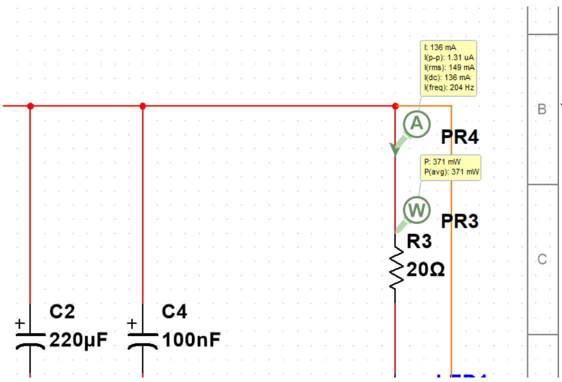
2.6 Current control

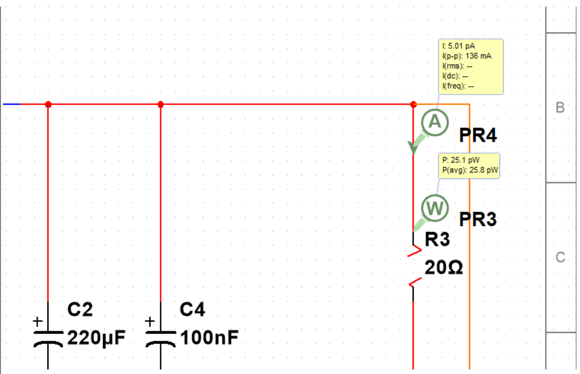
According to the parameters of the USB interface, when using the USB port as a charging port, the maximum current that can pass through it should not exceed 500mA (The value of maximum high power current). Therefore, we need to add a limiting resistor to the circuit to control the output current within a manageable range. Initially, we tried adding a resistor directly to the circuit, but the resulting current was too small to meet the power supply requirements of the USB interface.



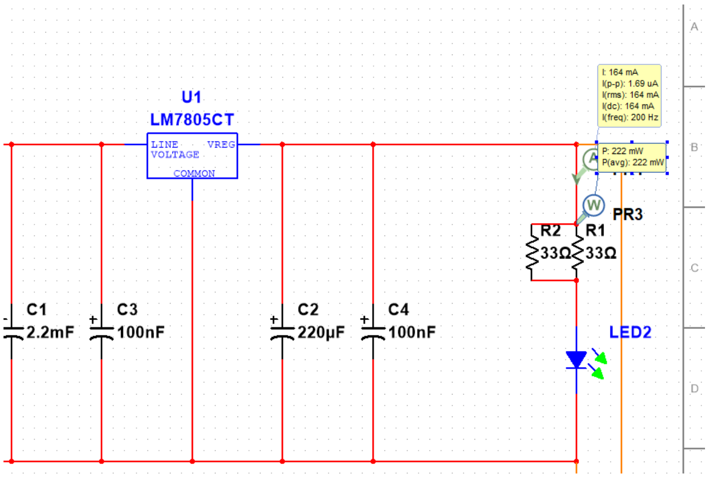
P2 The current is only 83.7mA

We tried changing the size of the resistor to 20 ohms, and the resulting current was 136mA, which met the requirements. However, the power on the resistor at this time was 371mW, exceeding the rated power of the resistor of 250mW. After a few seconds, the resistor burned out.





Therefore, we decided to connect two resistors in parallel. According to the properties of parallel circuits, the voltage applied across each branch remains constant. According to the formula for calculating the equivalent resistance of parallel resistors $R = \frac{R1 \times R2}{R1+R2}$ we know that the total resistance decreases after the resistors are connected in parallel. Through repeated attempts and calculations, we connected two 33 ohms resistors in parallel in the circuit. Each resistor could withstand a power of 222mW, which is within the safe range. At the same time, the current in the circuit was increased to 164mA, which well meets the power supply requirements of the USB interface.。



Using a current-limiting resistor can also serve as a protective measure that against the overcurrent. If the voltage and current surge unexpectedly or if there is a quality issue with the resistor that causing itself to burn out, the circuit will immediately break. It can ensuring the safety of the device being powered. Additionally, we added a light emitting diode to the circuit that illuminates to indicate that the circuit is functioning properly.

3. Result

By changing the input AC voltage several times, we get the following results:

Input voltage	Output voltage	Error
10V	5.000V	0
15V	5.0001V	0.0001
20V	5.0002V	0.0002
25V	5.0003V	0.0003
30V	5.0004V	0.0004

DC component (mean):

$$\bar{V} = \frac{1}{n}(\sum_{i=1}^{n} V_i)$$

So, the mean value of output voltage in out designed circuit is

$$\bar{V} = \frac{1}{5}(5.000 + 5.0001 + 5.0002 + 5.0003 + 5.0004) = 5.0002V$$

Noise (standard deviation):

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(V_i - \bar{V})^2}$$

So, the standard deviation output voltage in out designed circuit is:

$$\sigma = \frac{1}{5}(0.00000004 + 0.00000001 + 0 + 0.00000001 + 0.00000004) = 0.00000002$$

From the table and calculation results, it can be seen that our circuit has extremely high accuracy, which can meet the requirements of USB power supply perfectly. What's more, the cost of producing this circuit is super low, too.

Components	Price
3N248 Rectifier bridge*2	0.9£
2.2mF Capacitance	0.033£
100nF Capacitance*2	0.005£
220uF Capacitance	0.0093£
LM7805CT	0.47£
33 Ω Resistance *2	0.005£
Transformer*2	2£
17HS4401 Motor	3£
Total: 6.4223£	

4. Conclusion

Through the analysis of various parts of the circuit and the calculation of simulation results, it can convert input AC voltage into stable DC voltage for output. The mean value of output voltage in our designed circuit is 5.0002V, and the standard deviation is only 0.00000002, which can perfectly meet the power supply requirements of USB ports. At the same time, we have also designed simple protective measures in the circuit. When the current suddenly increases due to abnormal reasons, the resistor will be burnt out to break the circuit. The light-emitting diode can indicate that the circuit is operating normally. The total cost of components required for manufacturing our circuit is only 6.4223£, which is very easy to purchase and produce. We also hope to turn the circuit design into a finished product in the future, test its performance in real-life situations, and improve it as a reliable power supply circuit for camping enthusiasts, making life more convenient.