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Research Article

Design and Simulation of Automatic over and Under-voltage Protection Systems for Home Equipment

Lidia Bitew Techane[1], Mebratu Sintie Geremew[2, 3, *], Kassahun Ashagrie Chanie[2]

[1]Department of Electrical and Computer Engineering, University of Gondar, Gondar, Ethiopia

[2]Department of Electrical & Computer Engineering, College of Engineering and Technology, Mizan-Tepi University, Tepi, Ethiopia

[3]Institute of Energy and Enviromental Technology, Jomo Kenyatta University of Agriculture and Technology, Juja, Kenya

Abstract

Voltage magnitude fluctuation in AC mains supply is a common issue in power systems. Electronic devices in these conditions are sensitive and can be easily damaged, making it crucial to have a protection mechanism to safeguard the load. This paper aims to design a protection system that can protect low-power electrical appliances like home appliances from Undervoltage and overvoltage. The protection system designed in this paper possesses a tripping mechanism that is activated by the output of two comparators; one for undervoltage and the second for overvoltage. The designed protection system trips the loads in the event of the input voltage falling below 198 V or above 243 V. Two window comparators, formed from a quad comparator IC, generate an error output if the input voltage exceeds the voltage window. A relay is then operated to cut off the load for safety reasons. The designed system is simulated using Proteus 8.1. As a result the protection system trips off the load when the supply AC mains voltage is below 198 V or above 243 V; and when the supply voltage is between 198 V-243 V, the load is not disconnected. The system is fully automatic as it switches on the load when the supply voltage restores to its normal range. Therefore this paper is designed to protect over and under voltage for home appliances automatically to make the equipment safe.

Keywords

Home Equipment, Over and Under Voltage, Protection System

1. Introduction

Background of the Study

Electronic and electrical appliances used in most homes in the country are designed to operate at a nominal 220 V AC, which ought to be acceptable within certain tolerable limits [1]. Excessive fluctuations beyond these limits may cause the appliance to malfunction or get irreparably damaged. Voltage fluctuations in electric power supply can have detrimental effects on connected loads. These can be over voltage and under voltages which are caused by several reasons like voltage surges, lightning, overload, etc [2]. Over voltages are the voltages that exceed the normal or rated values which cause insulation damage to electrical appliances leading to

*Corresponding author: mastie712@gmail.com (Mebratu Sintie Geremew)

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short circuits. Under-voltage can lead to equipment overload, causing excess current through the device and inefficient performance [3-5].

This paper aims to enhance automatic functionality for turning off and on the main power supply to home devices in case of over or under voltage. Under and over-voltage protection systems for homes are designed to ensure the protection of home devices like fans, light lamps, televisions, refrigerators, and all other things needed to protect in case of under and overvoltage in main supply [6]. So automatic protection of home appliances is important to prevent the electrical equipment from damage [7, 8]. The outputs of the designed circuit are directly connected to the load or the appliance together with the relay. When over and under voltage comes the relay disconnects the load. In this case, the load or the electrical appliance is protected from over and under voltage. In this paper's design safe tolerable limit is 10%, so the normal supply range is between 198 V and 243 V. Whenever the voltage is below 198 V or above 243 V the load is disconnected. The appliance is automatically reconnected when the mains power returns to normal within that limit.

So, the main emphasis of this paper is.

a) To design the over or under-voltage protection system.
b) To design the DC power supply circuit for the protection system.
c) To model and simulate the over or under-voltage protection system by the established design parameters using proteus8 professionals.

2. Methodology and Data Analysis

2.1. General Procedure of System

As shown in Figure 1 below, the general methods of this paper are organized and accomplished through a sequence of stages. Before all, the reviewed related literature, the general block diagram of the system was used to easily analyze each component of the system and explain their type identification and specification explained.

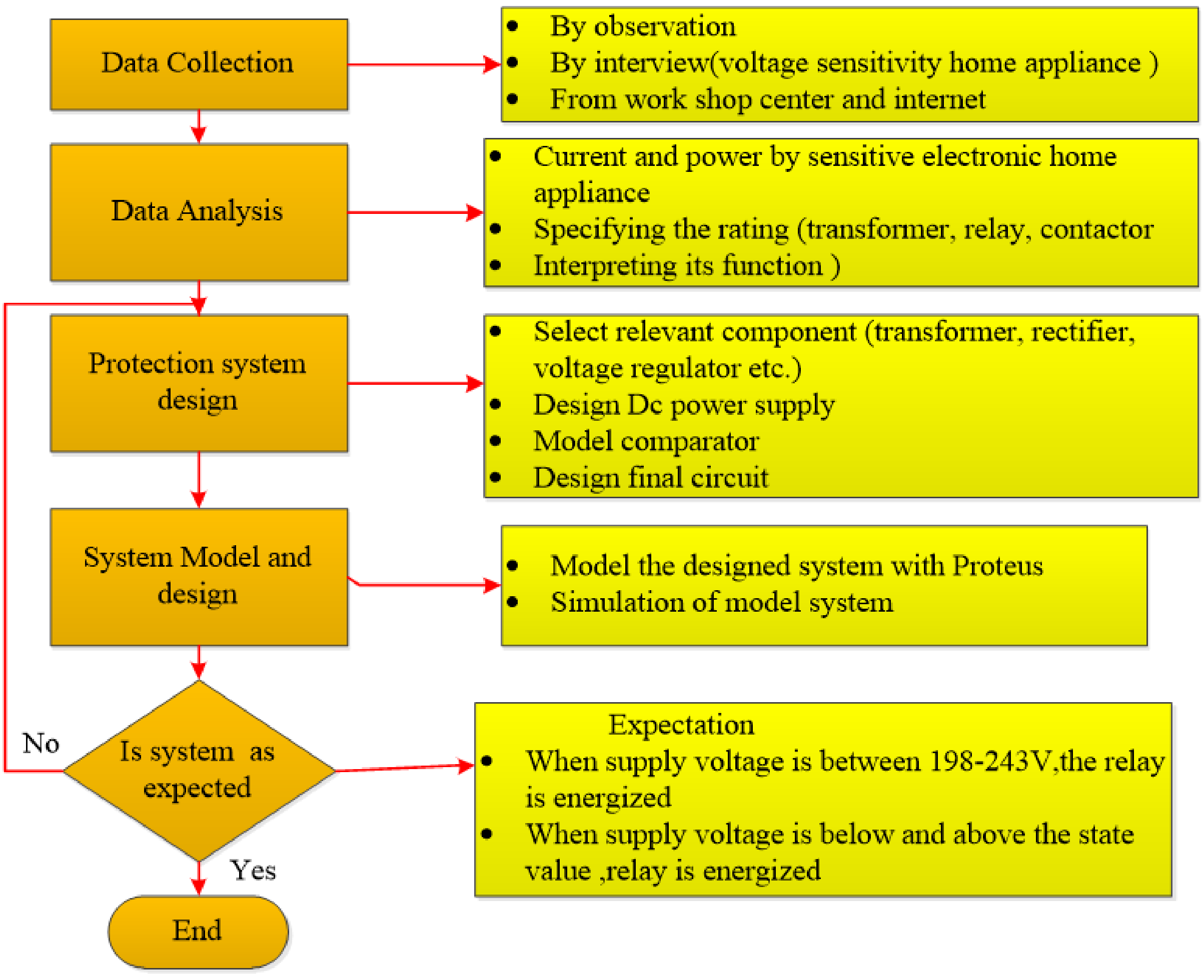

Figure 1. General procedure.

2.2. System Description and Overall Operation

Having investigated such a problem and reviewing related literature, finally proposed an automatic over and under-voltage protection as described in the general block diagram shown in Figure 2 below. The components and devices used in this system are explained in the sections below.

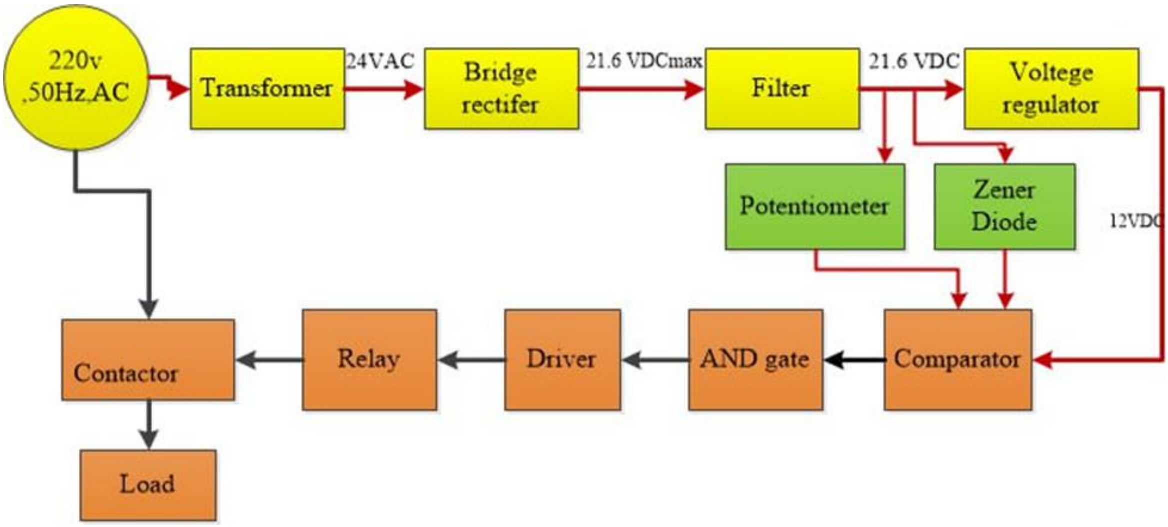

Figure 2. Overall block diagram of the system.

AC supply is stepped down to 24 V by using a step-down transformer. The AC supply is converted to a DC supply through a bridge rectifier. The supply is then filtered by capacitors connected across the rectifier to reduce harmonics. The unregulated supply is then fed to the voltage regulator whose output is given to the comparator Lpc661A. Then the output of the comparator is fed to the digital circuit and the signal is transferred to the relay as supply. Comparators detect overvoltage or Undervoltage, analyze preset conditions, signal relay trips, and switch off the load, protecting electrical appliances.

2.3. Design and Analysis of the System

2.3.1. Transformer Selection

To choose the required transformer the power rating, current rating, and voltage level should be considered. According to this paper, the design needs a step-down transformer that changes 220-volt AC into 24 V.

2.3.2. Transformer Parameter Calculation

1) Secondary winding calculation of transformer

The 220 V AC to 24 V AC step-down transformer is used for this system. The transformer has 110 turns of coil in the primary, therefore secondary winding turn's calculated using equation.

$$\frac{N_1}{N_2} = \frac{V_1}{V_2} \tag{1}$$

$$\frac{110}{N_2} = \frac{220}{24}$$

$$N_2 = 12 \text{ turn}$$

Where: -

N_1 & N_2 are the numbers of turns in the primary and secondary winding of the transformer respectively.

V_1 & V_2 voltage values on the primary and secondary winding of the transformer respectively.

The above calculation shows that the secondary transformer has 12 turns and the turn ratio of the transformer is N_1: N_2 (110: 12).

2) Transformer primary current calculation

The step-down transformer is a transformer that has a lower voltage in the secondary than the voltage in the primary. But in the case of current it would step up i.e. the current at the primary is lower than the current at the secondary side of the transformer. The secondary current is 1 A, and then the calculation will be verified using the equation as follows:

$$\frac{N_1}{N_2} = \frac{I_2}{I_1} \tag{2}$$

$$\frac{110}{12} = \frac{1}{I_1}$$

$$I_1 = 109.1 \text{ mA}$$

Where: -

I_1&I_2 Current rating of the primary and secondary winding of the transformer respectively.

The above calculation shows that the step-down transformer has stepped up the primary current from 109.1 mA to 1 A at the secondary.

2.4. Regulated DC Power Supply Circuit Design

This paper chose the primary and secondary turns of the step-down transformer 110 and 12 respectively. Then the DC and voltage are calculated as follows: $N_1/N_2 = a = V_1/V_2 = 110/12$. Using the turn ratio could calculate the secondary voltage of the transformer.

$$V_2 = \frac{N_2 V_1}{N_1}$$

$$V_2 = \frac{12*220}{110} = 24$$

the peak value of the input voltage (Vp) would be $\sqrt{2}$ times the R.M.S. $Vp = \sqrt{2}$ *24=33.9 V; Now the DC voltage (V_{dc}) would be

$$\text{Vdc} = \frac{1}{\pi}\int_0^{\pi} \text{Vsin}\omega\tau d\omega \quad \tau \tag{3}$$

$$\text{Vdc} = \frac{2*v}{\pi} = \frac{2*33.9}{3.14} = 21.6\text{V}$$

The load resistance is the total resistance connected next to the rectifier circuit: -

V_{R1}=10 kΩ, R_1=1.92 kΩ, R_2=1.28 kΩ, R_1 and R_2 calculated from zener diode specification R_3=9.9 kΩ, calculated from transistor.

V_{R1} and R_1, V_{R2}, and R_2 are in parallel orientation series with R_3. R_1 and R_2 are calculated below at zener regulation. Now

$$R_{total-1} = \frac{V_{R1} \times R_1}{V_{R1} + R_1} \tag{4}$$

$$\frac{10*1.92}{11.92} = 1.61\text{k}\Omega$$

$$R_{total-2} = \frac{V_{R2} \times R_2}{V_{R2} + R_2} \tag{5}$$

$$\frac{10*1.28}{11.28} = 1.14k\Omega$$

Then $R_{equ} = R_{total-1} // R_{total-2} + R_3 = \frac{1.61*1.14}{2.75} + 9.9 = 10.57\text{K}\Omega$

The Direct Current (DC) value should be

$$\text{Idc} = \frac{\text{Vdc}}{\text{R}} \tag{6}$$

$$\frac{21.6\text{V}}{10570\Omega} = 2.045\text{mA}$$

When the smoothing capacitance is added, It removes the ripples from the output of the rectifier and smoothens the DC output received from this filter is constant until the mains voltage and load is maintained constant. The value of the capacitance should be much greater than one over the product of the resistor and the ripple frequency.

i.e. $C >> \frac{1}{R*f}$, where is the resistor, C is the capacitor, f is the frequency

Now, $C >> \frac{1}{10570*100} = 0.95\mu f$

Hence, the value should be much greater than 1.013 μf

Choose capacitor value is 4000 μf

The ripple voltage (V_r) is calculated using the following formula

$$V_r = \frac{Idc}{c*f} \tag{7}$$

$$\frac{2.045\text{mA}}{400\mu f*100\text{HZ}} = 0.0051\text{V}$$

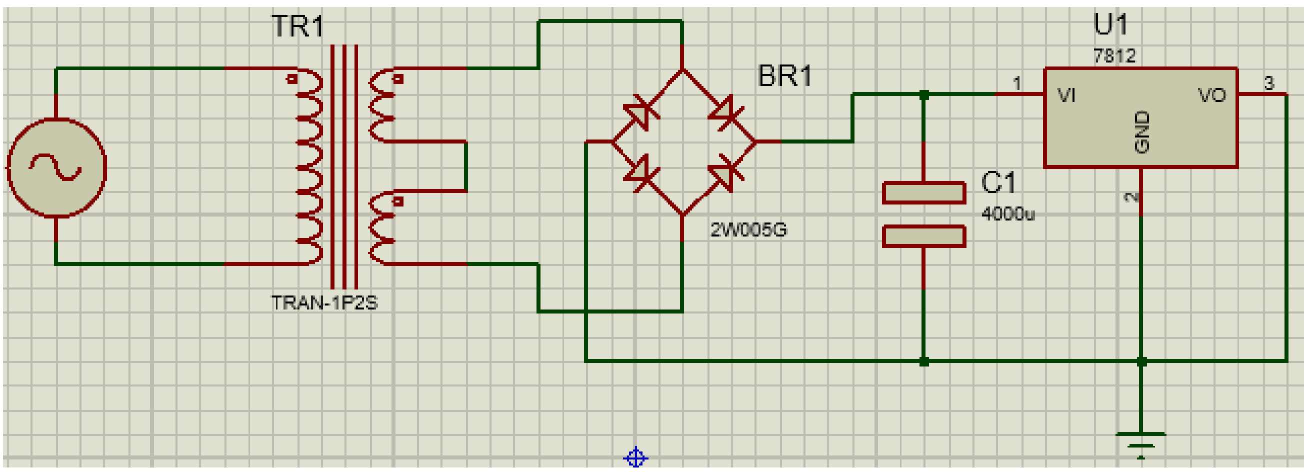

Figure 3. Regulated DC Power Supply Circuit design.

2.5. Voltage Sensing Comparator

One of the simpler circuits and more commonly used circuits is the op-amp comparator. A comparator compares two voltages and if one is greater than the other the output of the op-amp is either ON or OFF [9, 10]. There are two components that the comparator has to work with to determine at what voltage it switches ON and at what voltage it switches OFF [11]. Component 1: Reference Voltage; The reference voltage is a set voltage that would be used to compare against the sensing voltage. The reference voltage can be created using a voltage divider resistor network or a Zener diode. There are many ways to create a reference voltage but this paper used a zener diode for stability even if the supply voltage changes slightly. The Zener diode's nominal voltage is the reference voltage of the comparator. Component 2: The sensing voltage has been the input voltage. Instead of one reference voltage value, two reference voltages are implemented by a pair of voltage comparators. An op-amp comparator is triggered when an upper voltage threshold, VREF (UPPER), is detected, and a lower voltage threshold level, VREF (LOWER), is detected [12]. the overall circuit diagram of the voltage sensor comparator is shown in Figure 4 below.

Table 1. *Specification.*

Type	LPC661A
Operating Voltage	From +5 V to +5 V
Input Current	55 Ma
Specified load	100 kΩ and 5 kΩ
High voltage gain	120 Db

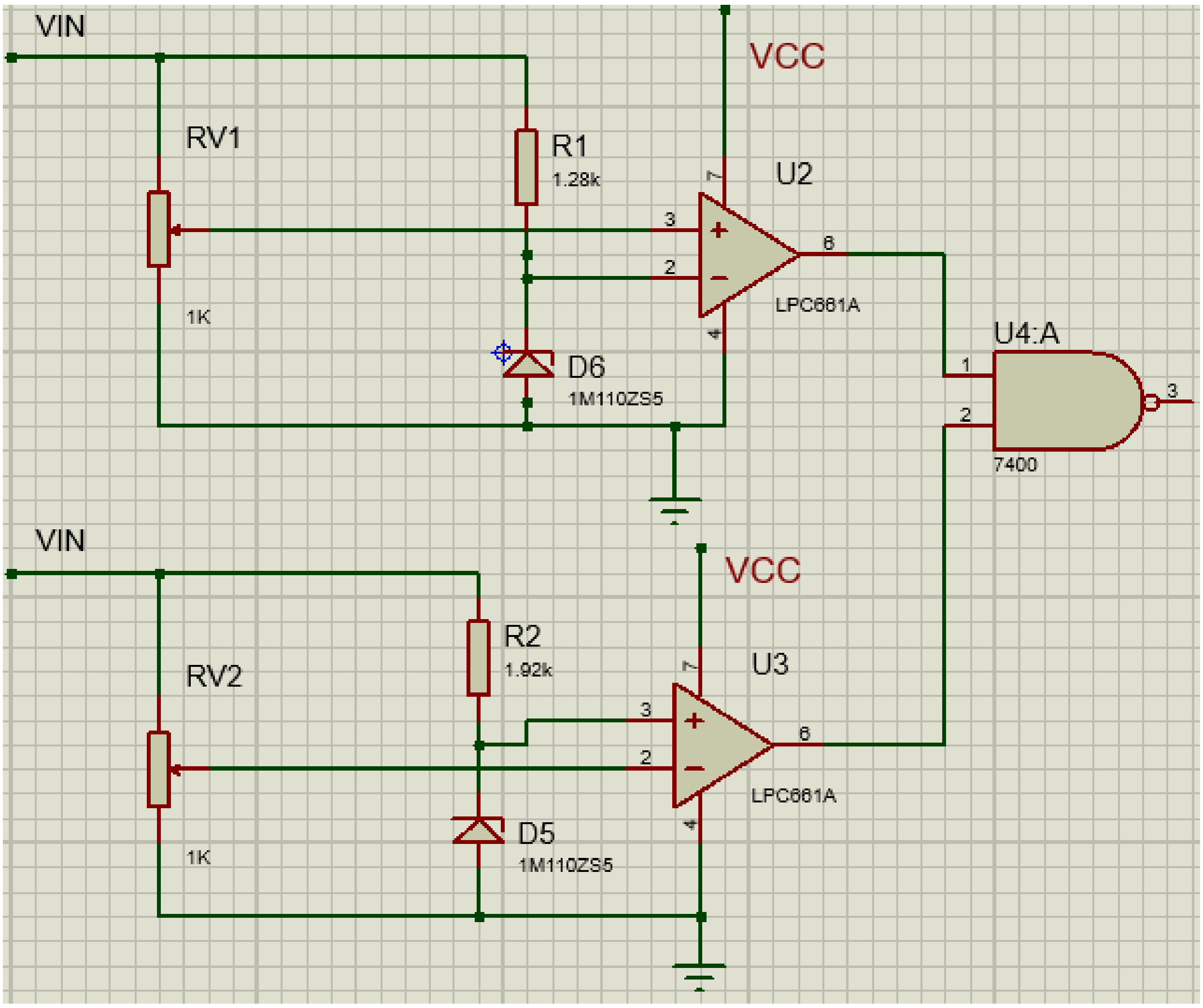

Figure 4. *Circuit diagram of voltage sensor comparator.*

Calculation of Resistors Series with Zener Diode

Based on the information gathered from the datasheet the parameter is calculated as follows: BZV90C5V6 Zener diode datasheet information [8]:

Maximum dissipation power =1.5 W, Nominal Voltage (VZ) = 5.6 V, Nominal current (IZ) =5 mA.

Then maximum resistor value is

$$R_1=\frac{\text{Vin}-\text{VZ}}{\text{IZ}}=\frac{12-5.6}{5\text{mA}}=1.28\text{k}\Omega$$

BZX84C2V4 Zener diode datasheet information [13]:

Maximum dissipation power = 350 mW, Nominal Voltage + 2.4 V to +51 V then select 2.4 V, Nominal current =5 mA.

The resistor value should be

$$R_2=\frac{Vin-VZ}{IZ}=\frac{12-2.4}{5mA}=1.92k\Omega$$

2.6. Transistor Parameter Calculation

The base-bias voltage source, V_{BB}, forward-biases the base-emitter junction, while the collector-bias voltage source, V_{CC}, reverse-biases it, resulting in a nominal forward voltage drop of 0.7 [14].

To calculate the value of the base resistor, the following were considered: V_{IN} = 12 V the relay that is used has a coil resistance of 240 Ω. Therefore, the relay coil current = collector saturating current $=I_{C\,SAT}$ = 12 V/240 Ω = 50 mA. Also, by using Ohm's law, Solving I_B and R_B

$$I_B R_B = V_{BB} - V_{BE} \quad (8)$$

$$R_B = \frac{V_{BB} - V_{BE}}{I_B}$$

where V_{BE}: is the DC voltage at the base concerning the emitter, I_B: is the DC base current, V_{BB}: is the base-bias voltage source, and R_B: is the base resistor.

By using this relationship, it is possible to calculate I_B:

$$\beta_{dc}=\frac{I_C}{I_B} \quad (9)$$

where β_{dc}: DC gain current, I_C: DC collector current

Typical values of β_{dc} range from 50 to 400. BDC is usually designated as an equivalent hybrid (h) parameter, hFE, on transistor datasheets

$$I_B=\frac{\text{IC}}{\beta\text{dc}}=\frac{50\text{mA}}{50}=1\text{mA}$$

$R_B=\frac{V_{BB}-V_{BE}}{I_B}=\frac{10.6-0.7}{1\text{mA}}=9.9k\Omega$, where V_{BB}=12 V-1.4 V=10.6 V

2.7. Selection of Contactor

Power rating of different home appliances

Table 2. *Power rating.*

No.	Appliance	Rating power (watt)
1	Refrigerator	150
2	Television	100
3	Fan	75
4	Cloth Dryer	4000
5	Coffee machine	1400
6	Washing machine	3000
7	Total load	8725

As shown above, the total rating value for the appliance is 8725 watts, so that is better to design:

a) Load (design) current (Ib)
b) Barker current carrying capacity (In)
c) Cable current carrying capacity (Iz)

Then by applying the above given, determine: Load or design current=P∗DF /V, assume pf= 0.8, diversity factor (DF) is 0.7.

$$\text{Ib}=\frac{8725*0.7}{220}=27.76\text{A}$$

Contactor current carrying capacity = $\frac{\text{Ib}}{\text{Pf}}$, In= $\frac{27.76}{0.8}$ = 34.7A

Cable current carrying capacity= $I_2=\frac{\text{In}}{ca*ct*cg}$, at normal temperature ca=ct=cg=1

$$\text{Iz}=\frac{34.75}{1*1*1}=34.7\text{A}\cong 40\text{A}$$

The conductor of cross-sectional area is equal to 4 mm^2 by 40 A current carrying capacity. According to IEC international standards, Generally, Ib < In ≤ Iz, Then selected the contactor that has the above rating value to sustain each appliance functionally [15].

2.8. Overall Circuit Diagram of the System

After calculating the necessary parameters, the next step is drawing or modeling the system. The Finalized circuit diagram of the system is shown in Figure 5 below.

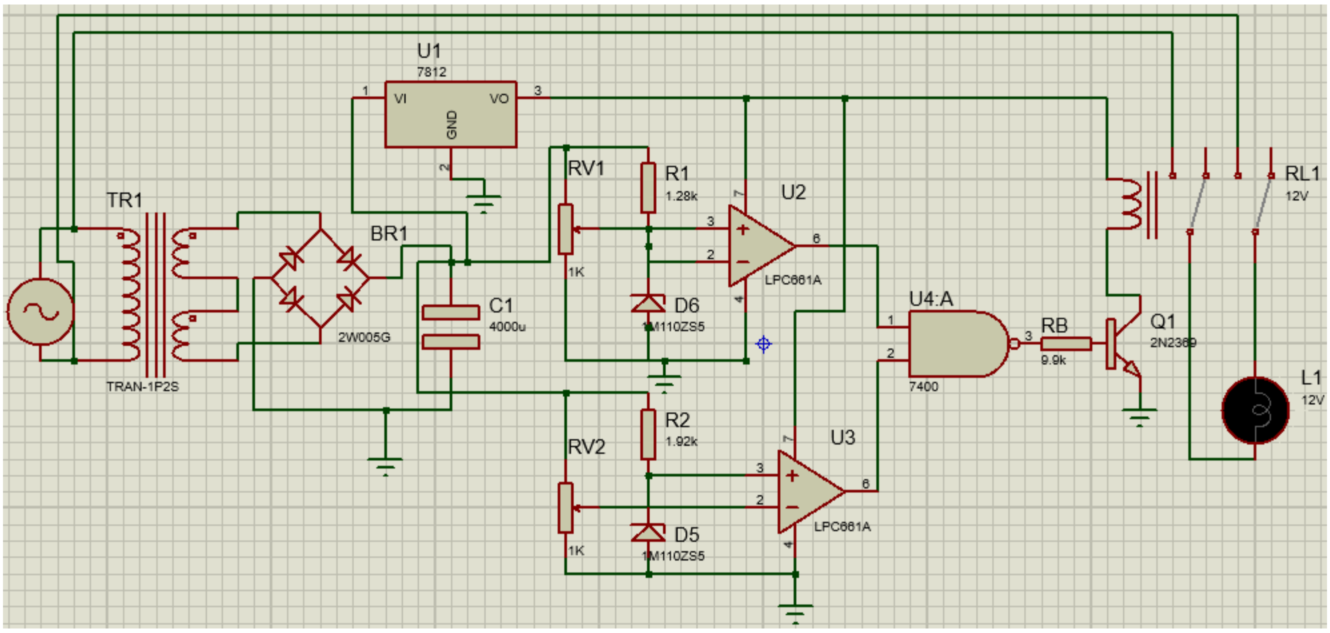

Figure 5. *Finalized circuit diagram of the system.*

The relay/load is turned off when the mains supply exceeds preset limits, and only on when the A.C. mains voltage reaches these limits. The presets V_{R1} and V_{R2} are used for presetting over or under voltage cut-off limits respectively. The limits are set according to load voltage requirements as per manufacturer specifications. Once the limits have been set, zener D_4 will conduct if the upper limit has been exceeded resulting in the cut-off of comparator 2. The same condition can also result when the mains voltage falls below the under-voltage setting as zener D_2 stops conducting. The sensing voltage in comparator 1 is applied to the non-inverting input, this will ensure that once the sensing voltage has exceeded the Reference voltage that must be placed on the inverting input the op-amp will turn ON. In comparator 2 the sensing voltage is applied to the inverting input and the reference voltage to the non-inverting input will have the op-amp OFF when the sensing voltage is above the reference voltage and the op-amp ON when the sensing voltage is below the reference voltage. Depending on the outputs of the comparators the signal is transferred to the logic gate as input resulting in either energizing or de-energizing of the relay that is connected to the load.

3. Simulation Result and Discussion

3.1. Simulation Result of DC Power Supply

The transformer steps down the high AC voltage to a low AC voltage. The pure 220 V AC is applied to the primary of the transformer and it steps down to 24 V AC to the secondary. The DC power supply of the system is shown in Figure 6 below. The yellow color or the sine wave indicates the applied voltage wave. During the positive half cycle of secondary voltage, diodes D_2 and D_3 are forward biased and diodes D_1 and D_4 are reverse biased, now the current flows through D_2–>Load– >D_3. During the negative half cycle of the secondary voltage, diodes D_1 and D_4 are forward biased and diodes D_2 and D_3 are reverse biased Now the current flows through D_4-D_1. In both the cycles load current flows in the same direction, hence having a pulsating DC voltage across the points. That means the blue color indicates the full wave rectification. The pulsating content was called ripples and a filter capacitor was used to remove the ripples from the pulsating DC. The red color above indicates the required filtered wave. When the instantaneous values of pulsating DC voltage decrease, the stored voltage in the capacitor reverse biases the diodes D_2 and D_4. Hence it would not conduct, capacitor discharges through the load. Then voltage across the capacitor decreases. During the next cycle, when the peak voltage exceeds the capacitor voltage, diode D_2 or D_4 forward biases accordingly, as a result capacitor again charges to the peak value. This process continues. At last, the green color indicates the regulated pure DC output after the 7812 regulator is added. the overall simulation result of the DC power supply is shown in Figure 7 below.

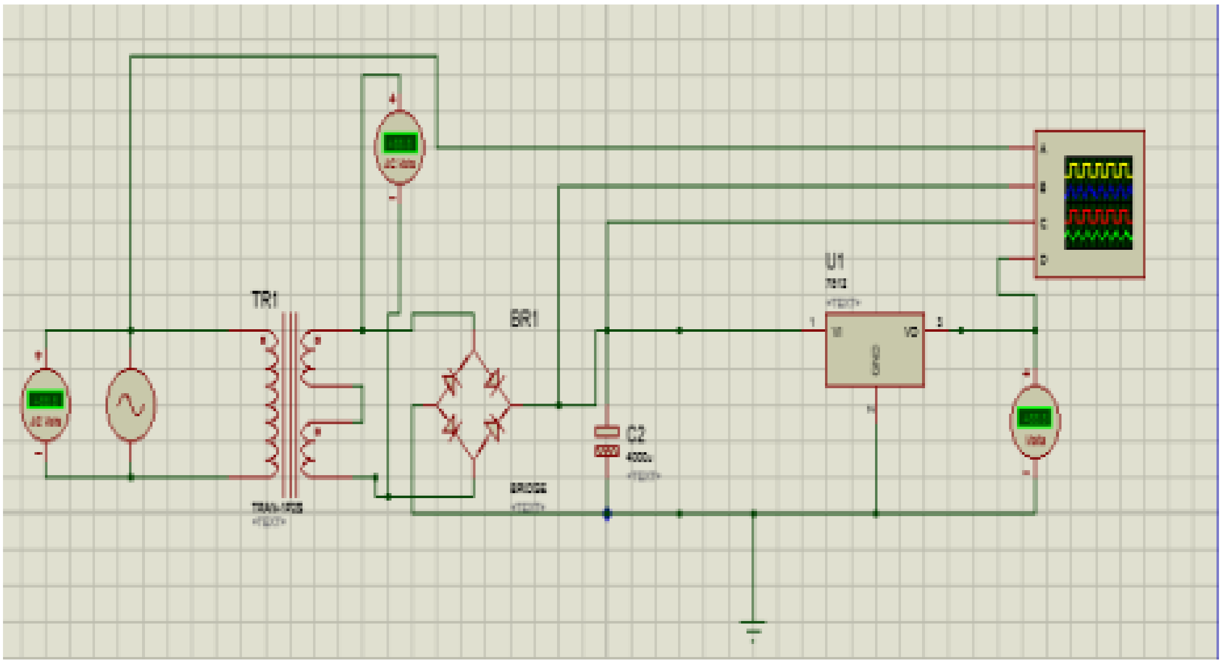

Figure 6. DC power supply.

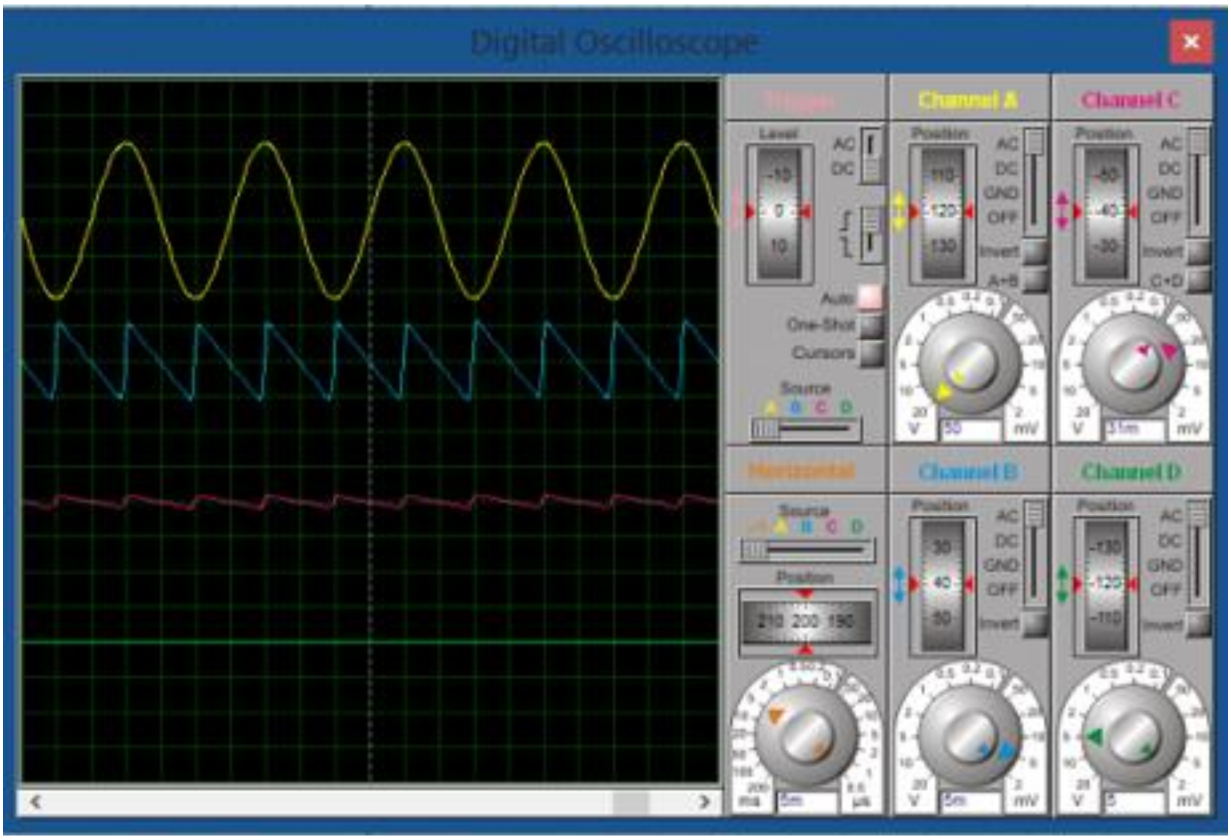

Figure 7. Simulation result of DC power supply.

3.2. Simulation Result of the Overall System

a) When the input voltage is in the normal range (198 V-243 V);

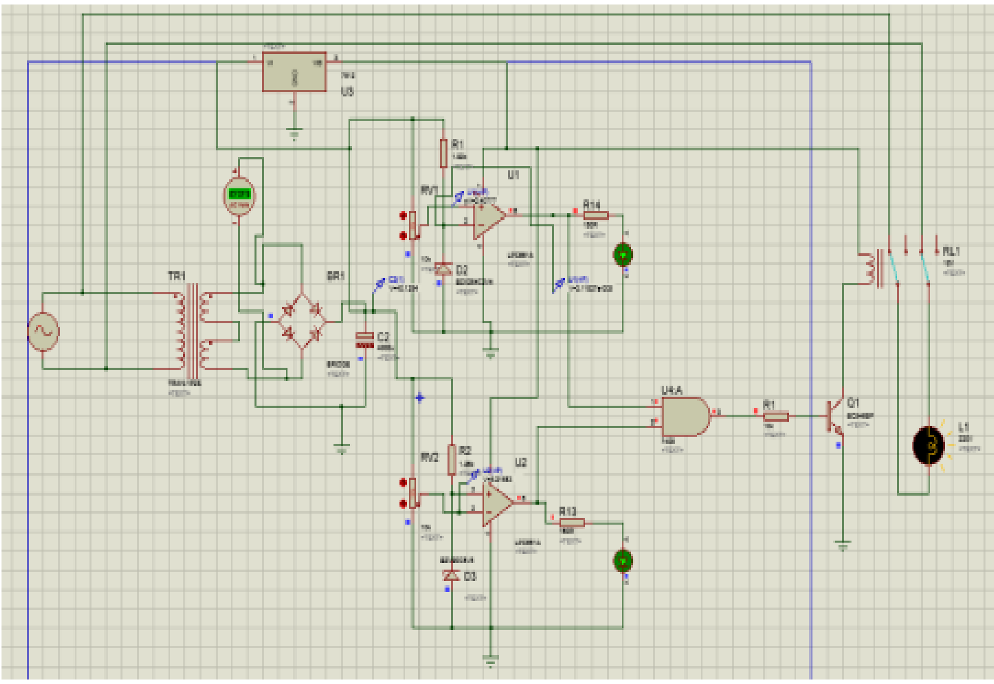

Figure 8. Circuit operation for normal supply voltage.

Figure 8 shows the simulation result of the system during normal supply voltage. the voltage limit ranging from 198 V-243 V, the sensing voltage in preset V_{R1} is higher than the reference voltage set by the Zener diode at the inverting terminal. For the sensing voltage of value greater than the reference value the output of the comparator1, U1 goes too high the LED1 indicator is on. On the other hand, at a normal operating voltage range the sensing voltage at V_{R2} must be lower than the reference voltage established by the Zener diode at the non-inverting terminal. so that the output of comparator2, U2 is high since the voltage is in the prescribed limit then LED2 is also on. Hence the signal input to the digital logic circuit is high level, so that its output is high the system remains in normal operating condition.

b) When the input voltage is below 198 V (under voltage)

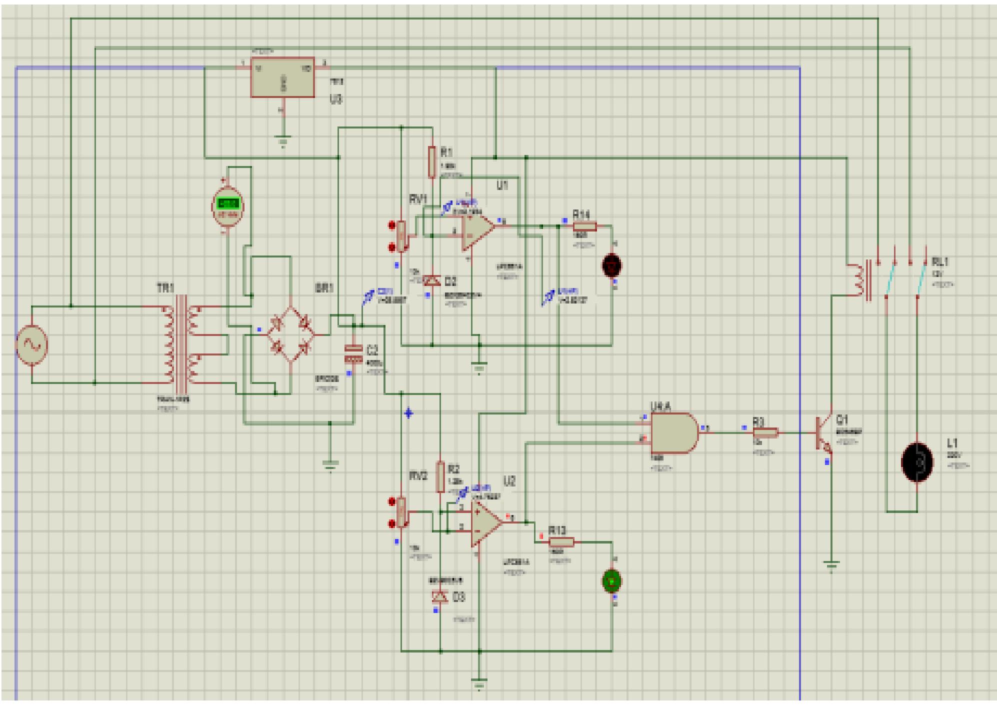

Figure 9. Circuit operation under voltage condition.

As shown in Figure 9, the load is disconnected from the source because the voltage is outside of the limit window. When the supply voltage is below 198 V the output of comparator1, U1 is low concerning the reference voltage, and the output of comparator2, U2 is high since the sensing voltage is below the reference voltage then the logic gate is not energized resulting in disconnecting the equipment.

c) When the supply voltage is above 243 V (over-voltage)

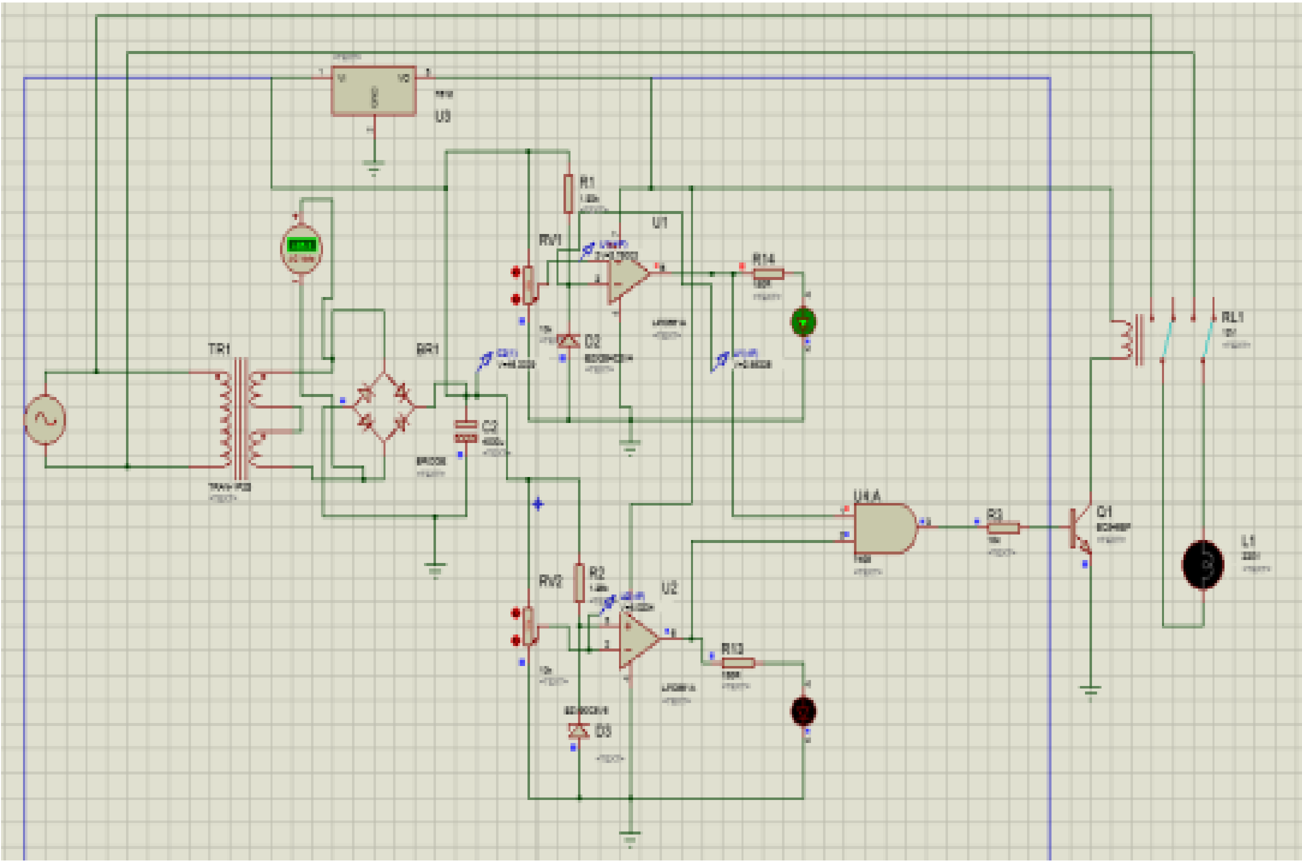

Figure 10. Circuit operation for over-voltage condition.

As shown in Figure 10, the load is disconnected from the source because the voltage is outside of the limit window. When the supply voltage exceeds the prescribed limit the output of U1 is high but the output of U2 is low, high, and low signals fed to the logic circuit resulting in low output, so that the relay is de-energized and protects the device from damage.

3.3. Experimental Result

To check the reliability of the system designed, the circuit is tested for a variety of supply voltage levels: i.e. for normal, under, and over voltage levels.

From the experiments that have been conducted to test the performance of the system, the following results are obtained.

Table 3. Experiment result.

Experiment	Voltage Supply	Load Contactor Status	Experiment	Voltage Supply	Load contactor status
1	100	OFF	9	230	ON
2	180	OFF	10	240	ON
3	197	OFF	11	243	ON
4	198	ON	12	244	OFF

Experiment	Voltage Supply	Load Contactor Status	Experiment	Voltage Supply	Load contactor status
5	200	ON	13	245	OFF
6	205	ON	14	250	OFF
7	208	ON	15	260	OFF
8	220	ON	16	300	OFF

When the input AC voltage is between 198-243 V, both comparator1 and comparator2 output go high. So, Load contactor status is ON. When the input voltage is below 198 V, the inverting terminal's voltage is less than the reference voltage, causing comparator2 to be high and comparator1's output to be low. When the input voltage exceeds 243 V, the non-inverting terminal voltage exceeds the reference voltage, causing high outputs in comparator1 and low outputs in comparator2, thereby turning off load contactor status.

4. Conclusion

This paper deals with the designing of automatic over and under-voltage protection. Following the true procedures that are relevant to this paper reach a final result that, design and software simulation is moreover much with the expectation. The system is accomplished by selecting suitable power electronics devices like, switching devices, comparators, logic gates, transformers, relays, and others based on the key features of the system principle. In this paperwork, a protection apparatus has been designed to protect single-phase home appliances from over and under-voltage phenomena that may appear at times in electric power distribution systems. The proposed protection device includes an electronic relaying system that detects overvoltage and Undervoltage and disconnects the home appliance from the supply network before it gets damaged. The system is designed to be used for households that may have electronic and/or electrical appliances of 220 V, 50 Hz. After the design has been finished, the system modeling has been done using Proteus 8 Professional software. The model has been tested to measure its performance.

According to the experimental results:

a) The load remains connected when the supply voltage is between 198 V-243 V.
b) The load gets disconnected from the supply by relay activated contactor when the supply is below 198 V.
c) The load is disconnected from the supply by the relay-activated contactor when the supply voltage is above 243 V.

Abbreviations

AC	Alternative Current
D	Diode
DC	Direct Current
IC	Integrated Circuit
LED	Light Emitted Diode
V	Voltage

Author Contributions

Lidia Bitew Techane: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing

Mebratu Sintie Geremew: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing

Kassahun Ashagrie Chanie: Data curation, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing

Declarations

Ethical Clearance and Participant Consent

Not relevant.

Permission to Publish

Not relevant

Data Availability Statement

All relevant data are within the manuscript and its Supporting Information files.

Conflicts of Interest

The authors declare no conflicts of interest.

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