Design, Construction, and Effectiveness of Electrical Outlet Box with Built-in High and Low Voltage Cut-off and Power-on Delay Circuit

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Abstract

The electrical outlets installed in houses and buildings have no means of protection to prevent the plugged-in electrical appliances from the risk of being hit by the voltage fluctuations, and sudden loss and recurrence of electricity. This study designed and constructed an electrical outlet box that disconnects the appliance from the power source when high and low voltage levels occurs. It also delays the connection to the power source at normal voltage level. It comprises a plastic enclosure securing therein the interconnections of a power supply circuit, a high and low voltage cut-off circuit, a power-on delay circuit, a relay driver circuit, a double pole double throw relay switch, and electrical outlet. The variable alternating current transformer was used to apply the high and low voltage levels to the electrical outlet box where the industrial fan was plugged. Results showed that the electrical outlet box disconnected the industrial fan from the power source at 231 and 199 V. Also, there was a four-minute waiting period before the industrial fan was connected to the power source when the 201-229 V was applied. Therefore, this device is effective in preventing appliances from being hit by voltage fluctuations and sudden loss and recurrence of electricity.

Keywords*:* design, effectiveness, voltage fluctuations, voltage cut-off, power-on delay

1. Introduction

Buildings and houses are installed with electrical outlets where the plug of an electrical appliance is inserted to receive the voltage from the electrical power source. However, one of the major issues on electrical power is voltage fluctuation (Lewis, 2018). Accordingly, abrupt voltage variations in the electricity supply have adverse effects on connected appliances (Agarwal, 2017). Similarly, Manish *et al.* (2015) mentioned that the occurrence of overvoltage and undervoltage may cause malfunction and failure in household appliances. Dimitriadis (2015) added that when the appliance receives higher energy, it will shorten the life of the circuit.

Meanwhile, it is also observed that power interruptions happen unexpectedly. By the time the household occupants arrive at the area to unplug the appliance, the electricity has returned, and the appliance operates at unstable voltage conditions. Balamiento (1982) pointed out that sudden loss and recurrence of power can damage compressor-type appliances such as freezers, air conditioners, and refrigerators.

Since voltage fluctuations are inevitable, electronics enthusiasts and inventors have created several circuits and devices to protect electrical appliances from the occurrence of high voltage. Hoopes (2004) claimed that his overvoltage protection circuit could protect electrical loads against excessive voltages. Another invention by Zhou (2014) presented an overvoltage protection circuit connected between the power source and the electronic device, which automatically disconnects the appliance when high voltage is received. Also, Zhang (2016) invented a thyristor controlled overvoltage protection circuit that automatically shuts down the electrical load when a high voltage level is detected. Schneider and Koenig (2018) patented a circuit that protects the motor from overvoltage pulses.

Moreover, other inventors have developed low voltage protection devices. For instance, Phillips (1973) invented a device that disconnects a load from a power source when the voltage falls below the first predetermined level. The said device reconnects the said load to the power source when the voltage rises above the second predetermined level. Kim (1999) registered a patent for a low voltage supply cut-off process and circuit to terminate the supply of electric power less than a required minimum voltage.

Since overvoltage and undervoltage protection devices were manufactured in individual packages, Galang *et al.* (2007) created a protection circuit that disconnects the device when it receives abnormal low or high voltages. Similarly, Manish *et al.* (2015) tested their overvoltage and undervoltage protection circuit in switching “on” and “off” different types of electrical loads. Results have shown that their device separates the resistive load from the power source at 150 V, while capacitive and inductive loads switch "off" at 148 V. Also, resistive and inductive loads decouple from the power source at 230 V, and the capacitive load turns "off" at 200 V.

In addition, Agarwal (2017) published the design of an overvoltage/under voltage tripping mechanism that permits the plugged-in device to operate safely within 180-240 V. Meanwhile, Kpochi *et al.* (2018) claimed that their microcontroller-based under and overvoltage protection device could connect the plugged-in appliance to the power source when the voltage level is 200-240 V. They further claimed that the device could turn the electrical load off when the applied voltage rises to 246 V or fall to 198 V. Similarly, the overvoltage and undervoltage protection system of Mohit *et al.* (2018) achieved a 176 V low voltage level cut-off and 250 V as high voltage level cut-off.

Despite of the promising effectiveness of overvoltage and undervoltage protection devices, other inventors have developed a delay circuit for electrical appliances to prevent them from unstable voltages associated with sudden loss and recurrence of electricity. Coy (1999) patented an adjustable delay circuit for electronic devices. Another invention by Wenzel (2006) is a power limiting time delay circuit for the power supply of electrical appliances. Also, Brooks *et al.* (2013) created a delay circuit that can be used to couple a netbook and power adapter.

Over the years, innovations on protection devices for electrical appliances against voltage fluctuations were significant. Recently, Singh *et al.* (2019) presented the tripping circuit that protects domestic appliances from over/under voltage levels. The device permits the appliance to operate safely when the line voltage is 180-230 V; and the user can monitor the line voltage level through global system for mobile (GSM) communications. Another electronic enthusiast Swagatam (2018) designed a circuit that turns the appliance off when high or low voltage levels occurs and delays the switching "on" of the said appliance for 3 min.

Given the above pieces of literature, it is apparent that the overvoltage and undervoltage protection devices can disconnect the appliance from the power source when the pre-set high and low voltage level exists. Also, adding a delay circuit to the overvoltage and undervoltage protection can further protect the appliance from voltage surges during sudden loss and recurrence of electric power. However, the predetermined high and low voltage cut-off levels, as discussed in published research works, can have adverse effects to the operation of the appliances. Allowing the appliance to operate at a high voltage of 240 V and low voltage of 180 V will result to overheating and inefficient performance; thus, the said appliance will have a shorter operation lifespan.

In this premise, this study designed and constructed an electrical outlet box with built-in high and low voltage cut-off and power "on" delay circuit. The pre-set high and low voltage cut-off was set to 11 V, increased and decreased from the nominal 220 V. Furthermore, this study tested the effectiveness of the pre-determined 231 V high voltage cut-off and 209 V low voltage cut-off and the 4-min power-on delay functions when the line voltage is within 210-230 V.

2. Methodology

2.1 Design of Electrical Outlet Box

Figure 1 presents the block diagram of the design concept of the electrical outlet box. The power supply circuit supplies all the needed power for the circuit to operate. The output of high and low voltage cut-off circuit is connected to the power-on delay circuit. The output of the power-on delay circuit is then fed into the relay driver circuit and the relay driver circuit is linked into the double pole double throw (DPDT) relay switch. Lastly, the DPDT relay switch is connected to the electrical outlet.

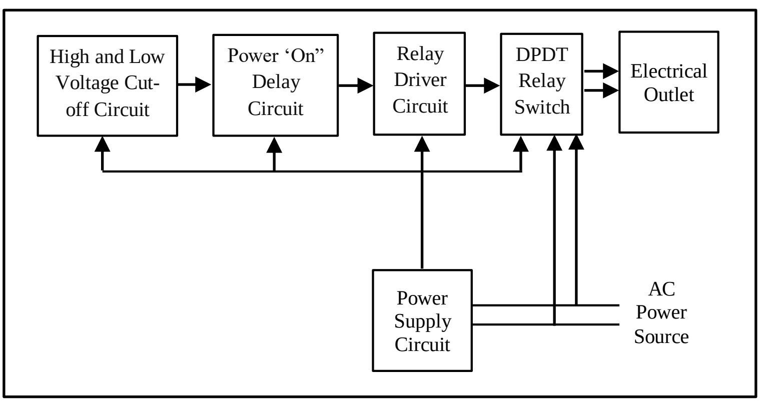

Figure 1. Block diagram of electrical outlet box with high and low voltage cut-off and power-on delay circuit

2.2 Schematic Diagram and Functions of High and Low Voltage Cut-Off And Power-on Delay Circuit

2.2.1 Power Circuit

Figure 2 shows the full-wave configuration of power supply circuit. The transformer T1 transforms the 220 alternating current (AC) voltage to 12 V AC. Consequently, the diodes D1 and D2 convert the AC voltage into pulsating direct current (DC) voltage. The capacitor C1 filters and smoothens the pulsating DC voltage, making it pure DC voltage. The pure DC voltage is fed into the other parts of the circuit.

2.2.2 High and Low Voltage Cut-off Circuit and Its function

Referring to Figure 2, the high voltage cut-off function is set by the trimmer resistor VR1 that is calibrated to provide the voltage at the cathode of the zener diode D3 to be more than 5.6 V when the line voltage level increases to 231 V. The presence of more than 5.6 V at the zener diode D3 causes the transistor Q1 to be forward biased. Since Q1 is forward biased, the ground voltage is fed into the cathode of the zener diode D4 via the collector of Q1. Since the voltage at the cathode of D4 is negative, the transistor Q2 is reverse biased, therefore Q2 will not conduct. When the transistor Q2 is not conducting, the negative line connection to the power-on delay circuit is disconnected. Thus the relay driver circuit and the DPDT relay switch is deactivated and the electrical outlet is disconnected from the AC power source.

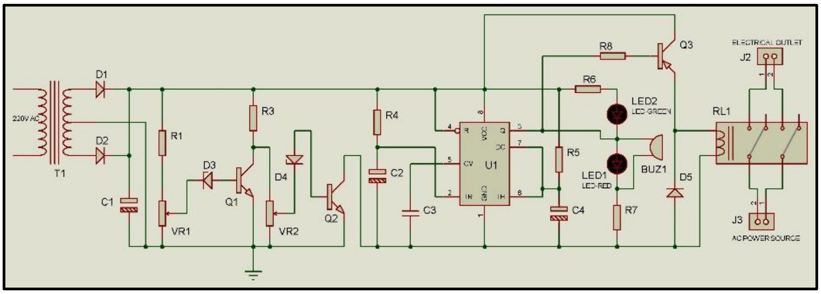

Figure 2. Schematic diagram of high and low voltage cut-off and power-on delay circuit

Similarly, the low voltage cut-off function is set by the trimmer resistor VR2 to provide a voltage to the zener diode D4 that is lower than 5.6 V when the line voltage decreases to 209 V. Since the voltage at the cathode of zener diode

D4 is below 5.6 V, the transistor Q2 would not conduct. When transistor Q2 is not conducting, the power-on delay circuit would not operate. Thus, the relay driver circuit and DPDT relay switch is deactivated and the electrical outlet is disconnected from the AC power source.

On the contrary, when the line voltage is within the 210-230 V, the voltage at the cathode of zener diode D3 is below 5.6 V and the transistor Q1 would not conduct. However, the voltage at the cathode of the zener diode D4 is more than 5.6 V which causes the transistor Q2 to conduct. When the transistor Q2 is conducting, the negative voltage is fed into the power-on delay circuit.

2.2.3 Power-on Delay Circuit

In Figure 2, the power-on delay circuit comprises a timer IC U1 configured to function in monostable mode. According to Balamiento (1982), the waiting period can be determined by the values of resistor R5 and capacitor C4 through the Formula 1.

$$T = 1.1(R5)\,(C4) \tag{1}$$

where:

T = waiting time in seconds
$R5$ = resistance of R5 in ohms
$C4$ = capacitance of C4 in farads

When the power-on delay circuit receives the negative voltage from the transistor Q2, the voltage across capacitor C4 is zero. Both pins 2 and 3 of timer IC U1 are almost similar to V+ level. The internal discharge transistor of the timer IC U1 is turned off, and a current path is provided for charging the capacitor C4 via resistor R5. The capacitor C4 charges towards two-thirds of the V+ level for 4 min. While the capacitor C4 is charging, the voltage at pin 3 of timer IC U1 is positive that lights up the red light emitting diode LED. The buzzer BUZ1 will then produce a beeping sound to indicate a waiting period. Once the two-thirds V+ level is reached by capacitor C4, the output voltage at pin 3 of timer IC U1 is equal to the negative voltage and turns off the LED1. The negative voltage at pin 3 of the timer IC U1 lights up the green light emitting diode LED2 to indicate that the waiting period is over. Lastly, the negative voltage at pin 3 of timer IC U1 is fed into the base terminal of transistor Q3 of the relay driver circuit.

2.2.4 Relay Driver Circuit

Another circuit embedded in Figure 2 is the relay driver circuit that is composed of resistor R8 and transistor Q3. The resistor R8 receives the negative voltage from pin 3 of timer IC U1 and feeds into the base of transistor Q3 to be forward biased. When the transistor Q3 is forward biased, it will fed the positive voltage into the coil of the DPDT relay switch.

2.2.5 Relay Circuit

The relay circuit in Figure 2 consists of diode D5 and DPDT relay switch RL1. The anode terminal of diode D5 and one electrode of the coil of the DPDT relay switch RL1 are connected to the ground. Therefore, the relay circuit is activated when the positive voltage at the emitter of transistor Q3 is applied to the cathode of diode D5 and one electrode of the relay coil. Once the DPDT relay switch RL1 is activated, the internal switch lever contacts connected to the normally close terminals will shift to normally open terminals.

2.2.6 Electrical Outlet

The terminals of electrical outlet J2, as shown in Figure 2, is connected to the normally open terminals of the DPDT relay switch. The connections of the electrical outlet shows that it can be connected to the AC power source J3 when the DPDT relay switch RL1 is activated. Also, it can be disconnected when the DPDT relay switch RL1 is deactivated.

It is apparent in the schematic diagram shown in Figure 2 that the power supply circuit provides the needed power of the entire circuit while the high and low voltage cut-off circuit controls the flow of the negative voltage to the power-on delay circuit. The power-on delay circuit manages the bias voltage of the relay driver circuit. Consequently, the relay driver circuit directs the flow of positive voltage to energize the DPDT relay switch. The energized relay switch connects the electrical outlet to the power source.

2.3 Materials, Tools and Instruments

Table 1 presents the materials, tools, and instruments used in making and testing the electrical outlet box.

Table 1. Materials, tools and instruments

Part No.	Rating	Description
R1	1.2 kΩ	¼ watt Resistor
VR1	5 kΩ	Trimmer Resistor
R3	1.5 kΩ	¼ watt Resistor
VR2	5 kΩ	Trimmer Resistor
R4	10 kΩ	¼ watt Resistor
R5	22 MΩ	¼ watt Resistor
R6-R7	560 Ω	¼ watt Resistor
R8	1 kΩ	¼ watt Resistor
C1	470 µf / 16 V	Electrolytic Capacitor
C2	100 nF / 50 V	Ceramic Disk Capacitor
C3	10 nF / 50 V	Ceramic Disk Capacitor
C4	10 µF / 16 V	Electrolytic Capacitor
D1-D2 & D5	1N4007	Rectifier Diode
D3 – D4	1N4734A	Zener Diode
LED1	Red	Light Emitting Diode (LED)
LED2	Green	Light Emitting Diode (LED)
Q1	BC547	NPN Transistor
Q2	BD139	NPN Transistor
Q3	BD136	PNP Transistor
RL1	12 V / 10 A	DPDT Relay Switch
BUZ1	12 V	Electronic Buzzer
T1	Primary 0 – 220 V Secondary 12V-0-12 V	Power Transformer
J1	3 pins	Terminal Block
J2 –J3	2 pins	Terminal Block
	One gang	Electrical Outlet
	2 ½ " x 4"	Plastic Enclosure
	2" x 3"	Copper Clad Board
	50 ml	Ferric Chloride Solution
	8.5" x 11"	Sticker Paper
	0.8 mm	Soldering Lead/Solder Wire
	#18	Stranded Wire
	1/8" x 1/4"	Screws
	1/8" x 3/8"	Bolt and Nuts
	40 watts	Soldering Iron
	12V DC	Mini Drill
	160 V – 315 V	Variable AC Transformer
	500 watts	Industrial Electric Fan
		Electrical Tape
		Blade Cutter
		De-soldering Pump
		Long-nose Pliers
		Diagonal Cutting Pliers
		Multi-tester

2.4 Preparation of the Printed Circuit Board (PCB)

The Proteus Design Suite 8.0 Advanced Routing and Editing Software (ARES) PCB Layout program was used to lay out the PCB of the electrical outlet box. Figure 3 shows the layout of the circuit board printed on a sticker paper and pasted on the copper side of the copper-clad board. The unwanted connections of the design were cut out using a cutter blade. The etching solution was poured into the plastic pan just enough to soak the copper clad board. The plastic pan was agitated to hasten the etching process, after which the PCB was taken out of the plastic pan and washed with water and detergent soap. The mini drill was used to bore the holes on the printed circuit board corresponding to the mounting location of electronic parts.

Figure 3. The preparation of the PCB

2.5 Assembly of the Electrical Outlet

Figure 4 shows the assembled electrical outlet box. The passive and active electronic parts like resistors, capacitors, semiconductors, and other electronic components were mounted and soldered on the PCB. Wires were used to connect the other electronic parts of the circuit into the said PCB and securely placed inside the plastic enclosure. The electrical outlet, light emitting diodes and electronic buzzer were securely fastened on top of the plastic enclosure.

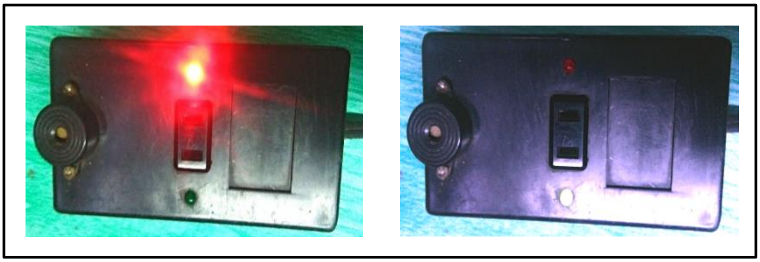

Figure 4. Complete assembly of the electrical outlet box

2.6 Testing the Electrical Outlet Box

2.6.1 Test Setup

Figure 5 shows the set-up for testing the electrical outlet box. The variable AC power transformer was connected to the AC voltage source. Subsequently, the electrical outlet box was connected to the output receptacle of the said variable AC power transformer. The industrial fan was then plugged into the electrical outlet of the said electrical outlet box. The industrial fan was used as the plugged-in appliance since it is an inductive load; and this type of electrical load is the most commonly plugged-in appliance in households and buildings. The test set-up was tested for three days.

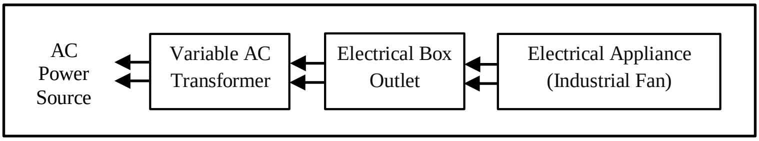

Figure 5. Setup for testing the electrical outlet box

2.6.2 Testing the Effectiveness of High and Low Voltage Cut-off Function

The effectiveness of high and low voltage level cut-off function of the electrical outlet box was tested by changing the position of the voltage adjustment knob of the variable AC power transformer. The voltage adjustment knob was rotated clockwise to increase the voltage level applied to the electrical outlet box until the plugged-in industrial fan was turned off. The voltage value set by the adjustment knob was recorded as the high voltage level cut-off.

In addition, the voltage adjustment knob of the variable AC power transformer was turned counter clockwise to decrease the voltage level applied to the electrical outlet box until it turned off the plugged-in industrial fan. The amount of voltage set by the voltage adjustment knob was recorded as low voltage cut-off.

2.6.3 Testing the Effectiveness of Power-on Delay Circuit

The voltage adjustment knob of the variable AC power transformer was gradually turned clockwise and momentarily stopped when the delay function was activated as indicated by the illumination of red LED and the beeping of the buzzer for 4 min. During the delay period, the plugged-in industrial fan remained "off." Meanwhile, the stop watch was started simultaneously with the activation of the delay function and stopped when the green LED illuminated. The time displayed on the stopwatch was recorded and checked if it was less than or more than 4 min. After the waiting period, the LED1 and the buzzer were turned off, the green LED lighted up, and the plugged-in industrial fan was turned "on."

3. Results and Discussion

3.1 Effectiveness of High Voltage and Low Voltage Cut-off Functions

Table 2 shows that the high voltage cut-off level of the electrical outlet box was at 231 V, and its low voltage cut-off was at 199 V. It means that the plugged-in industrial fan was automatically turned "off" when there was 11 V increase and 21 V decrease in the nominal line voltage 220 V. Also, the plugged-in industrial fan was turned "on" when the applied voltage was within the 201-229 V. It can be observed that there was a notable difference between the trials on the "on/off" operation of the plugged-in industrial fan at 230 and 200 V. The results can be attributed to the tolerance values of the electronic parts used in the construction of the high and low voltage cut-off circuit and the several devices connected to the power lines.

Table 2. Results of trials at different voltage levels of the electrical outlet box

Applied AC Voltage (V)	Trial 1 Industrial Fan (on/off)	Trial 2 Industrial Fan (on/off)	Trial 3 Industrial Fan (on/off)
232-240	off	off	off
231	off	off	off
230	on	off	on
201-229	on	on	on
200	on	off	off
199	off	off	off
190-198	off	off	off

Notably, the 231 V high voltage cut-off was the pre-set high voltage cut-off of the electrical outlet box. However, the 199 V low voltage cut-off was 10 V lower than the pre-set 209 V low voltage cut-off. The 10 V margin can be attributed to the tolerance values of trimmer resistor VR2 and the zener diode D4 that causes the transistor Q2 to conduct even the applied voltage was at 209 V.

The effectiveness of the high and low voltage cut-off function of the electrical outlet box to disconnect the plugged-in industrial fan from the power source when the high voltage and low voltage levels occur is in agreement with the results of the previous studies. Specifically, high voltage cut-off of the device developed by Manish *et al.* (2015) and Singh (2019) was 230 V. Similarly, the device of Kpochi *et al.* (2018) and Mohit (2018) have a high voltage cut-off of 246 and 250 V, respectively. In addition, the 199-volt low voltage cut-off was closely similar to the 198-volt low voltage cut-off of Kpochi *et al*. (2018). The device developed by Mohit (2018), Singh (2019) and Manish *et al.* (2015) the undervoltage cut-off was 176, 180 and 148 V, respectively.

However, it can be noted that the quantitative results on the effectiveness of high voltage cut-off 231 and 199 V low voltage level cut-off functions was different with the results of the previous studies. This can be attributed to the preferred predetermined value of high and low voltage levels set by the researchers. Also, the standard line voltage of the country where the research was conducted can also be abscribed to the said differences of overvoltage and undervoltage cut-off.

The results imply that the electrical outlet box can be used as overvoltage protection device for electrical appliances. This is because the high voltage cut-off function is similar to the patented overvoltage protection devices (Hoopes, 2004; Zhou, 2014; Zhang, 2016; Schneider and Koenig, 2018), that disconnect the appliance from the power source when excessive high voltage level occurs. Also, the low voltage cut-off function of the electrical outlet box is similar to the patented low voltage protection device of Phillips (1973) that detaches the electrical load from the power source when the voltage falls below the predetermined level.

The findings further suggest that the electrical outlet box is more advantageous to use over the patented products since it can perform both the high voltage and low voltage protection functions. It can also prevent the risk of electrical appliance from being hit by unstable voltage levels.

3.2 Effectiveness of Power "on" Delay Function

Table 3 shows the power "on" delay function of the electrical outlet box. Based on the three test trials, when the applied voltage was within the 230-240 V, the power-on delay function was deactivated, the red and green LEDs were off and the plugged-in industrial fan was also turned “off.” However, when the 201-229 V line voltage was applied, the power-on delay function was activated, then the red LED illuminated for 4 min. During this period, the green LED and the industrial fan were also off. After the 4-min waiting period, the red LED was turned off while the green LED and the industrial fan were turned on. It was also observed that when the voltage applied was below 201 V, the power-on delay function was deactivated. Thus, the two LEDs and the industrial fan were off.

Table 3. Results of trials from the power-on delay function of the electrical outlet box

Voltage Level (V)		Power-on Delay Function (activated/ deactivated)	0-4 min			4 min and more		
			Red LED (on/off)	Green LED (on/off)	Industrial Fan (on/off)	Red LED (on/off)	Green LED (on/off)	Industrial Fan (on/off)
Trial 1	230-240	Deactivated	off	off	off	off	off	off
	201-229	Activated	on	off	off	off	on	on
	Below 201	Deactivated	off	off	off	off	off	off
Trial 2	230-240	Deactivated	off	off	off	off	off	off
	201-229	Activated	on	off	off	off	on	on
	Below 201	Deactivated	off	off	off	off	off	off
Trial 3	230-240	Deactivated	off	off	off	off	off	off
	201-229	Activated	on	off	off	off	on	on
	Below 201	Deactivated	off	off	off	off	off	off

The delay function of the electrical outlet box is supported by the inventions of Coy (1999), Wenzel (2006), and Brooks *et al*. (2013) in which the switching-on of the appliance can be delayed for a specific period. Also, the time delay function observed in this study is in agreement with the circuit design of Swagatam (2018) that delays the switching on of the appliance for 3 min. The 4-min delay function of the developed outlet box implies that it can further protect the electrical appliance from the abrupt recurrence of electricity caused by unexpected brownouts and high and low voltage level cut-off.

Moreover, the findings in this study suggest that the device is comparable to the commercial products available in the market. When comparing the electrical outlet box and the circuit breaker type over/under voltage relays (Macromatic, n.d.), it is apparent that two devices can disconnect appliances from the power source where a high and low voltage condition is potentially damaging. However, the 0.1-10 seconds time delay of the said over/under voltage relays is shorter compared to the 4-min time delay of the electrical outlet box. It means that the electrical outlet box can further minimize the risk of electrical appliances from being hit by voltage surges during sudden loss and recurrence of electricity.

Furthermore, electrical appliances are also plugged into a voltage stabilizers that is designed to provide a constant voltage to a load regardless of the changes in the incoming supply voltage (Electrical Technology, n.d.). However, voltage stabilizers do not have a delay function that the electrical outlet box provides. The electrical outlet box can interrupt the operation of the appliance when a high or low voltage level is detected. This implies that the operation of the appliances plugged into voltage stabilizers will not be interrupted even though it receives potentially damaging voltage variation.

4. Conclusion and Recommendation

The electrical outlet box with high and low voltage cut-off and power-on delay circuit was designed and constructed to protect electrical appliances from unstable voltage conditions. The variable AC transformer was used to vary the amount of voltage applied to the electrical outlet box where the industrial fan was plugged in. The high voltage cut-off was 231 V, while the low voltage cut-off was 199 V. Interestingly, there was a 4-min on time delay when the voltage was within 201-209 V. Therefore, the electrical outlet box is operative in protecting the electrical appliances from the occurrence of high and low voltage, and sudden loss and recurrence of electricity. Thus, the electrical appliance will have longer operation lifespan.

Nevertheless, the testing on the effectiveness of the high and low voltage levels cut-off and power "on" delay functions of the electrical outlet box was limited to three replications and only one appliance was used. Hence, it is recommended that the device should undergo more test replications by using other household appliances. Potential consumers should likewise utilize the electrical outlet box to assess its effectiveness and acceptability.

5. Acknowledgement

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