Comparative Analysis of Transformer and Transformer Less-Based Variable DC Power Supply

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Abstract: *Electronics circuitry needs DC power source of a specific value to work effectively. This paper considers the design and evaluation of transformer-based and transformer less-based variable regulated DC power supply with the aim of presenting a comparative analysis between them; and their respective areas of applications. The quality, cost, size, weight, performance and efficient production of DC power supply thus pose a great deal of concern and attention in the DC power production of any electronic device. The design methodology used in this work involves Software design for component selection, improved hardware design, computer simulation and evaluation of transformation, rectification, filtration and regulation stages for both transformer-based and transformer less -based adjustable DC power supply with graphical outputs. The results obtained after following the design specification was very satisfactory. The transformer-based has a robust output current and well isolated from the supply voltage, which makes it more suitable for high current application, highly reliable for powering electronics devices while the transformer less based DC source has smaller size, weight and cheaper so as to miniaturize electronics devices but limited to low current devices . It also generates far less noise, heat, input harmonic distortion levels, and higher transient response but lack of proper isolation unlike its counterpart thus result in lower Mean Time To Failure (MTTF).Transformer less variable DC power supply should be considered a viable option for lower power, small and low current applications where achieving the highest availability is not the top concern and cost, size and weight restrictions inhibit the use of traditional transformer-based DC power supply.*

Keywords: *transformer, transformer-less, voltage regulator, simulation, variable DC power supply.*

I. Introduction

In electrical and telecommunication engineering field, systems and equipments like amplifiers, satellites, microwave link systems to name but a few depend upon the availability of a stable and quality well regulated Direct Current (DC) power supplies for their correct operations. No electronics laboratory or technology is complete without a well regulated (or variable) DC power supply. It is the first essential element required in any electronics device. The construction, design and evaluation of this piece of electronic equipment- will find use both now and in future. The main and basic requirements of a well regulated DC power supply unit are Isolation between source and load, Low ripple, Low output impedance, Power factor, High transient response, Low levels of input harmonic distortion , Reduced power losses ,Good regulations, Strict output short-circuits protection, Workable size and weight.

II. Related Works

In the work published by Mike Papadimitriou (----), LM317 was used for varying DC power supply. It is an adjustable 3−terminal positive voltage regulator capable of supplying in excess of 1.5A over an output voltage range of 1.2 V to 37 V. This voltage regulator is exceptionally easy to use and requires only two external resistors and capacitor to set the output voltage.

In a similar work by National Microchip co-operation (-----) on Transformer-less Power Supplies, resistor was used as the transformation device and a reliable circuit diagram was given that works fine in computer simulation but the circuit offered no protection against over-current and over voltage issue.

Williams, O.A. (1995) on Design and Construction of a Regulated Power Supply Unit used LM 78 XX device like the later. The voltage regulator is exceptionally easy to use and employs internal current limiting but capable of supplying in excess of 1.0A over an output voltage range of 1.2 V to 21 V and lacks internal thermal shutdown capability.

Ron J (2002) in his work, dealt with transformer-less power supply using X-rated capacitor for low current applications of 100mA current ratings and a voltage of 12V. It was effective but the main disadvantage was that, it offered no isolation from the supply voltage and presents more of a safety issue.

In the work published by Kiran Shrestha (Nov 2004) on Transformer less 12V Dual Power Supply. In this work two voltage output was achieved +12V and -12V using zener diode. This was proved and tested but still lacks protection against over-current and over voltage.

In a similar work, Garage (2006) designed a variable DC power supply using LM 78XX. All the stages were effectively considered except the protection stage.

In work published by Mohamkumar (2006) on Transformer less power supply, x-rated capacitor was used as transformation device instead of the transformer; and proved the effectiveness and efficiency of the x-rated capacitor and gave a well detailed circuit diagram of a fixed DC power supply using zener diode

In the work published by Shamsul and Bin (Nov 2010) on Development of DC Power supply using power electronics applications, a fixed DC power supply was developed, simulated and proved to have worked effectively but the input supply voltage lacks protection circuit, the output of the transformer lacked noise suppression capacitor and the LM 317 T was not protected.

Emerson Network Power (2012) contained vital information on comparing transformer based and transformer less uninterruptible power supplies. In this work emphasis were made on the uniqueness, differences and similarities between transformer and transformer-less based devices.

III. Design Methodology

The design methodology of both the transformer and transformer less based system involves five stages as shown in Fig.1 and Fig.2.

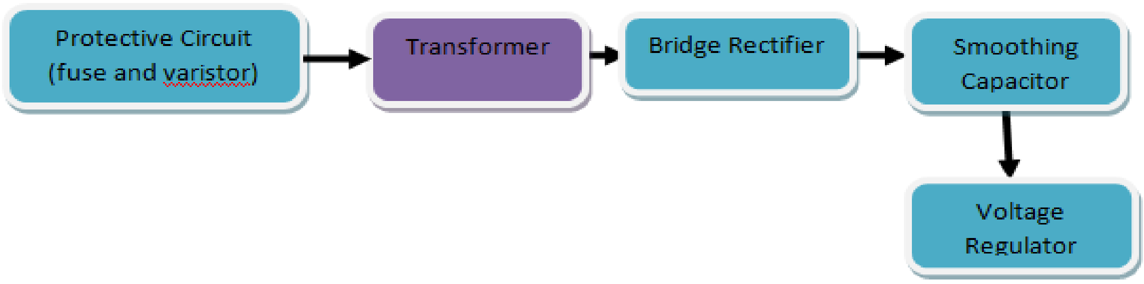

Fig.1: flow diagram of transformer-based DC power supply

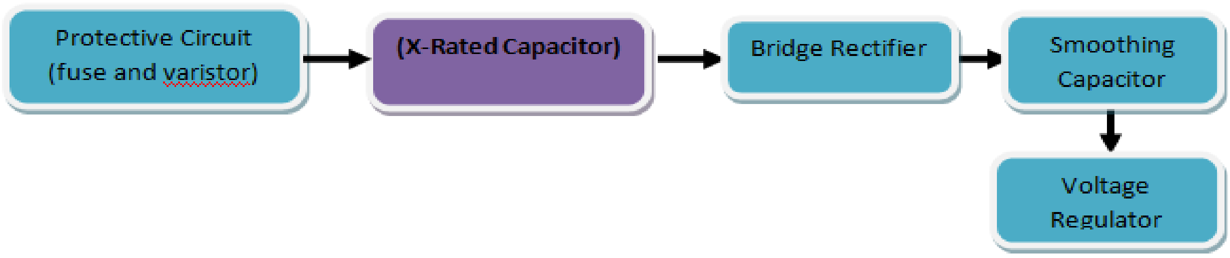

Fig.2: flow diagram of transformer less DC power supply

A. The protection stage provides reliable and economical protection against high voltage transients, surges and over-current which may be produced. It comprises of fuse and varistor.

In this work, the maximum current is 4A for the transformer-based and 1A for the transformer less type thus stating the rating of the fuse to be used in each of them. Since the main supply voltage is approximately 230V_{ac}, the voltage rating of the varistor used 250Vac; the protection circuit is as shown below:

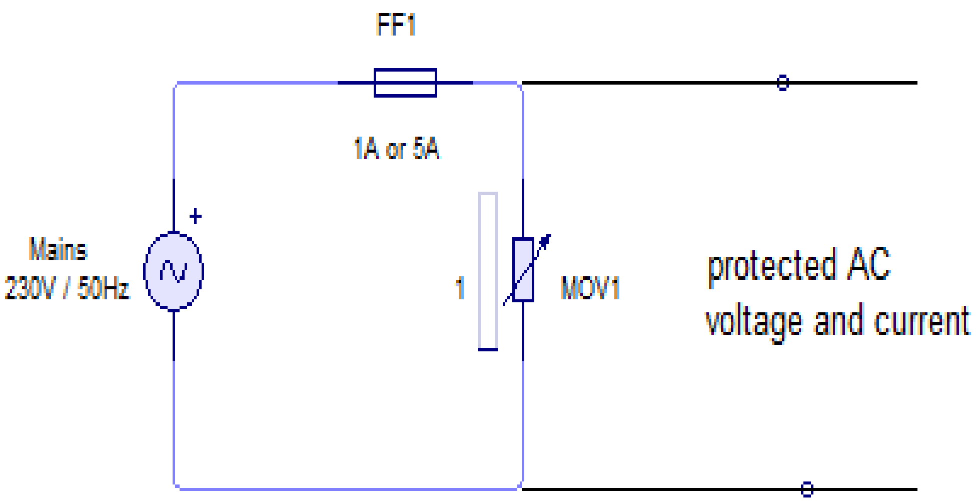

Fig.3: Protection circuit from the mains

3.1 Transformation stage is used to transform the incoming line voltage of 230V_{ac} down to a required voltage value for the power supply unit. For the two types of power supply that is the transformer less and the transformer based power supply, **x-rated capacitor** and **step-down transformer** are used respectively.

- **Step-down transformer:** The simulation waveform circuit analysis shown below involves both the protection and the transformation stage using transformer as the transformation device.

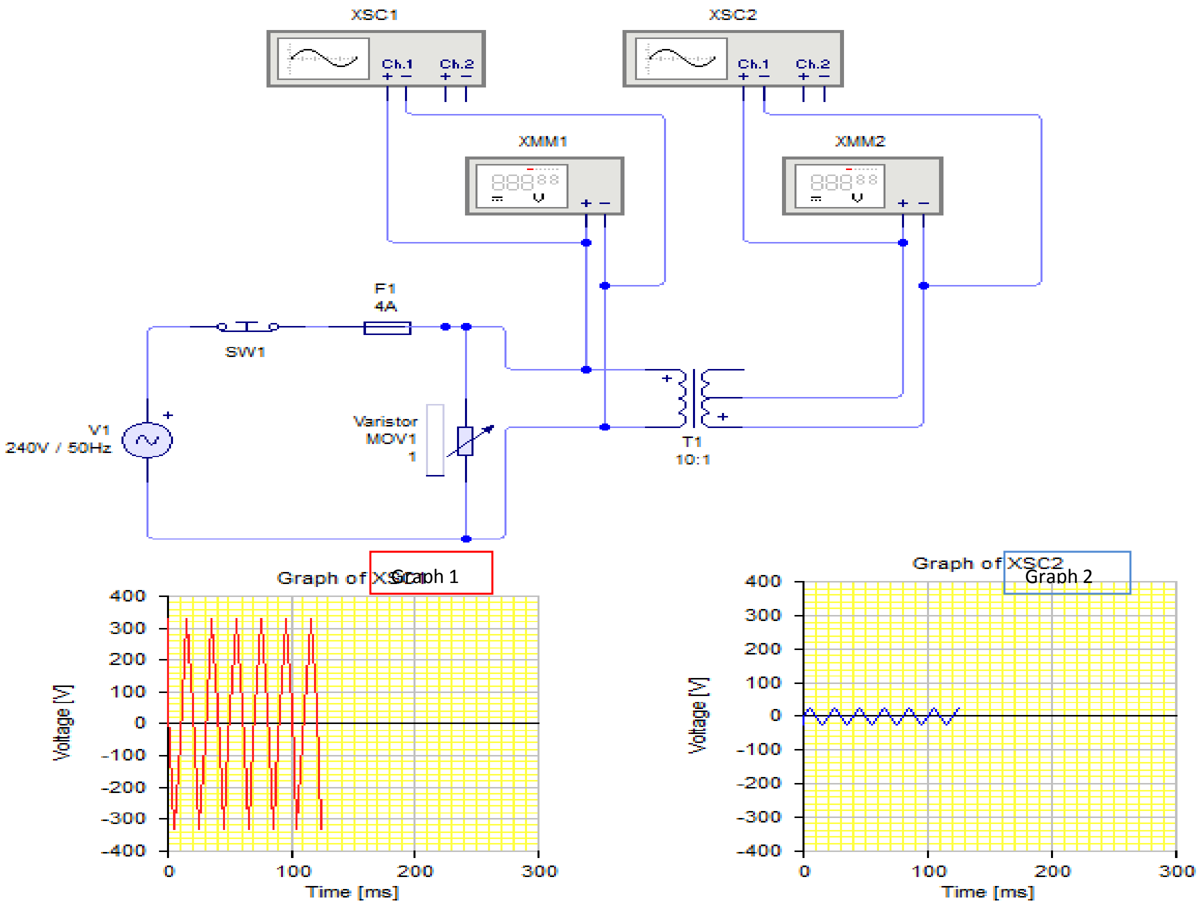

Fig. 4: waveform analysis of both protection and transformation stage for transformer based DC power supply

Using this formula

$$turns\ ratio = \frac{V_p}{V_s} = \frac{N_p}{N_s}$$

Where: V_p=primary (input) voltage,N_p=number of turns on the primary coil, V_s=secondary (output) voltage N_s= number of turns on the primary coil.

To produce a desired output voltage of 24 Vdc, a turn ratio of 10:1 transformer was chosen, thus.

$$\frac{240_p}{V_s} = \frac{10_p}{1_s}$$

$$V_s = 24\ volts$$

- **X-rated AC capacitor:** The simulation waveform circuit analysis shown below involves both the protection and the transformation stage using transformer as the transformation device.

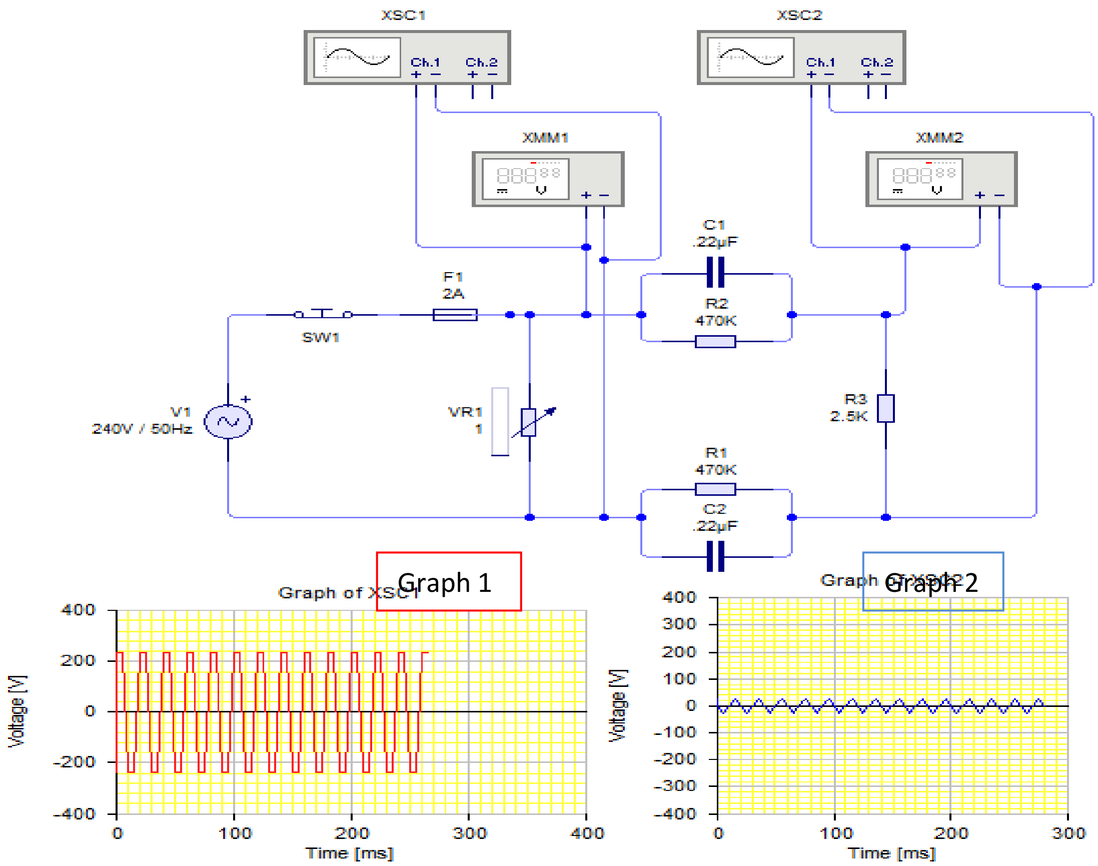

Figure 5: waveform analysis of both protection and transformation stage for transformer less based DC power supply

The reactance (X_c) of the capacitor (C) in the mains frequency (f) can be calculated using the formula:

$$X_c = \frac{1}{2\pi f C}$$

From the formula above, if an X-rated capacitor of 2.2μf is used as shown in figure 15, the reactance (X_c) will be as shown:

$$X_c = \frac{1}{2\pi * 50HZ * 2.2e - 6F}$$

$$X_c = \frac{1}{6.9115e - 4}\Omega$$

$$X_c = 1.44686k\ \Omega$$

The current that would be produced from a 2.2$\mu f/400V$ X-rated capacitor with an ac source of 230 V_{ac} can begotten using the ohmic equation:

$V = IR\ \ or\ \ V = IX_c$

$I = 165.88\ mA$

This value $I = 165.88\ mA$ is the ideal current value, but the actual current from a 2.2$\mu f - 225k\ /400V$ X-rated capacitor with an ac source of 230 V_{ac} is 100 mA cited from Table 2 . Practically a single 2.2μf X-rated capacitor could give a current$(I)\ of\ 100\ mA$, therefore, three of the 2.2μf X-rated capacitor connected in parallel with each other would give a current of 300 mA (i.e. three times $100\ mA$), this current rating is well over sufficient for all low current devices.

3.2 Rectification stage is the stage after transformation stage that aids in the conversion of AC to DC signal. In this work a full wave rectification is used, because of its fundamental advantages over the half wave rectifier counterpart. Bridge rectifier is used rather its counterpart because it does not require a special centre tapped transformer, thereby reducing its size and cost. The bridge rectifier consists of 4 IN4001 silicon diodes.

Livewire simulation of both the transformation and rectification stage for the transformer based and transformer less based Dc power supply are as shown below.

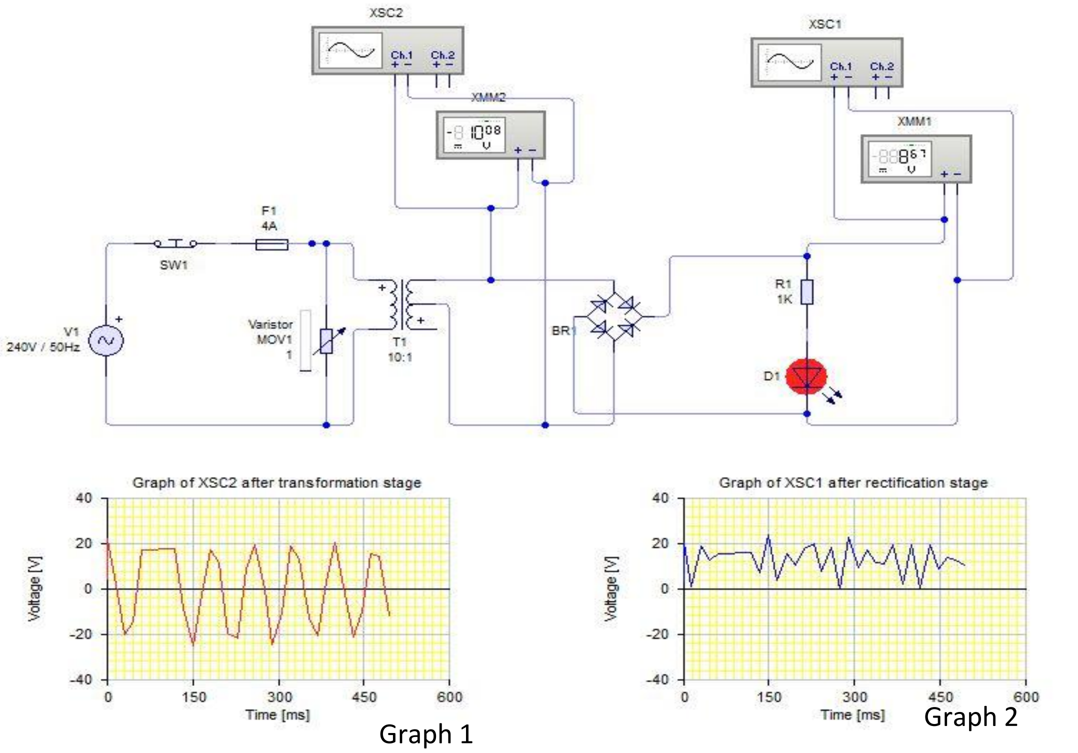

Fig. 6: waveform analysis of transformation and rectification stage for the transformer based circuit

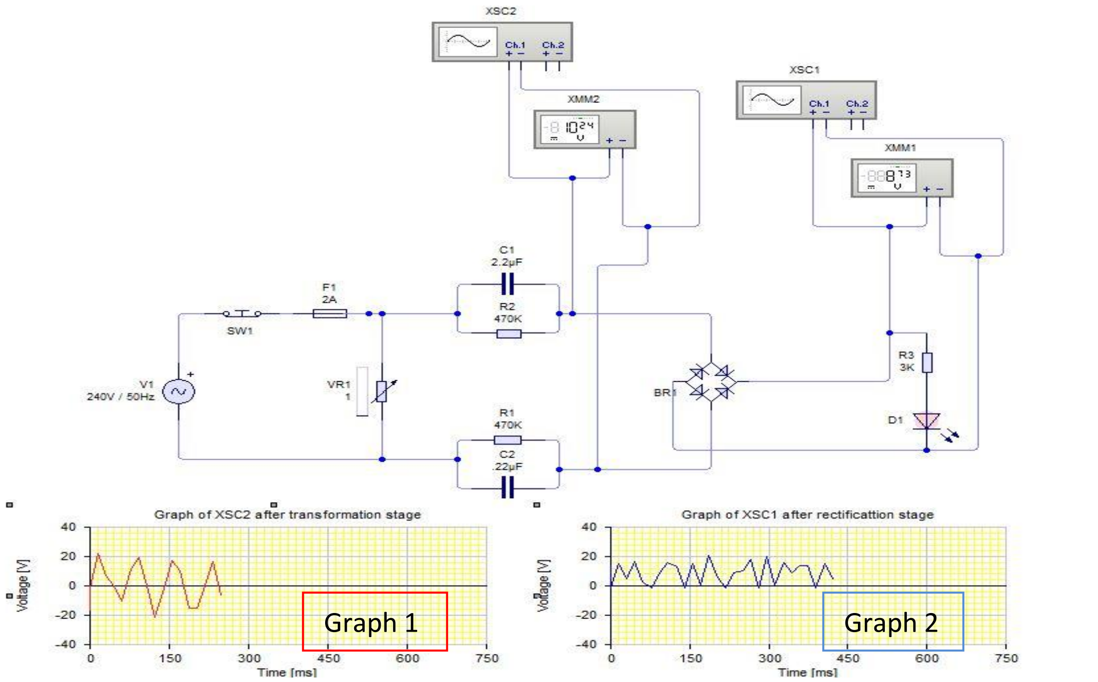

Figure 7: waveform analysis of transformation and rectification stage for the transformer less based circuit

From the figures 6 and 7 above the following mathematical expressions can be deduced.

V_s =Output AC signal from transformation stage

$V_{s,rms} = V_s\sqrt{2}$ =Peak to Peak AC signal from transformation stage

When passed through a bridge rectifier, the DC output signal is given by:

$$V_p = V_s - 2V_d \text{ = DC output signal}$$

$$V_{p,rms} = V_p\sqrt{2} \text{ =DC output signal } (peak\ to\ peak)$$

Note that in a full wave bridge rectifier only 2 of the 4 diodes works simultaneously at any given time. Each of the diodes has a voltage drop ranging from 0.4 to 0.7 V.

Reduction after rectification stage in the DC output voltage is as a result of the voltages drop across the two diodes $(2V_d)$ of the bridge rectifier.

The output DC voltage of the rectification stage has so many ripples in it that it cannot be used to power any useful device. It require a filter to improve on the output signal.

3.3 Filtration stage: Smoothing Capacitor is used to generate ripple free DC. Its function is to convert half wave / full wave output signal of the rectifier into smooth DC signal. Livewire simulation of both the rectification and filtration stage for the transformer based and transformer less based Dc power supply are as shown below.

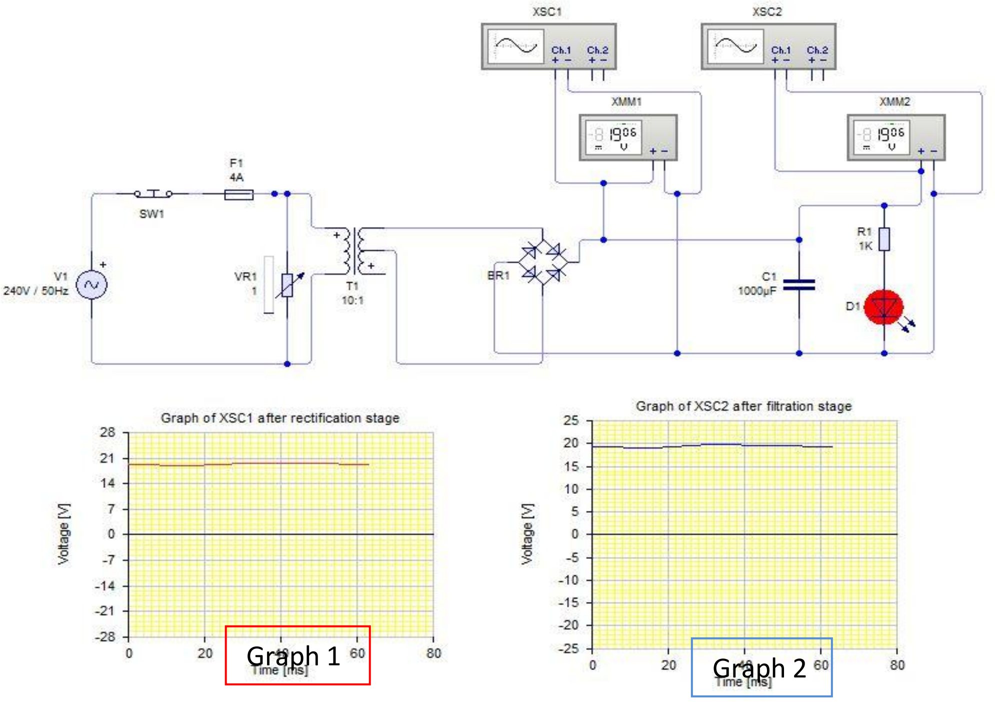

Figure 8: waveform circuit analysis of rectification and filtration stage for the transformer based circuit

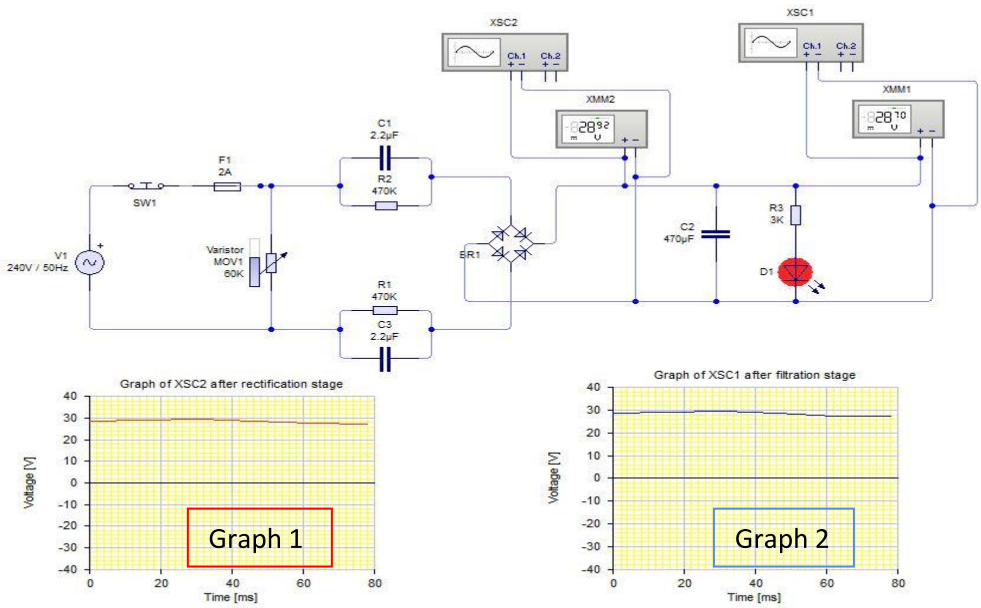

Figure 9: waveform circuit analysis of rectification and filtration stage for the transformer based circuit

The power rating and the capacitance of the capacitor are two most important aspects to be considered while selecting the smoothing capacitor. The power rating must be greater than the off load output voltage of the power supply. The capacitance value determines the amount of ripples that appear in the DC output when the load takes current (The larger the capacitor -for a given load, the smaller the ripple voltage).

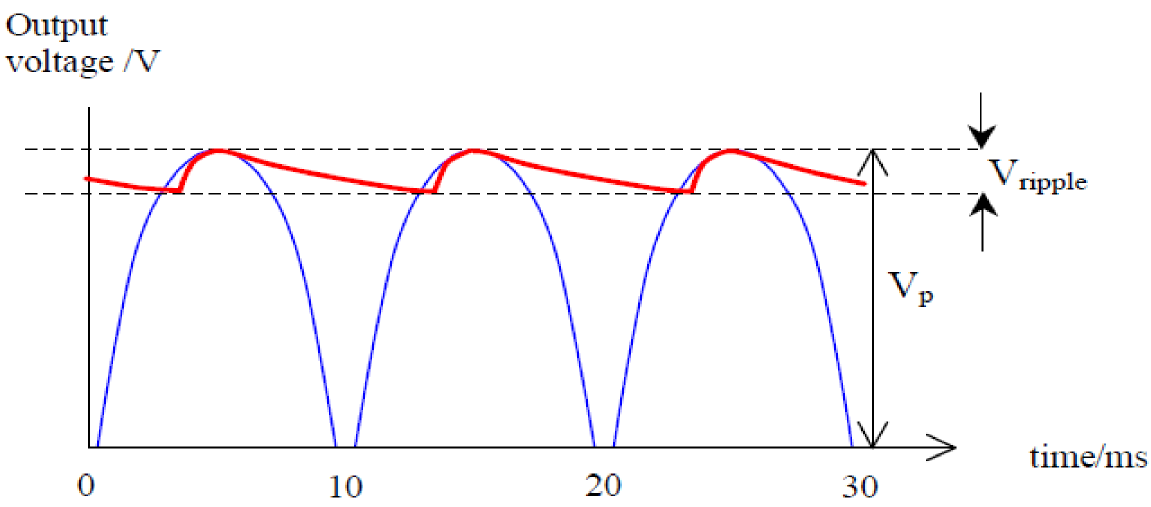

Figure 10: Output waveform of bridge rectifier with RC filter

As the output voltage from the bridge drops the capacitor discharges through the load and so a ripple voltage, V_r, appears on the output from the supply. The size of this voltage depends on the load resistance, R_L, the size of the smoothing capacitor, C, and the peak value of the output voltage, V_p, and is given by:

$$V_r = \left(\frac{V_p}{R_L C}\right) \Delta t$$

$$V_{DC,max} = 1.4 * V_p$$

$$V_{DC,min} = V_{DC,max} - V_p$$

$$V_{DC,average} = \frac{V_{DC,max} - V_{DC,min}}{2}$$

Where:

V_r = ripple voltage

V_p = Peak voltage

R_L = load impendance

V_{DC} = DC voltage

Δt = time between successive peaks of the output waveform from the rectifier circuit.

This will be 10ms if the ac frequency is 50Hz and a full wave bridge rectifier circuit is used. (But 20ms if a half wave rectifier circuit is used; the question could specify a different supply frequency, e.g. 60Hz, which would also affect Δt. This formula is an approximation and assumes that the ripple voltage is small. If the ripple voltage exceeds ~10% this formula becomes increasingly inaccurate.

3.4 Regulation stage: voltage regulation stage steps down and keeps voltage on a certain value and also suppresses unregulated voltage ripples that might have occurred or exist even after the filtration stage thereby producing a perfectly parallel output voltage, which can be used to power any device within the design ratings.

The project evaluated two voltage regulators namely; LM317 and zener diode in the production of variable DC power supply.

- **LM317** is an adjustable 3−terminal positive voltage regulator capable of supplying in excess of 1.5A over an output voltage range of 1.2 V to 37 V. This voltage regulator is exceptionally easy to use and requires only two external resistors and capacitor to set the output voltage. *(cited in National (2012), LM317 Regulator Datasheet Data Sheet)*Further, it employs internal current limiting, thermal shutdown and safe area compensation, making it essentially blow−out proof. This device can also be used to make a programmable output regulator or as a precision current regulator. Livewire simulation of both the filtration and regulation stage for the transformer based Variable Dc power supply is as shown below.

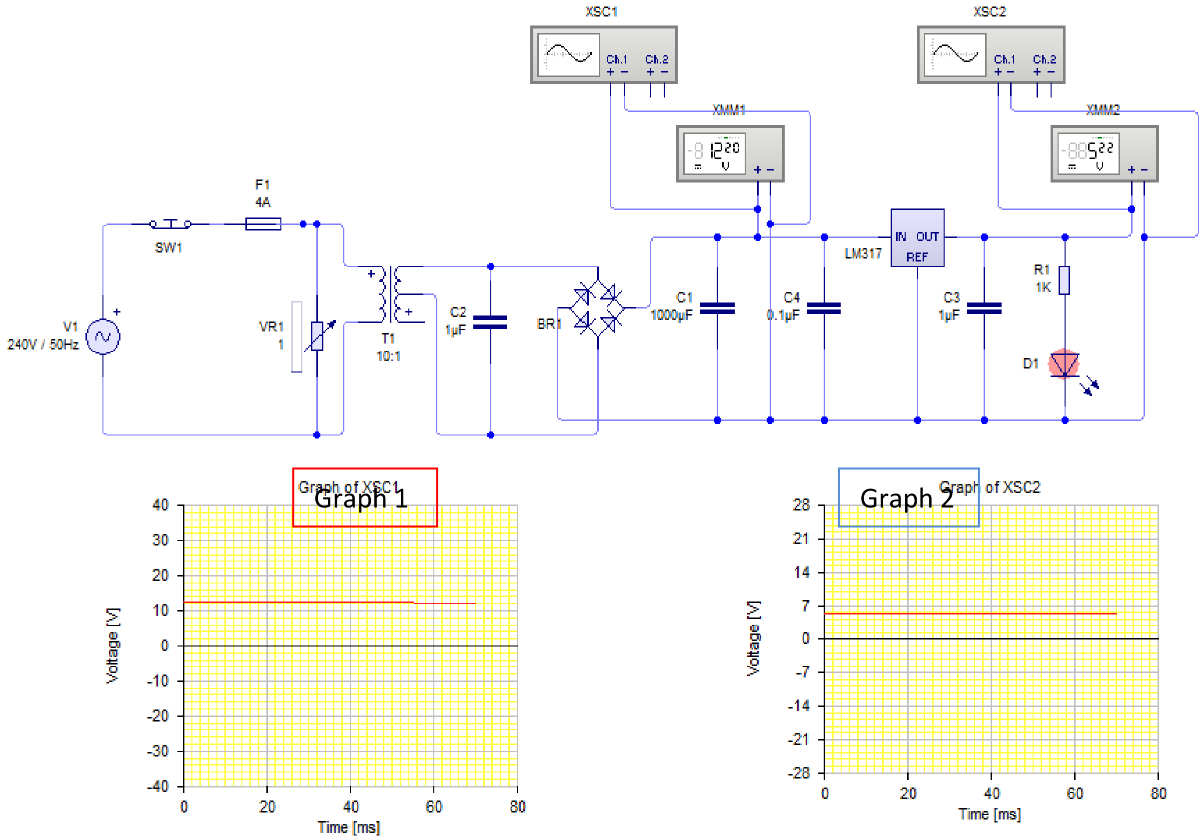

Figure 11: Waveform circuit analysis of filtration and regulation stage for the transformer based circuit using LM 317

From the figure 11 above, C3 is added to the output of the voltage regulator to improve the transient response. The voltage output of the equation is given as

$$V_{out} = 1.25 \times \left(1 + {}^{R2}/_{R1}\right) + I_{adj} \times R2$$

Where:
R2 = $adjustable\ resitor$
R1= $LM317\ resistor$
$I_{adj} = adjustment\ pin\ current$

From the LM 317 data sheet, the adjustment pin current is very small, its $50\mu A\ typical\ and\ 100\mu A\ maximum$, thus the equation can be re-expressed as since the adjustment current is very small and negligible:

$$V_{out} = 1.25 \times \left(1 + {}^{R2}/_{R1}\right)$$

R1 should be very small preferably within the ranges of 200 Ω to 500Ω because of the minimum load current requirement for the LM 317.

$$R1 = R2 \times \frac{1.25}{V_{out} - 1.25}\ \Omega$$

$$R2 = R1 \times \frac{V_{out} - 1.25}{1.25}\ \Omega$$

- Zener diode is preferably used in transformer less DC power supply instead of LM 317 regulator because experiment shows that X-Rated Capacitor with LM317 is highly unstable when the its being adjusted from one voltage value to the next. The livewire simulation of X-rated capacitor with LM series devices is as shown below:

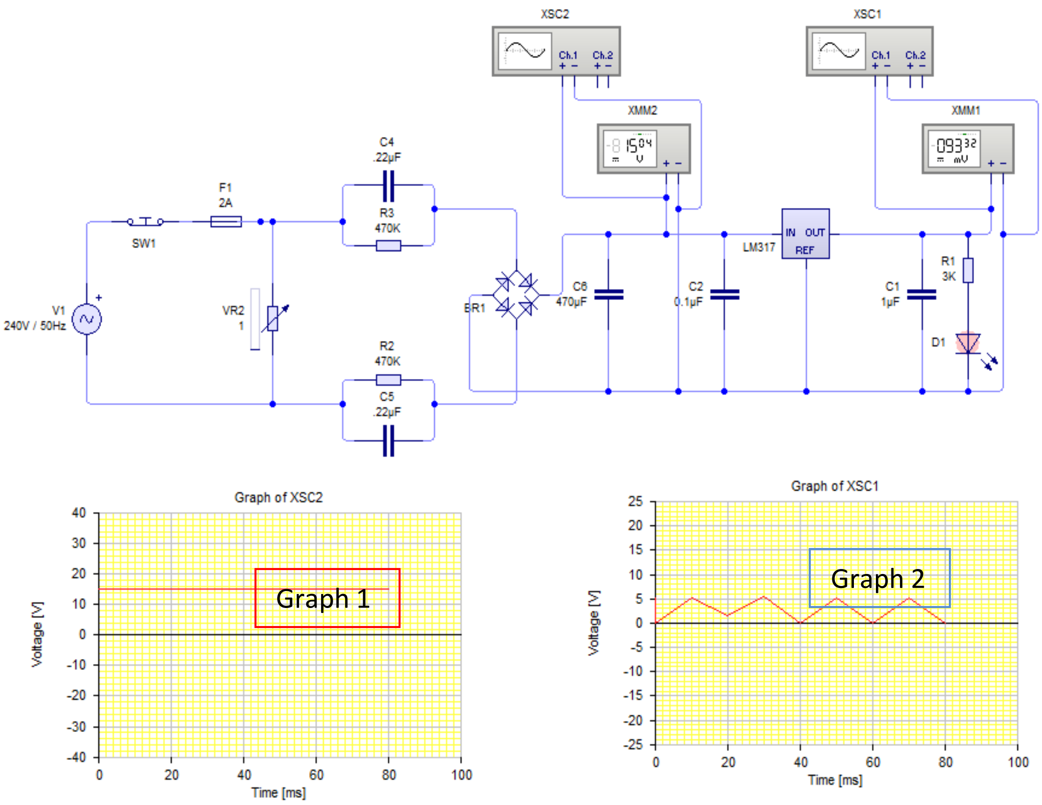

Figure 12: Waveform circuit analysis of filtration and regulation stage for the transformer less based circuit using LM 317

The ripple produced is too much, thus making it ineffective in powering any electronics device; instead zener diode regulation method is employed. The livewire simulation of zener diode regulation is as shown below.

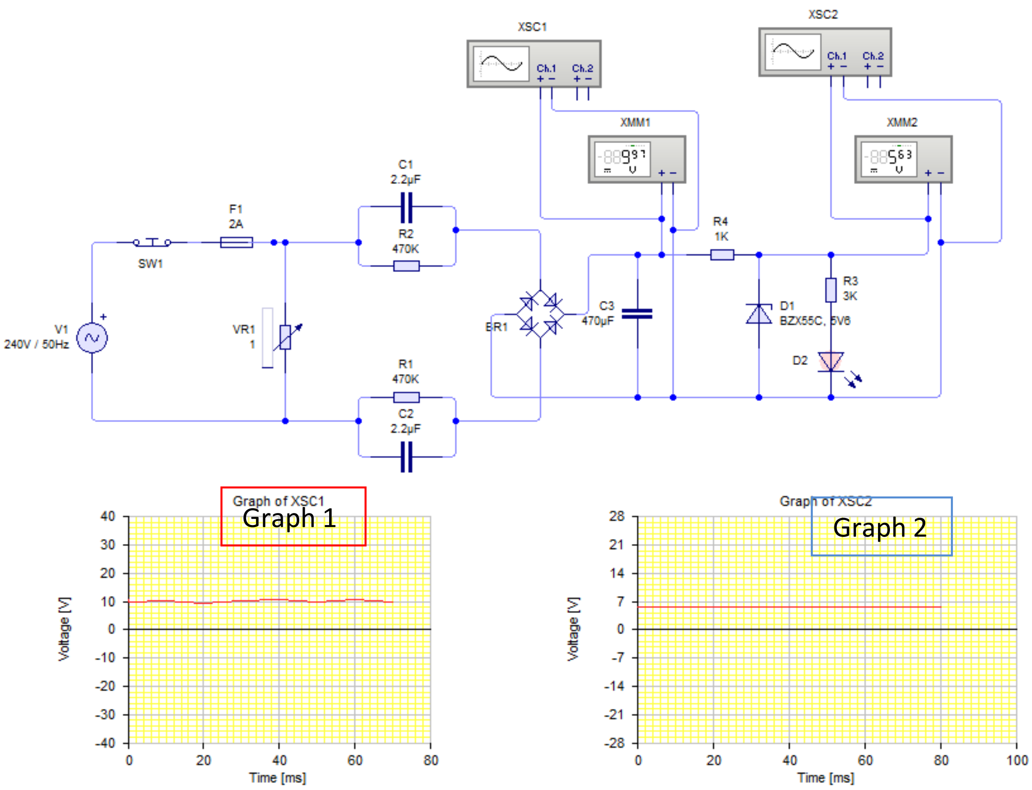

Figure 13: Waveform circuit analysis of filtration and regulation stage for the transformer less based circuit using LM 317

3.5 Working principle of Capacitive Variable DC Power Supply

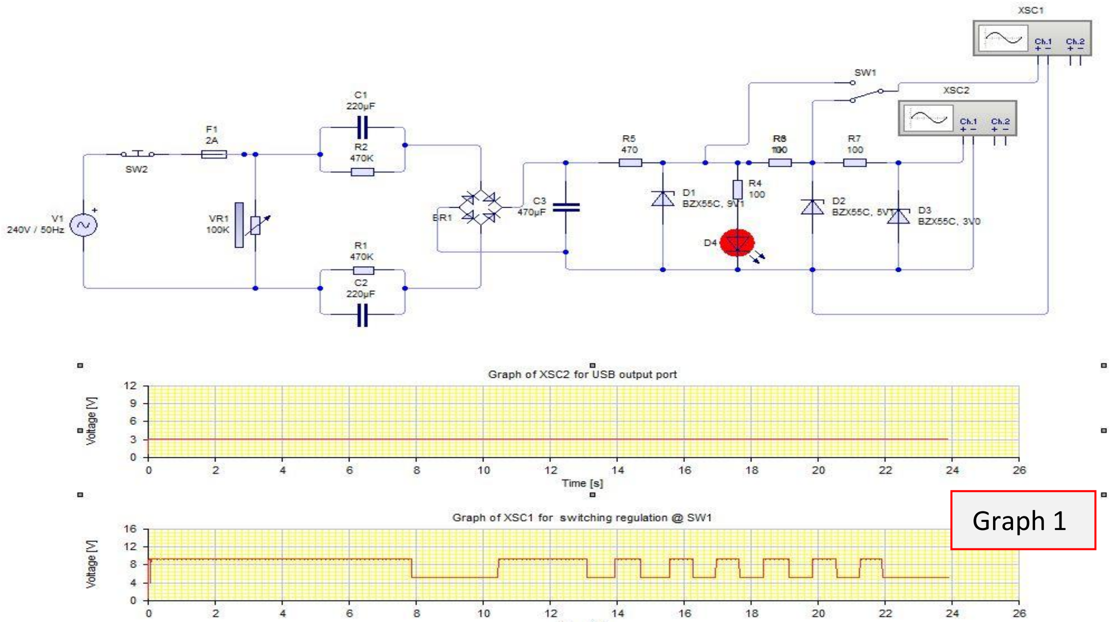

Figure 14: Detailed Circuit diagram of a Switching Regulation Method using Zener Diode for Transformer less Variable DC Power Supply

Graph 2

The figure 14 shown above is a transformer less or capacitive power supply. This capacitor power supply can deliver 12 volt DC and 100mA current to power low current devices. It is provided with surge protection and is totally isolated from mains supply using two X-rated capacitors in the phase and neutral lines. So the connected device is safe even if the phase and neutral lines changes.

The main supply is also connected to the protection circuit comprising of safety fuse in the phase line and an MOV across the phase and neutral lines as safety measure if there is voltage spike or short circuit in the mains.

The safety circuit is in turn connected across the two 225k J (2.2µF) 400 volts X rated capacitor that is in parallel with R1 and R2 known as the bleeder resistor. These resistors help remove the stored current from the capacitor when the circuit is unplugged.

A full wave rectifier is used to rectify the low voltage AC from the X-rated capacitors and C3 removes ripples from the DC. With this design, around 24 volts at 100mA current will be available in the output. This 24 volt DC can be regulated o required output voltage using a suitable 1 watt Zener.

Three zener diodes: ZD1=12V and ZD=5V are alternated by switch SW2 while ZD3 is outputted through the USB ports.

3.6 Working principle of Transformer Based Variable DC Power Supply

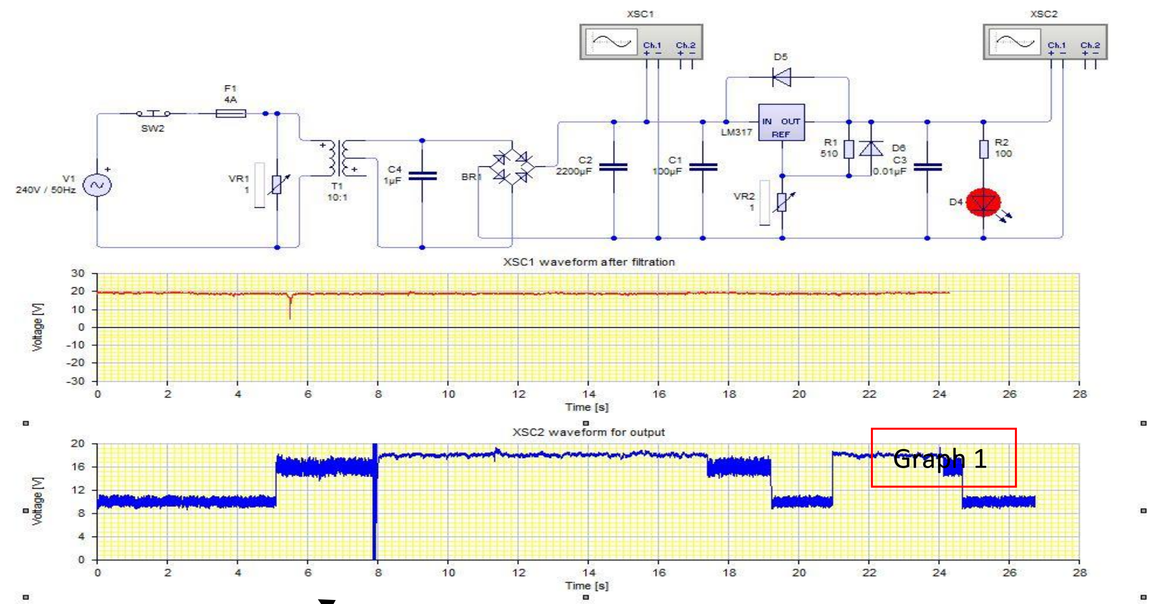

Figure 15: Detailed Circuit diagram of a voltage Regulation using LM 317 for Transformer Variable DC Power Supply

Graph 2

From the figure 15 above, the transformer based variable regulated DC power supply utilizes a supply voltage of 230 Vac and an AC frequency of 60 Hz which is then connected to the protection circuit comprising of a fuse of 1.5 A and varistor of 250 Vac. The protection circuit is connected to the transformer of ratio 10:1 that transforms the AC voltage to the required low voltage of 23V ac.

The stepped down voltage of the transformer is then connected to the bridge rectifier that rectifiers the AC voltage to the DC voltage, which is then filtered by a smoothing capacitor C2 and regulated by a voltage regulator (LM 317 T) resulting in an output of 19 V dc and 1.5 A under the right configuration of resistors (R1 and VR2) , capacitors (C1, C3, C4, C5) and diodes about the regulator.

- The resistors aids in the variation of the regulator outputs
- The capacitors-

a. C1 and C4: help reduce high frequency noise from the mains
b. C3: helps increasing the transient response
c. C5:helps increase the ripple rejection capability of the regulator

- The diode provides additional protection for the LM 317 voltage regulator against blow back current.

The circuit diagram from the figure above was implemented on a Vero board.

IV. Results and Discussion

Table 1 gives the exact detailed amount of each of the electronics components used in the hardware implementation of both the transformer less based and transformer based Variable DC Power Supply

Table 1: Transformer less based Variable DC Power Supply Cost Evaluation

Name	**Number**	**Amount (in Naira)**
Switch (SW1 and SW2)	2	100
Fuse (2A)	1	20
Varistor (250 Vac)	1	150
X-rated Capacitor (C1 and C2-225K/400V)	2	300
Bleeder Resistor (R1 and R2- 470K,1W))	2	50
Bridge Diode (4-diodes-IN4007)	1	200
Filter Capacitor (470uF/50V)	1	50
Resistor (R3,R5,R6- 100 ohms, 1W)	3	150
Zener Diode (12V/1W)	1	20
LED Resistor (R4-1K, 1/4W)	1	20
LED (red)	1	30
Zener Diode (5V/1W)	1	20
Zener Diode (3.7V/1W)	1	20
USB Female port	1	50
Package (box, lead and Vero Board)	3	500
Total	**21**	**1680**

Table 2: Transformer based Variable DC Power Supply Cost Evaluation

Transformer based Variable DC Power Supply Cost Evaluation		
Name	**Number**	**Amount (#)**
Switch (SW1)	**1**	**50**
Fuse (4A)	**1**	**30**
Varistor (250 Vac)	**1**	**150**
Transformer (24V/1.5A)	**1**	**600**
Noise Suppressor Capacitor (C2 and C4)	**2**	**100**
Filter Capacitor (C1-1000uF/50V)	**1**	**70**
Ripple Rejection Capacitor (C5-1uF/16V)	**1**	**50**
Transients Capacitor (C3-1uF/25V)	**1**	**50**
LM 317 Resistor (R1-240 ohms,1W)	**1**	**50**
LM 317 Variable Resistor (VR1-5K)	**1**	**150**
LM317 Protective Diodes (IN4007)	**2**	**40**
VR1 knob	**1**	**100**
Packaging	**1**	**1180**
Total	**15**	**2620**

The results and key difference between transformer less and transformer based variable DC power supply based on the key requirements of DC power supply are as shown in table 3

Table 3: The results of transformer less and transformer variable DC power supply

Factors			Transformer less DC power supply (capacitive power supply)	Transformer DC power supply
1: Protection Stage		Result:	From figure 4- the device was effectively protected from fatal shock, over current and voltage but still caution is required when handling without its package.	Still figure 3- same but it has an added advantage in that it completely isolates the supply voltage from the remaining stages via transformer.
		Status:	Satisfactory	Excellent
2: Transformation stage		Result:	From figure 5- the device was very effective in that the supply voltage of 240Vac was reduced to 24 Vac as stated in the datasheet of 225K x-rated capacitor *(calculation cited in section 3.2.2)*	From figure 4-excelent transformation of supply voltage to the 24Vac based on the rating of the transformer *(turn ratio- calculation is cited in section 3.2.1)*
		Status:	Excellent	Excellent
3: Rectification Stage		Result:	From figure 7- the waveform on this stage was well rectified via bridge rectifier	From figure 6- same result as figure 17
		Status:	Excellent	Excellent
4: Filtration stage		Result:	From figure 8-the waveform and the hardware showed well filtered DC signals with a smoothing capacitor of 470Uf	From figure 7-the waveform and the hardware showed well filtered DC signals with a smoothing capacitor of 1000uF *(calculation is cited in section 3.4)*
		Status:	Excellent	Excellent
4: Regulation stage	**Fixed**	Result:	From figure 12, graph 2- using LM series electronics component regulator the resulting waveform had a lot of ripples as though the DC power was unfiltered while using zener diode as the regulator the resulting waveform showed an excellently filtered DC signal as shown in figure 13, graph 2	From figure 11- the resulting waveform was well regulated using LM 317 regulator
		Status:	Satisfactory *(limitation to use LM series devices)*	Excellent
	Variable	Result:	From figure 14-using a switching regulation method the resulting waveform showed three voltage levels variation using zener diodes; graph 1 showed a constant voltage of 3.7 volts while graph 2 showed voltage switched between 5 and 10 volts.	From figure 15, graph 2-the waveform as shown in graph 2 was well varied between 1.25 and 21 volts, sudden increase in the potentiometer would result highly increased level of ripples and small level of ripples are readily present in this devices but the ripple values increases as the voltage tends to a lower value thus requiring a large heat sink.
		Status:	Excellent	Excellent
6: Robust	**Output Current**	Result:	The current of the X-rated capacitor is limited to low current devices as stated in its datasheet.	The ratings of devices in dependent on the transformer. The current rating of a transformer is robust.
		Status:	Satisfactory	Excellent
	Output Voltage	Result:	From table 2: any voltage value can be obtained but at low current.	The voltage rating of the transformer is robust
		Status:	Excellent	Excellent
7: Power Loss		Result:	The power loss in this device is negligible because of low current flow through the device.	Power loss could be very large as the difference the input voltage to the regulator and output voltage increases; but the heating effect is controlled with heat sink
		Status:	Excellent	Satisfactory
8: Noise Production		Result:	No Noise produced	Noise is produced but suppressed with C2 in figure 28
		Status:	Excellent	Satisfactory
9: Input Harmonics Distortion		Result:	Lower harmonics distortion than its counterpart	Low harmonics distortion
		Status:	Excellent	Satisfactory
10: Cost, Size and Weight		Result:	From table 1: it is cheap. Smaller size and lighter weight than its counterpart	From table 2: it is expensive. Size is dependent on current ratings and has weight
		Status:	Excellent	Satisfactory

Both technologies have their place in today's power efficiency and safety scenarios but the key differences (as shown in table 3) can be deduced from the following key requirement of a proper DC source are: Isolation between source and load, Noise yield, High transient response, Levels of input harmonic distortion, Power losses and , efficiency, Workable size and weight

The transformer-based has a robust output current and well isolated from the supply voltage, which makes it more suitable for high current application, highly reliable for powering electronics devices; the results were excellent for all the five stages involved in the production of DC power supply.

The main purpose behind the introduction of transformer less units was because of cost effectiveness and to sell out the total bodily size and weight so as to miniaturise electronics devices. It also generates far less noise, heat, lower input harmonic distortion levels, high transient response than transformer-based circuitry but it is limited to low current application devices and lack of proper isolation unlike its counterpart thus results in lower Mean Time To Failure (MTTF).

V. Conclusion

In this paper, a comparative analysis of Transformer-based and Transformer less-based variable DC Power supply systems have been achieved with their design analysis successfully presented too.

The software design and design simulation of the both transformer less and transformer based variable DC power supply with their performance analysis using livewire simulation software was satisfactory.

Hardware production of transformer less of variable voltage between 3-10 Volts, 100mA and transformer based of variable voltage between 1.25 -25 Volts, 1.5A DC power supply was tested and results were satisfactory.

The transformer-based has a robust output current and well isolated from the supply voltage, which makes it more suitable for high current application, highly reliable for powering electronics devices while the transformer less based DC source has smaller size, weight and cheaper so as to miniaturize electronics devices but limited to low current devices . It also generates far less noise, heat, input harmonic distortion levels, and higher transient response but lack of proper isolation unlike its counterpart thus result in lower Mean Time To Failure (MTTF).

Transformer less variable DC power supply should be considered a viable option for lower power, small and low current applications where achieving the highest availability is not the top concern and cost, size and weight restrictions inhibit the use of traditional transformer-based DC power supply.

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