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DESIGN AND DEVELOPMENT OF A MULTIPLE OUTPUT SWITCH MODE POWER SUPPLY FOR OFF-GRID APPLICATION USING SPENT E-BIKE BATTERY

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Abstract

This paper presents the design and construction of switch mode power supply (SMPS) for an off-grid application using spent e-bike battery. This project is a multiple output power supply with input voltage range of 36V to 48V dc, output voltages of 5V, 12V, 24V dc with an output current of 0.1A, 1A and 1A respectively; it has an efficiency of 93%. The circuit is made up of both passive and active components, with LM2586-Adjustable as the controller. It was designed purposely to use spent Lithium -ion battery from e-bike/vehicle. It was intended to abide by all relevant standards (regulation) including protection against electromagnetic interference (EMI), electric shock, etc. the circuit is built with printed circuit board (PCB), portable with few components and compact enclosure.

Keywords; *Flyback, Converter, Regulator, Transformation, Spent Lithium-ion battery*

Introduction

Lithium-ion batteries are becoming popular than its counterpart Lead-Acid batteries due to its efficiency, durability, and light weight, which give the user edge most especially the electric vehicle industries, as soon as the cell capacity falls below 60%, it cannot be used to power electric vehicle (Useless). Instead of disposing of it which may cause environmental hazard and explosion. What to do with this battery must be decided on which lead to the design of a high-efficiency switch mode power supply that can power common electrical devices, such as radio, light cooking appliances.

An electrical power supply is a device that provides electrical energy to an electrical load, the importance of any power supply is to convert one form of electrical energy to another. There are different types of the power supply; some are inbuilt, discrete, stand-alone. All power supply receives the energy they consume and supply to load from another source (Corub, 2010). Depending on the design supply to any power supply may be from storage devices such as solar power, fuel cells, generators, batteries, or it may be from transmission lines, or another power supply. The power supply may be divided into three sections; the input where the energy enters into the power supply, the output where the energy goes out of the power supply, in between the input and output are electrical components or hardware's which are connected according to one's specification. Power supply can also be classified according to its functional features, such as:

Regulated power supply, which maintains its output voltage and current despite the variation in load;

Unregulated power supply, this change significantly when there is variation in load current or input voltage

Adjustable power supplies the output voltage or current can be control manually or programmed (Monalisa 2014). Others are Isolated powers supply, which has output power that is electrically independent of the input power.

There is a great advancement in technology today, as a result, there is the need for portability, efficiency, weight reduction, durability and waste reduction are the very important component for consideration in industry.

Methodology

The design of a switch mode power supply (SMPS) with multiple outputs is a complex procedure due to the number of parameters involved and the interdependence of these circuit parameters. However, when broken down into stages, it becomes much easier to manage. The design specifications are shown in Table 1.

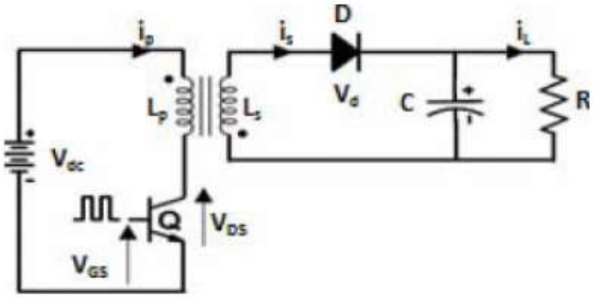
Table 1: Specifications of the switch mode power supply (SMPS) to be designed

Parameters	**Values**
Input voltage, (V_{IN})	36V - 48V
Output voltage, (V_O)	5V, 12V, 24V
Output Current (I_O)	0.1A, 1A, 1A
Output Power (P_O)	37W
Estimated transformer efficiency, h	93%

The specification is a vital aspect of design; it gives the designer guide on what is expected from a particular work. The efficiency of any power supply is determined by various attributes which contain in the specification, this attribute includes the following:

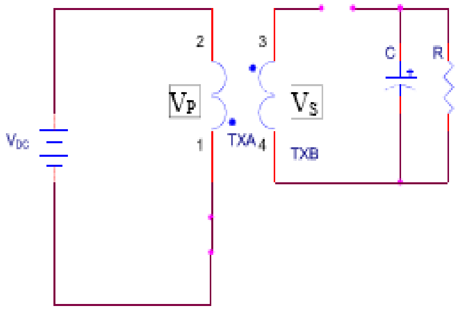
Given specification

Input Voltage: 36-48Vdc



Outputs: V_{1out}-5.0 V I_{1out}- 0.1A
V_{2out}- 12.0 V I_{2out}- 1A
V_{3out}- 24.0 V I_{3out}- 1A

Figure 1: Simple flyback converter



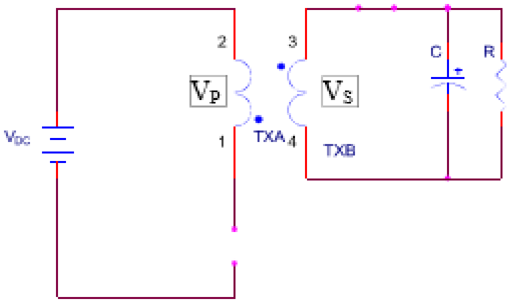


Figure 2: Switch Q in ON **Figure 3: Switch Q in OFF state**

Fly back design approach

At steady -state the mean voltage over inductor is equal to zero.

$$(V_{dc} - V_{DS}) \times t_{on} = (V_o + V_d) \times t_{off} \times n \qquad (1)$$

(Amit, 2013)

Where:

V_{dc}	input voltage
V_{DS}	output voltage
T_{on}	Turn-On time
T_{off}	Turn-Off time
T_d	dead time
V_d	Conduction voltage drop of diode D,
V_{DS}	Conduction voltage drop of switch Q,
N	transformation ratio of inductors
L_p	Primary inductance,
L_s	Secondary inductance

For continuous current mode (CCM), switching period is given as

$$T = t_{on} + t_{off} \qquad (2)$$

For DCM mode, the switching period is given by adding dead time t_d to equation (3) which gives

$$T = ton + toff + td \qquad (3)$$

0.8 x T = ton + toff (4)

$t_{off} = T - t_{on}$ Insert these in equation (2), equation (3) will now be

$$t_{on} = \frac{T \times n \times (V_o + V_d)}{(V_{dc} - V_{DS}) + n \times (V_o + V_d)}$$

(5) (Amit, 2013).

As it can be seen above only the input voltage that is varied, $t_{on\text{-}max}$. Occur at $V_{dc\text{-}min}$.

$$t_{on\_max} = \frac{T \times n \times (V_o + V_d)}{(V_{dc\_min} - V_{DS}) + n \times (V_o + V_d)}$$

(6)

It is evidently seen that when the switch is ON, the primary current rise linearly since there is constant input voltage and it reach the peak at ton-max., maximum ton occur at minimum input voltage. Therefore $I_{p\text{-}max}$. Is given as

$$i_{p\_max} = \frac{(V_{dc\_min} - V_{DS}) \times t_{on\_max}}{L_p}$$

(7)

The energy stored in the primary inductor can be obtained by replacing $I_{p\text{-}max}$ in equation (1) since there is energy transfer.

Therefore, input power in watt is given as

$$P_i = \frac{1}{2} \times \frac{L_p \times i_{p\_max}^{\ 2}}{T}$$

(8) (Bloom and Eris, 2012).

The voltage drop during conduction is 1V, which is negligible, the input power can, therefore, begotten by placing equation (7) on (8) it will yield

$$P_i = \frac{\left[V_{dc\_min} \times t_{on\_max}\right]^2}{2 \times T \times L_p}$$

(9)

When the switch is turned OFF, the stored energy at the air gap is transferred to the secondary inductor, therefore secondary current decreases linearly on the Resistive load.

It is noteworthy to know that fly-back converter operates at a very high efficiency of about 80% and above.

$P_i = 1.25 \text{ x } P_o$ (10)

Equation (9) and (10) gives the primary inductance

$$L_p = \frac{\left[V_{dc}\_\min \times t_{on}\_\max\right]^2}{2{,}5 \times T \times P_o} \qquad (11)$$

Maximum value of secondary current can be obtained as

$$i_s\_\max = i_p\_\max \times n \qquad (12)$$

(Coruh and Urgun, 2010).

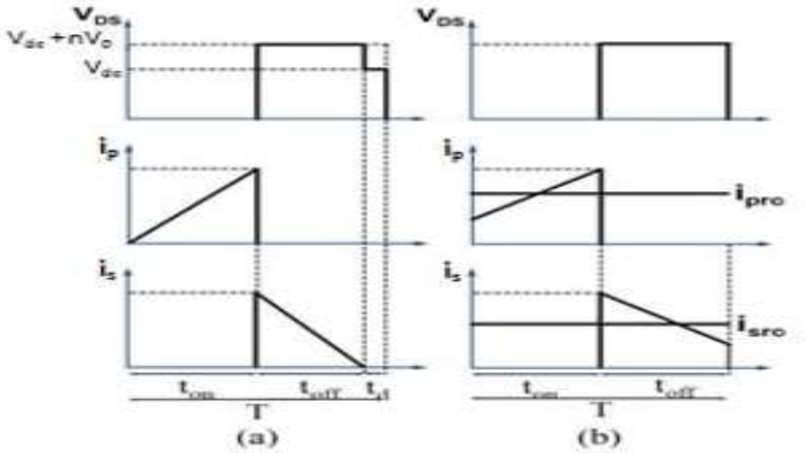


Figure 4 (a) DCM characteristics, (b) CCM characteristics (Coruh and Urgun, *2010).*

The operational mode of flyback converter can be defined by the magnetising inductance and load current, which can also change when the load current varies.

Due to the inability of CCM mode to discharge all its current before the next ton (fig. 3b), the equation of current and inductor has to be different from DCM equation. Since both secondary and primary currents are ramp functions, if I_{sro} is the centre of secondary ramp and I_{pro} is the centre of primary ramp the output is given by (Amit, S.,2013)

$$P_o = V_o \times \mathrm{i}_{sro} \times \left(\frac{1 - t_{on}\_\max}{T}\right) \qquad (13)$$

(Pandey, 2014).

Centre of the secondary ramp will be

$$\mathrm{i}_{sro} = \frac{P_o}{V_o \times \left(\frac{1 - t_{on}\_\max}{T}\right)} \qquad (14)$$

Centre of primary ramp will be (15) at 80% efficiency

$$i_{pro} = \frac{1.25 \times P_o}{V_{dc\_min} \times \left(\frac{t_{on\_max}}{T}\right)} \quad (15)$$

It is seen from above that the minimum primary current can occur at minimum output power, given the centre of the ramp as the half of current variation.

$$i_{pro} = \frac{di_p}{2} \quad (16)$$

Primary inductance Lp is given as

$$L_p = \frac{\left(V_{dc\_min} - 1\right) \times t_{on\_max}}{di_p} \quad (17)$$

When equation (16) is put on (17), then the primary inductance will become

$$L_p = \frac{\left(V_{dc\_min} - 1\right) \times V_{dc\_min} \times t_{on\_max}{}^2}{2.5 \times P_{o\_min} \times T} \quad (18)$$

Transformer Design

Transformers and inductor is a vital part in the design of SMPS; many methods can be applied in achieving optimum design. One of these is iterative methods which are normally supplied by most core manufacturers, customise with their product

Another generalise method called Area product is also used, though this way is full of the equation, it removes the iteration problem. In this work a simple, non-iterative technique is employed, it based on area product principle and it is not specific to a certain types or manufacturer of the core. As far as the core dimension and maximum flux density are known. The detail derivation is given below (Gow and Bleijs, 2012).

The Area product (AP) is a quantity that describes the geometry of a given core and its winding area. A_p is defined as the product of the usable core cross- sectional area(A_c) and the available winding window area (A_w).

Therefore $A_p = A_w A_c$ (19)

When relating the area product with the characteristics of the desired transformer or inductor, we have these

$$AP = \left(\frac{P_t \cdot 10^4}{4 B_m f W_f K_j}\right)^{1.16} \quad (20)$$

Where Pt is the total transformer power, Bm is the maximum flux density; Wf is the winding factor, F is the frequency, Kj is the current density.

Winding factor (Wf) is defined as the total winding area that is occupied by copper.

Assumptions

- The primary voltage is the square wave with 50% duty cycle.
- The value of Kj is known
- It uses the transformer power to link electrical parameters to magnetic parameters

To derive expression for transformer core area Ac, let the number of turns in primary of the transformer be Np when Faradays law of induction is applied, then $\phi = BA_c$. (Gow and Bleijs, 2012).

$$A_c = \frac{V_{\max} t_{on}}{dB_{\max} N_p} \tag{21}$$

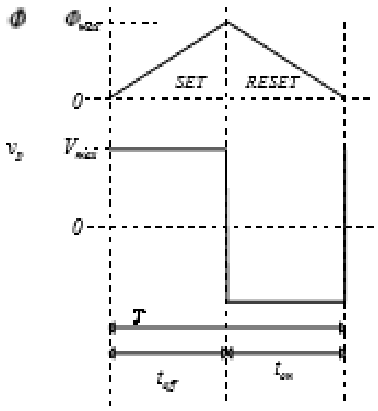


Figure 5a: Flux and voltage waveforms in primary

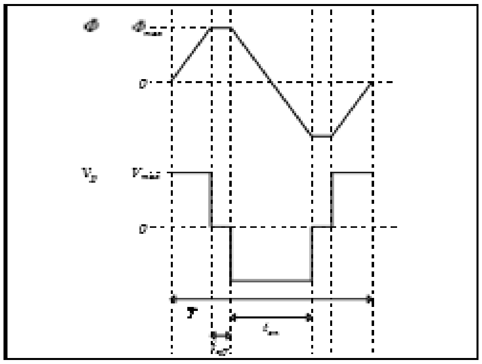


Fig 5b: Flux and voltage waveform in primary of a transformer in a single – ended Application

W

The window area is related to current and current density, if the current density of both primary and secondary are the same, then window area can be calculated as follows.

$$A_w = \frac{1}{W_f J}\left(N_p I_p + N_s I_s\right) \tag{22}$$

$$I_s = I_p \frac{N_p}{N_s} \tag{23}$$

$$A_w = \frac{2 N_p I_p}{J W_f} \tag{24}$$

Where I_p and I_s are the rms of primary and secondary currents

The winding area is equal to (24)

Area Product

When equation (23) and (24) is combine

We have the area

$$A_w A_c = AP = \frac{2V_{\max} I_p t_{on}}{dB_{\max} J W_f} \qquad (25)$$

The area product given in in equation (25) refer all terms to primary side, therefore, is the minimum area required to support the transformer at the specified maximum flux density and current density. After the area product has been determined, it is necessary to determine the number of turns, rearranging equation (22) it gives

$$N_p = \frac{V_{\max} t_{on}}{dB_{\max} A_c} \qquad (26)$$

Equation (26) gives the number of turns without affecting maximum flux density. Secondary turns can now be calculated from the turn ratio of the transformer.

Therefore,

$$N_s = N_p \cdot \frac{N_s}{N_p} = N_p \frac{V_s}{V_p} \qquad (27)$$

(Gow and Bleijs, 2012).

Power transformer stage

$$P_{out} = (24 \times 1) + (12 \times 1) + (5 \times 0.1)$$
$$= 24 + 12 + 0.5$$
$$= 36.5 \approx 37W$$
$$\delta = \frac{V_{Ref}}{V_{in.Min} \times V_{Ref}}$$
$$0.45 = \frac{V_{Ref}}{36 \times V_{Ref}}$$
$$V_{Ref} = 29.45V$$

From data sheet, efficiency (Ƞ) = 95% =0.95

$$P_{in} = \frac{P_{out}}{\eta} = \frac{37}{0.95} = 38.95 \approx 39W$$
$$I_{avg} = \frac{P_{in}}{V_{inMin.}} = \frac{39}{36} = 1.08A$$
$$I_{peak} = \frac{2xI_{avg}}{\delta} = \frac{2x1.08}{0.45} = 4.8A$$
$$L_p = \frac{V_{Max} \times \delta}{f_s \times I_{peak}} = \frac{48 \times 0.45}{100 \times 4.8 \times 10^3} = 45\mu H$$

$$\boldsymbol{N_p} = \frac{V_{max}\times\delta}{f_s\times dB_{sat}\times A_c} = \frac{48\times0.45}{100\times10^3\times320\times10^{-3}\times83\times10^{-6}}$$

$$= 18$$

Gap length (L_g)

$$L_g = \frac{\mu_0\times N_p^2\times A_c}{L_p} = \frac{4\times\pi\times10^{-7}\times8.1^2\times83\times10^{-6}}{45\times10^{-6}} = 0.15mm$$

$$\boldsymbol{N_p} = \sqrt{\frac{L_p}{A_l}} = \sqrt{\frac{45\times10^{-6}}{145\times10^{-9}}} = 18$$

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

$$\boldsymbol{N_s} = \frac{N_p\times V_s}{V_p}$$

$$\boldsymbol{N_{s1}} = \frac{18\times24.6}{29.45} = \mathbf{15.04} \approx \mathbf{15}$$

$$\boldsymbol{N_{s2}} = \frac{18\times12.6}{29.45} = \mathbf{7.70} \approx \mathbf{8}$$

$$\boldsymbol{N_{s3}} = \frac{18\times5.6}{29.45} = \mathbf{3.42} \approx \mathbf{3}$$

To calculate the cross-sectional area of the copper conductor

From equation 30 taken Current density of copper to be $5mA/m^s$

$$\boldsymbol{P_{dia}} = 2\sqrt{\frac{I_p}{J\pi}}$$

Therefore, $\boldsymbol{P_{dia}} = 2\sqrt{\frac{1.05}{5\times10^6\times3.143}}$

$$= \mathbf{0.517} \approx \mathbf{0.5}\boldsymbol{mm}$$

For secondary diameter using equation 31

$$\boldsymbol{S_{dia}} = 2\sqrt{\frac{I_p\times N_p}{J\pi\, N_{s1}}}$$

$$\boldsymbol{S1_{dia}} = 2\sqrt{\frac{1.05\times18}{5\times10^6\times3.143\times15}}$$

$$= \mathbf{0.566} \approx \mathbf{0.5}\boldsymbol{mm}$$

$$\boldsymbol{S1_{dia}} = 2\sqrt{\frac{1.05\times18}{5\times10^6\times3.143\times8}}$$

$$= \mathbf{0.7} \approx \mathbf{0.7}\boldsymbol{mm}$$

$$\boldsymbol{S1_{dia}} = 2\sqrt{\frac{1.05\times18}{5\times10^6\times3.143\times3}}$$

$$= \mathbf{1.26} \approx \mathbf{1}\boldsymbol{mm}$$

Output Capacitance

$$T = RC = R_2 \times C_2$$

$$T = \frac{1}{f_s} = \frac{1}{100 \times 10^3} = 10 \times 10^{-6} s$$

$$R_2 = \frac{T}{C_2} = \frac{10 \times 10^{-6}}{0.47 \times 10^{-6}} = 21.28\Omega$$

$$V_{ripple} \approx 100mV$$

$$N_{cp} =$$

$10\ Number\ of\ clock\ cycle\ needed\ to\ go\ from\ minimum\ to\ maximum$

$$C = \frac{I_{out} N_{cp}}{f_s \times V_{ripple}}$$

$$C_3 = \frac{1 \times 10}{100 \times 10^3 \times 100 \times 10^{-3}} = 1000\mu F$$

$$C_4 = \frac{1 \times 10}{100 \times 10^3 \times 100 \times 10^{-3}} = 1000\mu F$$

$$C_3 = \frac{0.1 \times 10}{100 \times 10^3 \times 100 \times 10^{-3}} = 100\mu F$$

Programming Output voltage (Selecting R3 and R4)

R3 and R4 were used to programme the output voltage through this formula:

$$V_{out} = V_{REF}(1 + R_3/R_4) \tag{28}$$

Where V_{REF} = 1.24V = Reference voltage

V_{out} =12 is the output voltage (12V)

R3 and R4 divide the output voltage down so that it can be compared with the 1.23V internal reference voltage If R4 is between 1k and 5k, R3 is:

$$R_3 = R_4(V_{OUT}/V_{REF} - 1) \tag{29}$$

Substitute the values to formula above

R1 and R2 can be calculated using above formula.

$$R_3 = 48.75k\ , R_4 = 5.62k$$

1% metal film resistor was recommended for best temperature coefficient and stability with time. (LM 2586, Data sheet).

Selection of limiting Resistor: external resistor was used which can withstand the maximum switch current of 3A.

Fly back converter input Capacitors

Fly back converter draws discontinuous pulses of current from the input supply. It then needs input capacitors for energy storage, and filtering, a storage capacitor of about 100uf is needed to maintain constant and stable voltage supply to the IC. A small ceramic bypass capacitor of about 1.0uf is required to eliminate the noise generated by the input current pulses.

Switch Voltage Limit

In the fly back converter, the maximum steady state voltage appearing at the switch when it turns off is determined by the transformer turn ratio(N), the output voltage and the maximum input voltage V_{inMax}:

Therefore, $V_{SW(OFF)} = V_{IN(Max)} + (V_{OUT} + V_F)/N$ (30)

Where Vf is the forward biased voltage of the output diode which is typically 0.5v for schttky diode and 0.8 v for ultra-fast recovery diodes (Data sheet).

EMI protection (SNUBBER)

In flyback there is situation of having a voltage spike (V_{LL}), which super impose upon the steady voltage. Transformer leakage inductance and output rectifier recovery time usually cause this spike. To clamp the voltage at the switch from exceeding its maximum value a transient suppressor in series with the diode can be inserted across the transformer primary. Using LM2586, there is the tendency for the voltage at the switch PIN 5 to go negative when the switch is turns ON; the ringing voltage appear at the switch pin 5, this is cause by the the output diode capacitance and the transformer leakage inductance forming a resonance at the secondary. The resonant circuit generates the ringing voltage which gets reflected through the transformer to the switch pin. The method used to eliminate ringing is to insert Schottky clamp between pin 4 and pin 5b this prevent voltage at pin 5 from dropping below -0.4V. as shown in figure 9.

The equation gives the maximum output voltage: $V_{OUT} = N \times V_{IN} \times D/(1 - D)$

While the duty cycle of fly back is determined by:

$$D = \frac{V_{OUT}+V_F}{N(V_{IN}-V_{SAT})+V_{OUT}+V_F} \approx \frac{V_{OUT}}{N(V_{IN})+V_{OUT}} \qquad (31)\ (\text{LM 2586, Data sheet})$$

Noisy input line condition an RC capacitor can be connected to the input pin 7, to ground the resistor to divert the noisy input.

Stability: All current- mode controlled converter suffers from instability call subharmonic oscillation when they operate above 50% duty cycle (Data sheet).

LM 2586 fly back regulator (controller)

LM2586 -Adjustable was selected as the controller for this project, the reasons behind its choice are briefly described as follows.

This Integrated circuit (IC) is a simple switcher, especially design for flyback converter applications, it requires very few number of external components, it is cost effective and very simple to use. The switch is 3A, NPN device that can withstand voltage of 65V. The switch is protected by thermal and current limiting circuit with low voltage protection (Pandey S. K, et al, 2014).

The IC has an adjustable frequency oscillator which can be programmed up to 200KHz, its oscillator can be synchronised with other devices for multiple devices to operate at the same frequency.it is a family of standard inductor and transformer, it has wide input voltage range of 4V to 40V,with an adjustable frequency of 100 KHz to 200KHz.

Principle of operation of fly back regulator

This IC is ideal for fly back converter topology, it can produce single and multiple output voltages as used in this study, the regulator generates the output voltage that is in the range of the input voltage, and this is a unique feature of the fly back converter. The output voltage is control through modulating the peak switch current this action was done by feeding back a portion of the output voltage to the error amplifier as shown above, which in turn amplifies the differences between the feedback voltage and a 1.23V reference voltage. The error amplifier output voltage is compared to a ramp voltage proportional to the switch current. (The inductor current during the switch on time). The comparator terminates the switch on time when the two voltages are equal, thereby controlling the peak switch current to maintain a constant output voltage.

Switching waveforms

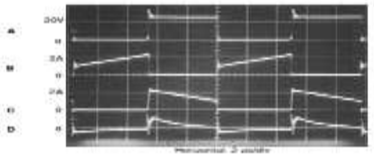


Figure 6: LM2586 switching waveform

LM2586 Special features

Shutdown control

One of the special features of this IC is the ability to shut down the device when is middle, using its ON/OFF PIN 1, this feature conserves the input power, the device will shut down when a voltage equal or greater than 3V is applied to its PIN 1 And ON again when the Pin is left floating with the use of isolating diode.

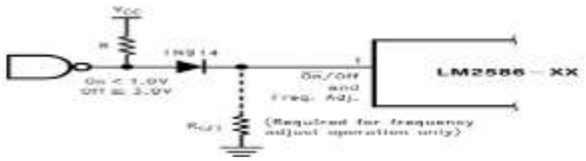


Figure 7: Shut down operation/ Frequency Adjustment

Figure 8: Frequency Synchronisation

Frequency Adjustment

Another unique feature of this IC is its ability to adjust its switching frequency from 100KHz to 200KHz by connecting the external resistor between PIN 1 and the ground. This allows the user to optimise the size of the magnetics and the output capacitors. This feature does not affect its shutdown function despite both are in PIN 1.

Frequency Synchronization

Frequency synchronisation is another special feature of this IC; it synchronises the switching frequency to an external source by the use of its PIN 6. It allows the user to multiple parallel devices to deliver more output power.

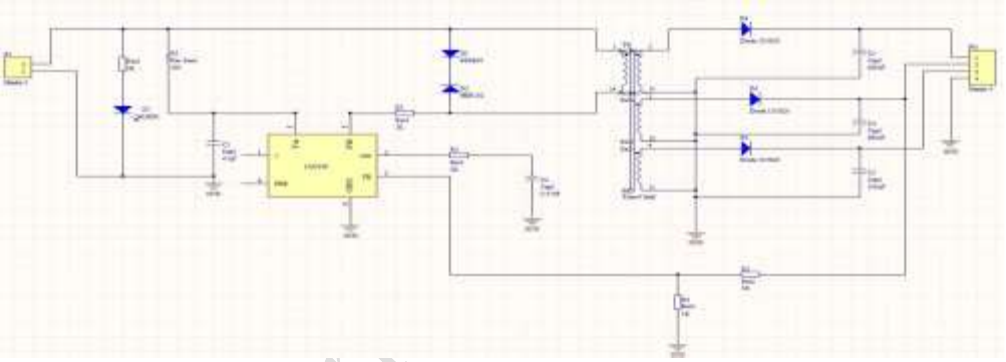
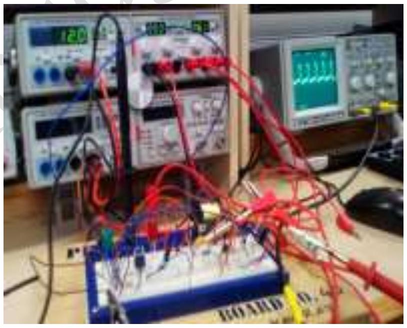


Figure 9: Schematic diagram of SMPS

Test, Result, and Discussion

After the design calculation, the circuit was built on Breadboard, as seen in figure 17, voltage, current and switching frequency of the design were tested and the result display on voltmeter and oscilloscope as seen in figure 17a and 17b below. Results 100Hz was gotten from oscilloscope which proves that the circuit is in order.



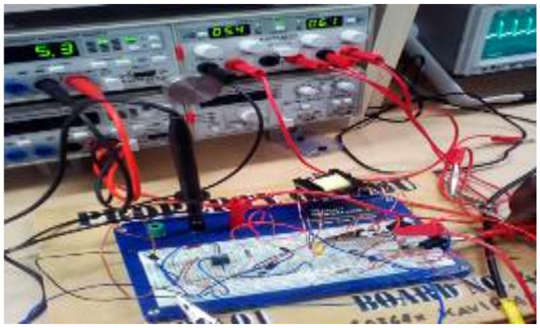


***Figure 10*a: testing on Breadboard** ***Figure 10*b: Testing on Breadboard**

The final design project is shown in figure 11a -figure 11b, several test and inspection were carried out on the final product, and the result are as follows.

Voltage test: the input voltage is in the range of 36V to 48V.The output voltage is 24.1V, 12.0V and 5.3V respectively.

The input current is 1.05A. The output current are $I_{1\ out} = 0.1A$, $I_{2\ out}$ and $I_{3out} = 1A$, Output power is 37W.

The main purpose of this testing and inspection is to detect faults before any dangerous situation arises, also to check if the design conforms to specification and standards from relevant bodies.

The earth continuity was tested, short circuit and open circuit test was carried out, the result was satisfactory. The enclosure is plastic to prevent shock.

Figure 11a: Top view of power pack s

Enclosure

The plastic enclosure of 130mmx50mmx70mm is used to ensure safety and portability as seen in the figure.

Figure 11b: How PCB is connected to enclosure

Conclusion and Recommendation

The design and implementation of multiple outputs SMPS for the off-grid application using spent battery was completed, Flyback topology was used in the design due to its numerous advantages over others, among which are simplicity in design, few external component, and reduce cost. The discontinuous current mode was used with voltage mode feedback. Schottky and Zenner diode used as the snubber to prevent electromagnetic interference (EMI). Area product approach was used to calculate the transformer turns, in which primary turn Np=18, while the secondary turns were 15, 8 and 3, for N1, N2 and N3 respectively. At the end, the functional output voltages are 24V, 12V and 5V for V1, V2 and V3 respectively.

The plastic enclosure was used, with the banana socket as the input and output socket, which is firmly attached to the plastic enclosure.

The design of multiple output SMPS was done successfully, with all expected values of voltages and the current was gotten as specification required. This design is recommending for mass production of power supply to equipment that is less than 150W.

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