



## Single Input Multiple Output (SIMO) Flyback DC – DC Converter for Off-grid Photovoltaic Applications

<sup>1</sup>Imam A. M., Kunya<sup>2</sup> A. B. and Sagagi Y. M.<sup>1</sup>

<sup>a</sup>Physics with Electronics Department, Federal University Birnin Kebbi, 862104, Kebbi State, Nigeria.

<sup>b</sup>Electrical Engineering Department, Ahmadu Bello University (ABU) Zaria, Kaduna State

### ABSTRACT

Flyback is the most used and popular topology in DC -DC converters for its advantages of galvanic isolation, simple control technique and design simplicity. It enables additional design freedom that can be used to achieve high voltage boost ability; varying turns ratio, low ports count and multiple voltage outputs. This paper presents the design and methods of development of a single input multiple outputs (SIMO) flyback DC – DC converter prototype developed using ferrite-core magnetic transformer. The number of turns, serving as function of output voltages was used to obtain output voltages of 24V, 15V, 12V and 5V. The proposed flyback converter was fabricated. A miniaturized developed prototype with multiple outputs for off-grid photovoltaic application on DC gadgets was tested and analyzed; little variation of output voltages was recorded between the experimental and calculated values which is due to discrepancies in components' variations. The proposed prototype has 91.9% efficiency.

**Keywords:** DC-DC converter; flyback; inductor; switch; transformer; ferrite-core.

### INTRODUCTION

The photovoltaic system's output voltage is variable due to instability of the irradiances (Eke and Betts, 2017; Yadav and Chandel, 2017). DC-DC converters are employed to provide constant regulated output voltage (Kawano and Goto, 2017). For the past six decades (since the establishment of the DC-DC technique in 1920s), DC-DC converters have received significant research interest (Sivakumar *et al.*, 2016) and they play a very significant role in power science and technology. Converters replace the use of conventional rheostats and potential dividers in photovoltaic systems whose efficiency is very less (Sivakumar *et al.*, 2016). There is a consistent demand for small-sized, reliable and efficient DC-DC converters for various DC-DC applications (Forouzesh *et al.* 2017). It is envisioned that DC – DC converters would be used more often in future to reduce the number of conversion stages, power loss and increase power density (Zhanget *al.* 2017).

The DC power system includes the DC source, converter, loads and backup battery in some cases. The adopted DC – DC topologies are of two types; isolated DC -DC converters and non-isolated DC -DC converters (Sivakumar *et al.*, 2016). Because of the need for galvanic isolation to separate the input (primary) and the output (secondary) sides to protect sensitive loads, isolated converters have electrical barriers with high frequency transformers. Whereas, non-isolated converters have no electrical barrier and are simple in design.

There are quite a number of topologies of isolated DC – DC converters; flyback; push-pull, etc.

Flyback converters are the most used DC -DC converters in switched mode power supplies. Low number of components in flyback converters makes them good for low power applications (Prieto *et al.*, 1996). One of the most important components of flyback converter is “transformer”. The transformer turns ratio enables additional design freedom that can be used along with the duty cycle to achieve high voltage boost ability (Forouzesh *et al.*, 2017). The transformers also gives galvanic isolation between the components and loads (Sontiet *al.* 2017). Although, leakage inductance in transformer can cause spikes and switching losses across the switching components, the effects might be important in some techniques (Chuet *al.*, 2014) and they make the converter applicable in high voltage applications (Han, 2013; Tran, 2014; Wu *et al.*, 2015; Rathore *et al.*, 2016). The flyback magnetic component in converters stores energy instead of transferring it, as such, it has a different behavior than a basic transformer. Therefore, unlike the design of transformer, the design of flyback is same with that of an inductor. Flyback topology doesn't require output inductor and enables design simplicity, varying turns ratio, low ports count and multiple voltage outputs (Watanabe and Itoh, 2017). Although, flyback gives lower output power and needs output loads (Özkara *et al.*, 2017).

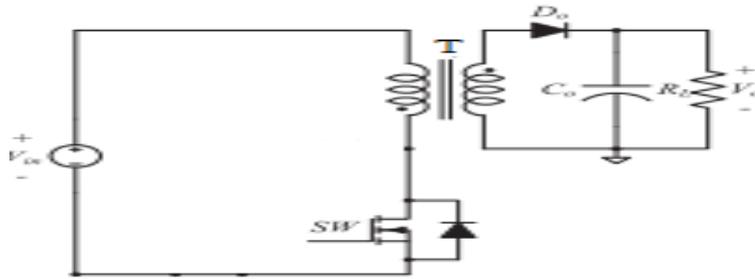


Fig. 1 Conventional flyback DC -DC converter( Bretz, 1999;Jung *et al.*, 2005;Belloni *et al.*, 2008)

Although transformers and coupled inductors have similarities like several windings on a magnetic core, they have wide differences in terms of their principles of operation in switching converters. Whereas transformers are used for power transfer, a coupled-inductor like the one being used in this prototype and paper is for energy storage during converter switching cycle. The power going into the coupled-inductor is not the same as the power leaving it (Witulski, 1995). The transformers are used mostly for dc isolation, voltage and current scaling and to enable multiple outputs from a single converter; thereby reducing the number of components. Couple inductors reduces the converter volume using one core, instead of two or more, favors multiple outputs in converter and reduce ripples between windings (Witulski, 1995). Three laws; Ampere’s, Faraday’s and Gauss laws are the laws used in magnetic analyses.

Power transformers enable high efficiency by either boosting the voltage or stepping it down in generation or distribution respectively (Sheet *et al.*, 2013). A ferrite core transformer is a type with magnetic core on which the transformer windings are wound. It has high permeability and low electrical

conductivity, which helps in preventing eddy currents (Albacht *et al.*, 1996). Ferrite core transformers have comparatively low losses at high frequency and high resistance to high current (Cogiore *et al.*,1993). Ferrite-core transformers provides shielding, leakage control, safety isolation and impedance matching. The need to provide miniaturization and at the same time meeting the performance needs with very low harmonic distortion and leakages drives the advantage of using ferrite -core transformers in power systems (Wedley, 2011).

In this paper, a single input multiple output (SIMO) flyback DC – DC converter is proposed. The proposed converter was implemented with a ferrite-core magnetic transformer (acting as a coupled-inductor).24, 15, 12 and 5 turns winding were done on the transformer to give different output voltages according to the function of turns at the windings based on Faraday’s law. UC3843 oscillator supplies the pulses and its used to sense the current and regulate the PWM.

**Proposed Flyback Converter**

Flyback uses pulse width modulation (PWM) for voltage control.

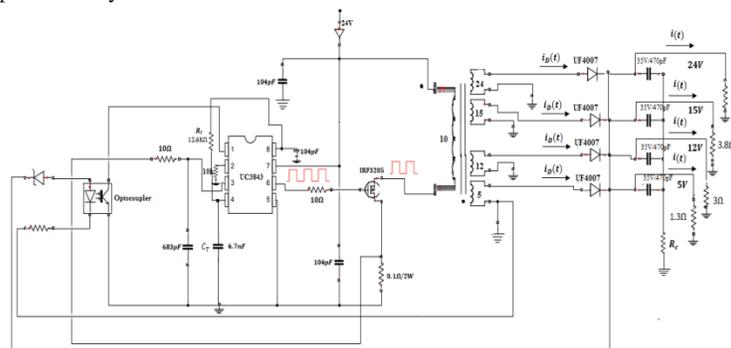


Fig. 2: Proposed flyback converter prototype.

A 24V DC is applied on the PWM generator UC3843 IC. This IC generates PWM signal with a frequency controlled by a feedback resistor(Tibajja and Talampas, 2011). The UC3843 with a start-up current of less than 1 mA ensures latched operation with its pulse-width modulation (PWM) comparator

providing current-limit control and an output stage that sources high-peak current. The output pin, which directly drives the MOSFET is low when in the OFF state and source or sink currents of up to 1 A (Jing-Hui andYong-Gao, 2017). The average voltage is as in Fig. 3.

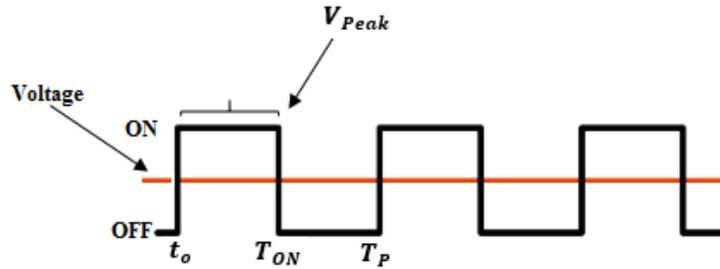


Fig. 3: Average voltage and peak voltage illustration.

The average voltage in flyback is given as;

$$V_{Average} = \frac{1}{T_p} \int_0^{T_p} U(t) dt = \frac{1}{T_p} \int_0^{T_{ON}} V_{peak} dt + \frac{1}{T_p} \int_{T_{ON}}^{T_p} 0 dt \dots\dots 1$$

$$= \frac{T_{ON} \cdot V_{peak}}{T_p} \dots\dots\dots 2$$

$$= D \cdot V_{peak} \dots\dots\dots 3$$

$$\frac{T_{ON}}{T_p} = \text{duty cycle, } D \dots\dots\dots 4$$

$$T_p = \text{Time period} = \frac{1}{\text{frequency}} \dots\dots\dots 5$$

$T_{ON}$  = ON time.

So, the MOSFET gate voltage is as in Fig.



Fig. 4: Illustration of MOSFET gate voltage.

$$T_{ON} = \text{Mosfet ON time} = D \dots\dots\dots 6$$

$$T_{OFF} = \text{Mosfet OFF time} = D \cdot T_p = (1 - D)T_p = D' \dots\dots\dots 7$$

$$\text{The duty cycle, } D = \frac{T_{ON}}{T_p} = \frac{\text{Mosfet ON time}}{\text{Time period}} \dots\dots\dots 8$$

**Transformer Design**

Transformers and coupled inductors have several windings on a magnetic core, but their operation in switching converters differs. In this design, a coupled-inductor is acting as energy storage during converter switching cycle. The power going

into the coupled-inductor is not the same as the power leaving it (Witulski, 1995).

From Faraday’s Law, the voltage across the winding of a transformer is a function of the number of turns as well as the rate of change of magnetic flux in the core (Witulski, 1995; Harlow, 2012; Hurley and Wölfle, 2013).

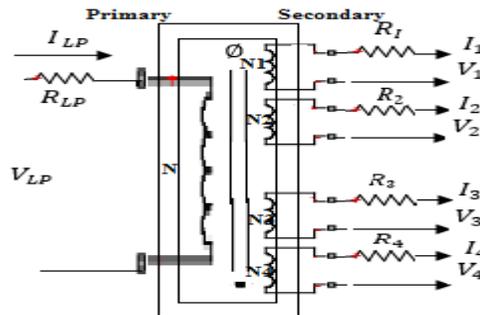


Fig. 5: Transformer (coupled inductor) illustration

$$V = n \frac{d\phi}{dt} \dots\dots\dots 9$$

This implies,

$$\frac{d\phi}{dt} = \frac{V}{n} \dots\dots\dots 10$$

The magnetic flux  $B$  in the core is given as

$$B = \frac{\phi}{A_c} = \frac{1}{nA_c} \int V dt \dots\dots\dots 11$$

Where  $A_c$  is the cross-sectional area of the core. The flux lines are going through the core.

From Eqn. 9,

$$V_1 = n_1 \frac{d\phi_1}{dt}, V_2 = n_2 \frac{d\phi_2}{dt}, V_3 = n_3 \frac{d\phi_3}{dt}, \text{ and } V_4 = n_4 \frac{d\phi_4}{dt}.$$

Since there are more than one windings on the core, the rate of the flux in the windings  $V_1$  is the same as that of  $V_2, V_3$  and  $V_4$ . Assuming  $\phi_1 = \phi_2 = \phi_3 = \phi_4$ .

$$\text{Thus, } \frac{d\phi_1}{dt} = \frac{d\phi_2}{dt} = \frac{d\phi_3}{dt} = \frac{d\phi_4}{dt}.$$

The current flowing will initiate a magnetic field into the core. Dealing with the DC current, the effect of the magnetic flux  $\Phi$  is constant, therefore, the change in the magnetic flux  $\frac{d\Phi}{dt}$  doesn't exist.

This implies,

$$V = n$$

$$12$$

From Eqn. 12, it implies that for  $n = 24, 15, 12$  and  $5$  turns,  $V = 24, 15, 12$  and  $5$  volts respectively.

**Flyback Analyses**

A flyback is acting as a coupled inductor not as a true transformer converter (Yang and Do, 2017). By replacing the inductor in a basic converter with a coupled-inductor and adding one diode at the output, converter with less components and high conversion ratio is achieved (Berkovich and Axelrod, 2011). The diode in a non-oscillatory manner

conducts for a short period of time and circulates the leakage inductance energy to the load.

The performance of the transformer in flyback converter is such that it stores energy in the core and gap when the switch is ON. During this time, current flows through the primary winding. When the switch is OFF, the energy stored in the gap and core are transferred to the secondary windings. Some of its features are;

1. Flyback transformer is designed not to transfer energy forward, but to store it.
2. There can be more than one windings, and the current does not flow in the windings at the same time.

Therefore, flyback transformer performs like two coupled inductors in which current do not flow through the windings at the same time. Considering the circuit in Fig. 6.

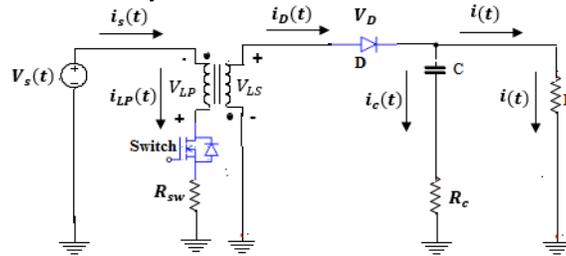


Fig. 6: Flyback schematic.

**i. Time ON**

The switch SW is closed, the MOSFET conducts (Erickson & Maksimovic, 2007) and there will be a positive voltage at the dotted sides of the primary and

secondary. Since the non-dotted side on the primary is connected to the ground, there will be a negative voltage on that side

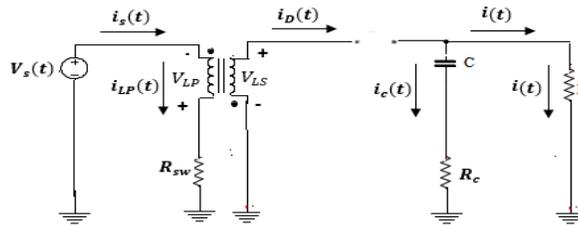


Fig. 7: Time ON schematic of the flyback

The negative on the non-dotted side of the secondary goes to the anode of the diode and turns it OFF, making the diode open. During this time, at steady state, the voltage to the load is provided by the capacitor C. Basically, the capacitor is providing the voltage to the load. Now, looking at the circuit in Fig. 7, the primary voltage,  $V_{LP}$  is going to be  $V_s(t) - 0$ . So,

$$V_{LP} = V_s(t) - 0 \dots\dots\dots 13$$

$$V_{LP} = V_s(t) \dots\dots\dots 14$$

Combining Eqn.5 and 6, it implies,

$$T_{ON} = \frac{D}{\text{Frequency}}$$

$$15$$

The primary current  $i_{LP}$  is dependent on the voltage  $V_s(t)$ . When the SW switch is ON, the current goes up and come down to zero when switch is OFF until the next cycle.



Fig. 8: Time ON/OFF illustration.

During this time, the slope is

$$\text{Slope} = \frac{V_s(t)}{L} \cdot T_{ON} \dots\dots\dots 16$$

At this interval, the inductor voltage  $V_L(t)$  is,

$$V_L(t) = V_s(t) - i_s(t)R_{sw}(t) \dots\dots\dots 17$$

The capacitor current  $i_c(t)$  becomes,

$$i_c(t) = -\frac{V_c(t)}{R+R_c} \dots\dots\dots 18$$

The converter output voltage  $V(t)$  is,

$$V(t) = \frac{V_c(t)R}{R+R_c} \dots\dots\dots 19$$

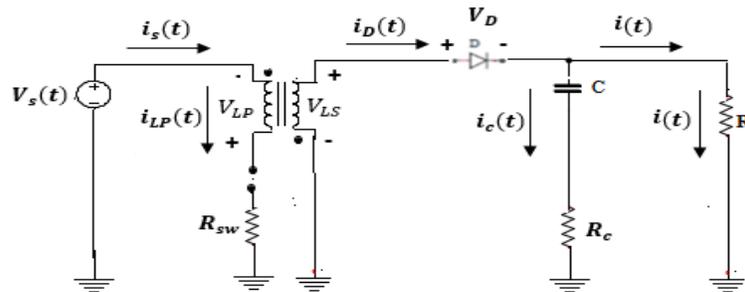


Fig. 9: Time OFF schematic

Basically, the non-dotted side of the primary becomes positive and the dotted becomes negative. At the secondary, the dotted becomes negative while the non-dotted becomes positive so the diode is ON. During this time, the energy stored in the flyback is used to charge the capacitor and is also used to charge the load. In this case, the inductor is discharging to capacitor C and the load.

Looking at the primary and secondary voltages, there will be a reflected voltage back to the primary. The primary voltage  $V_{LP}$  becomes,

$$V_{LP} = \frac{-V_o}{n} \dots\dots\dots 21$$

During this OFF time, the time period is  $(1 - D)$ . Time OFF is therefore,

$$T_{OFF} = (1 - D) \cdot T_p \dots\dots\dots 22$$

Since the switch is open, no current flows through it. During this timeperiod, the current going to the primary  $i_{LP}$  is zero. Thus,

$$i_{LP} = 0. \dots\dots\dots 23$$

The inductor voltage  $V_L(t)$  is,

$$V_L(t) = V_c(t) - R_c i_c(t) - V_d)n \dots\dots\dots 24$$

The capacitor current  $i_c(t)$  is,

$$i_c(t) = -[i_{LP}(t)n + \frac{V(t)}{R}] \dots\dots\dots 25$$

The converter output voltage  $V(t)$  is,

$$V(t) = V_c(t) - R_c i_c(t) \dots\dots\dots 26$$

And the converter input current becomes,

And the converter input current  $i_c(t)$  is,

$$i_s(t) = i_{LP}(t) \dots\dots\dots 20$$

**Time OFF**

Considering the circuit in Fig. 9, during the OFF time, the MOSFET is open and the diode conducts (Erickson and Maksimovic, 2007). As such, the energy has already been stored and the current keeps flowing.

$$i_s(t) = 0 \dots\dots\dots 27$$

$$n = \frac{N_1}{N_2} \dots\dots\dots 28$$

Since the transformer is out of phase;

- The energy is stored in the flyback during the  $T_{ON}$  period.
- Energy is released to the capacitor and to the load during  $T_{OFF}$  period.

The diode rectifies the voltage and the capacitor stores the charge.

The input and output powers are obtained from

$$P = IV \dots\dots\dots 29$$

The average input current  $I_{Average}$  is

$$I_{Average} = \frac{P_{IN}}{V_{IN}} \dots\dots\dots 30$$

The peak current  $I_{Peak}$  of the primary of the transformer is

$$I_{Peak} = 4 \times I_{Average} \dots\dots\dots 31$$

The primary inductance can be obtained from

$$V = L \frac{di}{dt} \dots\dots\dots 32$$

$$L = V \frac{dt}{di} = \frac{V_{IN \text{ minimum}}}{I_{Peak}} \times T_{ON} \dots\dots\dots 33$$

The energy stored in the inductor is

$$E = \frac{LI^2}{2} \dots\dots\dots 35$$

Table 1: Specifications of the designed flyback converter.

$V_0$	5v	12v	15v	24v
$V_i$	24v	24v	24v	24v
$I_i$	0.5A	0.5A	0.5A	0.5A
$I_{peak}$	2A	2A	2A	2A
$I_0$	4A	4A	4A	4A
$P_0$	20W	48W	60W	96W
R	1.3 $\Omega$	3 $\Omega$	3.8 $\Omega$	6 $\Omega$

**RESULTS AND DISCUSSION**

The developed prototype is in Fig. 10 showing all the basic components.

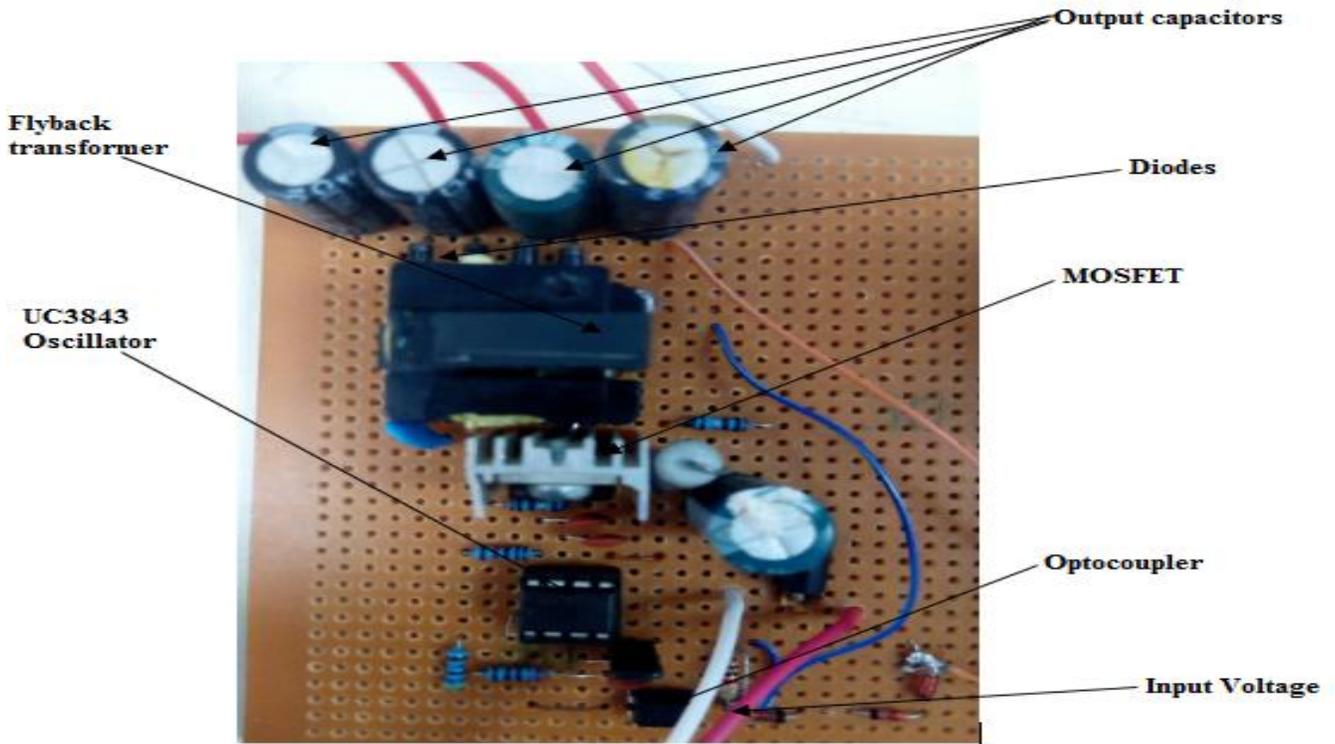


Fig. 10: Developed prototype

Multimeters and scopes were used to view the output signals. The responses of the developed system are illustrated in Fig. 11.

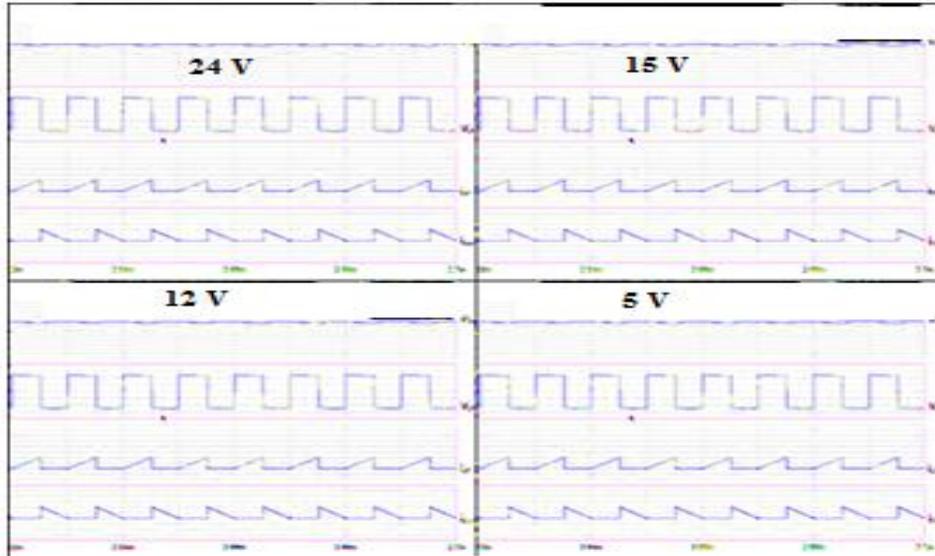


Fig. 11: Simulation results. (a)24V (b) 15V (c) 12V and (d) 5V.

As in Fig. 11 (a), the first plot shows the output voltage of 24V, though with some ripples. The second plot is the input voltage ranging from  $\pm 24$ . The third plot is the input current rising to the peak of 2A. The input current of 0.5 A was injected, upon switching ON and OFF, it rises to the peak of 2A. During time ON, it rises to the peak and come down to zero during the period of time OFF. It remains at zero until it

is switched ON again. The fourth plot  $i_o$  represents the output current. It doubles the input current. This is the same for all other output voltages of 15, 12 and 5 in Figs. 11 (b), (c), and (d) respectively, unless that the output voltage changes according to the design and winding at the flyback. The output voltages were recorded using multimeter as given in Table 2.

Table 2. Designed and experimental results

Calculated Results	Experimental Results	%Error	Efficiency
5V	4.1V	0.9	82
12V	11.3V	0.7	94.2
15V	14.2V	0.8	94.7
24V	23.2V	0.8	96.7

Table 2 illustrates the designed/calculated output voltages of the flyback and the experimentally measured output voltages at the corresponding outputs. Slight variation is observed,

which may be due to some losses incurred at the transformer or other output components.

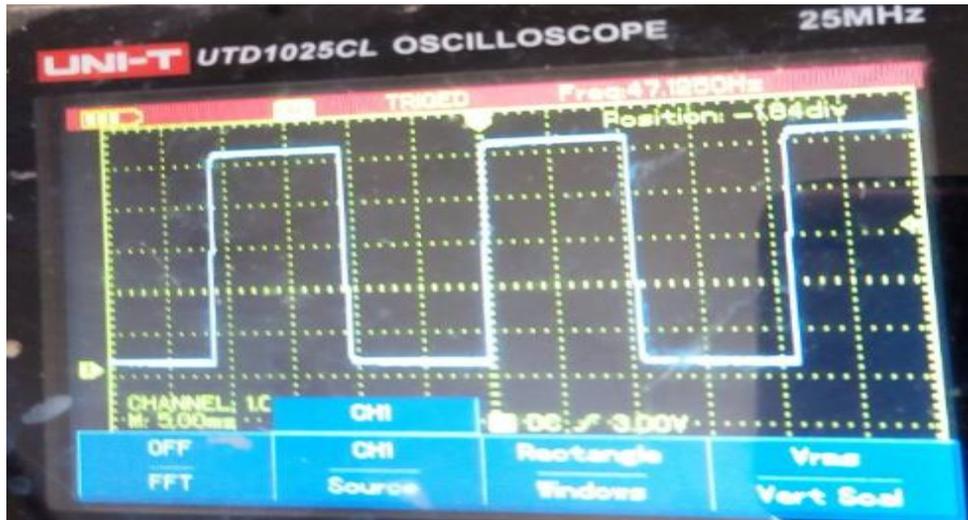


Fig. 12: Oscillator simulation and MOSFET gate voltage.

Fig. 12 shows the signal obtained from the UC3843 oscillator serving as PWM and the voltage at the MOSFET gate, which is fed to the flyback as input voltage.

As in Table 2, there is higher efficiency with the higher number of windings and output voltages as plotted in Figs. 13.

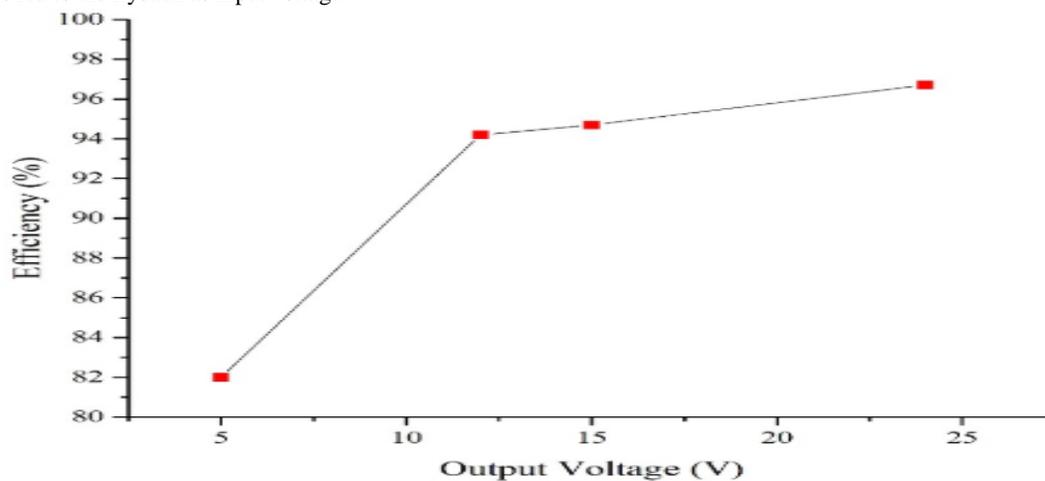


Table 3 shows comparison of efficiencies of recently developed flyback converters. The proposed system has significantly higher percentage of efficiency.

Table 3: SIMO flyback converters comparison of efficiency

Single inductor SIMO converter	Efficiency (%)
(Moon, Roh, Gong, & Yoo, 2012)	80
(Y. Zhang & Ma, 2014)	82.8
(Ma, Ki, Tsui, & Mok, 2001)	88.8
(Lu, Qian, & Hong, 2014)	87

(Wai & Jheng, 2013)	91
Proposed SIMO flyback converter	91.9

Off-grid photovoltaic systems can provide an affordable means of getting access to electricity depending on the availability of the solar energy at the places. Therefore, off-grid PV systems have potentials to compensate the outage of power in remote areas. The significance of off-grid solar systems is to optimize suitable designs to tap and generate the available solar energy at most economically feasible cost and enhanced efficiency to satisfy the energy demands. The proposed system would provide easy and less costly means of achieving stable photovoltaic power in off-grid homes. The system, being the intermediary between the solar panels and the loads has the ability to regulate the generated DC power into the proposed five levels and apply on the appropriate loads.

## CONCLUSION

A miniaturized SIMO flyback converter was designed and implemented. The proposed flyback converter was successfully fabricated. One of the major objectives of flyback is to enable flexibility of design with multiple outputs and to multiply the current. A flyback SIMO converter with four outputs of 24V, 15V, 12V and 5V was designed and developed. A ferrite-core flyback transformer was wound with multiple windings to give the outputs according to Faraday's assumption. The energy is stored in the flyback during the  $T_{ON}$  period and released to the capacitor and subsequently to the load during  $T_{OFF}$  period. The prototype was developed on Vero board with all the components and it was tested. The purpose of achieving miniaturization was realized by developing a very portable and miniaturized multi-ports converter for off-grid photovoltaic applications on DC gadgets, avoiding multiple conversion stages and enhancing portability. Very slight variation was observed between the designed and experimental values. The design and development methods are presented in this paper. Overall converter's efficiency stands at 91.9%.

## AKNOWLEDGEMENT

The authors would like to thank Ibnu Sina Institute for Scientific and Industrial Research (ISI-SIR), Universiti Teknologi Malaysia (UTM) for providing research facilities.

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