Design of a Low Cost High Efficiency Multiple Output Self Oscillating Flyback Converter

Yogi Sawitra[1], Prapto Nugroho[1], Eka Firmansyah[1], Wahyu Dewanto[1], Rudy Hartanto[1], Tiyono[1], Tumiran[1]

***Abstract*—The use of some integrated circuits in an SMPS circuit are the main factor that increasing the cost. Self-oscillating feedback converter topology is a well-known circuit topology for low-cost application without using any single integrated circuit chip. In this paper, a Low Cost with high efficiency converter without any single integrated circuit component was analysed and designed. It has also multiple outputs of 3.3 V/1 A, 5 V/0.5 A, and 12 V/0.1 A so that it can be used as power supply for DVD player. Experiment results showed that it can deliver continuously output voltage as designed and a total output power of 7.3 W, with an efficiency for about 70%.**

***Keyword* — SMPS, DC converter, flyback converter, self oscillating flyback converter.**

I. INTRODUCTION

The use of an integrated circuit in a switching mode power supply (SMPS) circuit, despite its advantages on the wide range of the features offered, has increasing production cost, in other word, it becomes more expensive. For example, most of the SMPS used in DVD player exploit one or more integrated circuits, this increase the production cost. To reduce the cost, the SMPS circuit must be designed without any single integrated circuit chip. To realize that, there is a popular topology that can be used, namely self-oscillating flyback. It uses fewer components and do not use any single IC controller. This topology is also popular for low cost application due to its simplicity. It also capable to provide multiple outputs so that it suitable for low power equipment’s [1]—[7].

There are some previous works related to this topology, such as B. Khemmanee and D. Isarakorn that discussed a design of an off-line power supply based on self-oscillating flyback converter for piezoelectric energy harvesting [1]. They choose to use self-oscillating flyback converter because of its low cost.

In another research, a self-oscillating feedback converter with efficiency enhancement mechanism using lossless snubber and energy recovery winding was presented [2]. Efficiency conversion, which became an issue on conventional design, was improved by employing lossless snubber.

A small signal model was proposed to be used for more precise optimization of the circuits [3]. This because the operation of the circuits was not fully understood and a self-oscillating feedback circuit usually designed by trial and error methods. It designed and analysed self oscillating flyback converter with 5V/2A single output.

This paper presents a self-oscillation flyback converter topology to reduce the cost and complexity of SMPS circuit used especially on DVD Player that need three different voltages: 3.3 V/1A, 5 V/0.5 A, and 12 V/0.1 A. It can supply until 7.3W. It employs lossless snubber to get better efficiency. Design steps are explained in detail in the next chapter.

II. FLYBACK CONVERTER CIRCUITS

A basic flyback converter is a combination of an isolation transformer, a switching transistor, an oscillator and a set of diode bridge. Flyback converter topology is the best choice to be used in an application which has multiple outputs from single input. It can produce power as big as 150 W [4].

Proposed flyback circuit schematic is shown in Fig. 1. It consists of some blocks: protection block, control block, output rectifier block, and feedback or flyback converter block. Protection block included surge protection or transient suppression to protect main circuit from the lightning surge or high voltage produced by a switching when at the first time the power is switched on. Metal Oxide Varistor (MOV) is used for this purpose since it resistance decrease significantly when a high voltage applied over it. An EMI filter also being used to protect other equipment from EMI produced by switching activity inside the SMPS. EMI filter or protection circuit contain passive components R, L, C. Before the output rectifier block, there is a step-down transformer that have a flyer primary inductor NP and four secondary part NS1, NS2, NS3, and NS4. Three rectifiers have been used to provide three different output voltages 3.3 V/1 A, 5 V/0.5 A, and 12 V/0.1 A. Control circuit using a power switching MOSFET Q1 rather using an IC regulator since it can reduce the cost, complementary NS1 inductor, BJT T2 switching, R8 current sense resistor, cross zero detection C3, diode rectifier D5, filter capacitor C5, filter resistor R9, pass capacitor C4, and input clamper D6. A start up resistor R1 and a DC link capacitor C2 are also included. Flyback regulator block is a feedback circuit as the input for control block that consists of VR1, R15, C6, R14, R16 and R17 which function as shunt regulator, OK1 optocoupler, R13 resistor, and resistor R7. There is also D9, R18, and C10 that perform a function as snubber.

A. Start Up Process

DC voltage is filtered by R11 and C2 that then be used to charge the gate voltage of MOSFET Q1 through R5 and R4. Gate voltage start to increase until the threshold value to turn on Q1 is surpassed. When MOSFET Q1 on, some amount of current flow through the transformer’s primary winding NP so

[1]*Department of Electrical Engineering and Information Technology, Faculty of Engineering, Universitas Gadjah Mada, Jalan Grafika 2 Kampus UGM Yogyakarta, 55281, INDONESIA, (tlp: 0274-552305, e-mail: tatok@ugm.ac.id)*

that the voltage on the NP begin to rise, hence the process of energy storing began. Current through transformer’s primary winding NP increases linearly, which then flows through the R8 resistor which is a part of voltage divider for the base of transistor T2. The rising voltage on the NP is also followed by the increase of the NS1 voltage so that MOSFET Q1 turned on.

The current passing through the resistor R8 cause a voltage drop across this resistor. Its voltage value continues to rise as the current increases. If the voltage reaches threshold voltage of the base-emitter voltage of transistor T2, the transistor is turned on, causing some charge derived from R4 and R5 to the Q1 gate are forced to flow through the T2 collector to ground. This condition makes the voltage at the gate of MOSFET Q1 to decrease significantly to ground level to make Q1 turned off. Resistor R8 is named as current sensing resistor because it serves to read the passing current.

B. Transfer Energy Process

When Q1 is turned off, no current flows through the drain MOSFET so that the voltage on the drain increases. The current on the transformer’s primary winding NP keeps flowing but the direction has changed so that the polarity is also changed. The change of the polarity in the NP is also followed by the polarity of transformer’s secondary windings NS1, NS2, NS3, and NS4. This polarity change makes diodes D7, D10, and D11 in the condition of forward bias and thus demagnetization process begins where the energy collected on the transformer's primary winding will be transferred to the secondary ones. This process then followed by the discharging process of the electric current on the secondary inductant through the diodes D7, D10, D11.

Next process is the transfer of charge from transformers through diodes to capacitors C7, C9, C13 and ended in the load. This process will continue even if the T2 transistor is off, this is because of the negative polarity of NS1 that will keep Q1 remain turned off until the current on the secondary inductant is exhausted, which make NS1 can no longer hold Q1 off. Consequently Q1 will set back on the start-up process through resistor R4 and R5, and the same cycle repeated again.

C. Output Rectifying process

Combination of IC TL431 and optocoupler OK1 serve as a negative feedback circuit. When output voltage is greater than 3.3V, current flowing through TL431 increase that makes optocoupler’s LED OK1 becomes brighter as the result of the increasing current that flows from the collector to the emitter of optocoupler OK1. This condition forces transistor T1 to turn on faster, which causing Q1 needs much longer time to turn off. This has effect on the duty cycle that became buckling and the output voltage start to drop.

Conversely, if the output voltage is lower than 3.3V, current flowing through TL431 decrease so that optocoupler’s LED OK1 becomes dimm, and emitter collector current of the optocoupler OK1 also decreasing, which makes the time to turn off transistor T2 longer and hence put Q1 turned on in longer time. This cause its duty cycle bigger then before, followed by the rise of the output voltage.

III. Hardware Design

A. Hardware specification

List of hardware specification are shown in Table I.

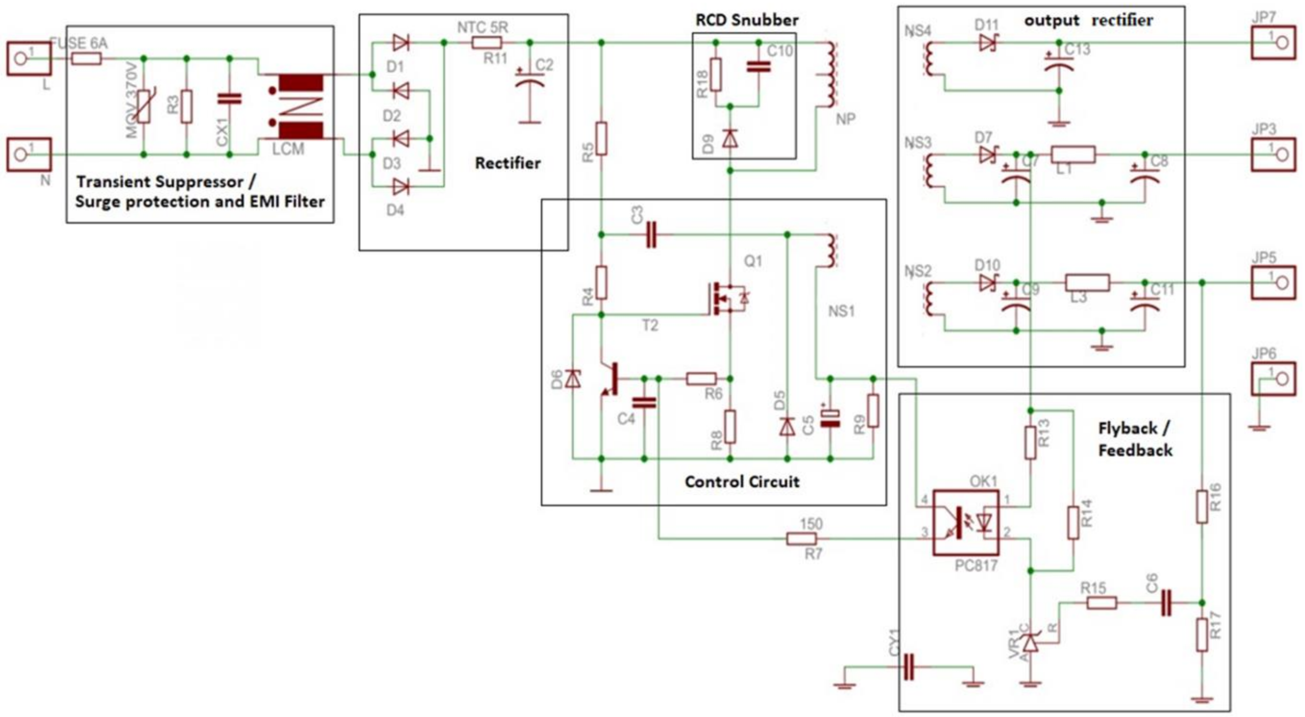

Fig. 1 Proposed self-oscillating flyback circuit.

TABLE I
HARDWARE SPECIFICATION

Parameter	Nilai
Minimum input voltage, $\mathbf{V_{in\_min}}$	85 VAC
Maximum input voltage, $\mathbf{V_{in\_max}}$	250 VAC
Minimum peak voltage, $\mathbf{V_{pk\_min}}$	120 V
Maximum peak voltage, $\mathbf{V_{pk\_max}}$	375 V
line frequency, $\mathbf{f_L}$	50/ 60 Hz
Output power, $\mathbf{P_{out}}$	7.3 W
Efficiency, $\boldsymbol{\eta}$	0,7
Output Voltage 1, $\mathbf{V_{out1}}$	3.3 V
Output Voltage 2, $\mathbf{V_{out2}}$	5 V
Output Voltage 3, $\mathbf{V_{out3}}$	12 V
Output Current 1, $\mathbf{I_{out1}}$	1 A
Output Current 2, $\mathbf{I_{out2}}$	0.5 A
Output Current 3, $\mathbf{I_{out3}}$	0.1 A
Auxiliary Current	0.1 A
Input Current, $\mathbf{I_{in}}$	0.075 A
switching frequency, $\mathbf{f_{sw}}$	70 kHz

B. Components for Input Circuit

1) Diode Rectifier: Diode rectifier to be used should be able to work at high voltage. Here are the specifications to be considered and the equations to determine the minimum specifications of the diodes.

Peak voltage

$$V_{peak} = 250V * \sqrt{2} = 353\ V \quad (1)$$

Forward current

$$I_F \geq 1,5 * I_{in} \quad (2)$$

$$I_F \geq 0,112\ A$$

Transient current

$$I_{FSM} \geq 5 * I_F \quad (3)$$

$$I_{FSM} \geq 0,562\ A$$

Based on (1), (2), and (3) a diode1N4007 is suitable to be used in the rectifier circuit.

2) Bulk Capacitor (C_{bulk}): Bulk capacitor is a capacitor that capable to reduce the ripple of the output voltage by rectifier circuit. The value of the bulk capacitor for that function is calculated using the following equation.

$$C_{bulk} = \frac{(P_{out}/\eta)}{f_L * \left(V_{pk\_min}{}^2 - \left(0,68V_{pk\_min} - V_D\right)^2\right)} \quad (4)$$

P_{out}, η, f_L, V_{pk_min} are specified at Table I. V_D is the forward voltage from rectifier diode.

C. Minimum rating of the MOSFET

The voltage rating of the V_{DS} of the MOSFET is at least about 1.4 times higher than the amount of maximum DC voltage (Vpk_max) [4]. MOSFET type for the self-oscillating flyback converter circuit is IRF840, package TO 220. The IRF840 MOSFET has a maximum V_{DS} voltage rating of 500 V that is equivalent to 1.3 times the Vpk_max voltage. This mean safe enough to be used in this SMPS circuit.

D. Determine the core size (V_{RO}) and Maximum Duty Cycle (D_{max})

The size of the transformer core will determine the amount of power that can be transferred from input to output. Equation [6] is used to determine the core size of the transformer. The core measurement of the transformer being used is EE25. Maximum duty cycle must be determined so that the MOSFET can bear high stress voltage to make it last longer. The maximum duty cycle value of the MOSFET can be determined using these equations below [4].

$$V_{DCmin} = \left(2 * \left(V_{in\_min}\right)^2 - \frac{\left(P_{in} * (1 - D_{ch})\right)}{f_L * C_{bulk}}\right)^{1/2} \quad (5)$$

$$V_{DCmin} = 101,23\ V$$

$$V_{RO} = 0,85 * V_{DS} - V_{pk\_max} = 50\ V \quad (6)$$

$$D_{max} = V_{RO}/(V_{DCmin} + V_{RO}) = 0,33 \quad (7)$$

V_{DCmin} is the minimum DC voltage value of a power link, D_{ch} is the value of charging duty ratio of a bulk capacitor with a value of 0.2 [4]. V_{DS} is the maximum voltage rating between drain and source on MOSFET. V_{RO} is the value of the reflection voltage from output to input. $V_{in\ min}$, P_{in}, f_L, and V_{pk_max} have been specified in Table I.

E. Flyback Transformer Design

Below are the step by step to design the transformer

1) Determine Primary Inductance Value (L_m): The primary inductance value of a flyback transformer can be determined using the following equation [4].

$$L_m = (V_{DCmin} * D_{max})^2/(2 * P_{in} * f_{sw} * K_{RF}) = 0,7\ mH \quad (8)$$

V_{DCmin}, D_{max} has been stated in (5) & (7), P_{in}, f_{sw} can be seen in Table I. KRF is the ripple factor value at full load and minimum input voltage with a value of 1 for boundary mode CCM / DCM [4].

2) Determine the Number of Primary Twists (N_{pri}): The number of primary windings can be determined by the following equations.

$$I_D = (2 * P_{in})/(V_{DCmin} * D_{max}) = 0,62\ A \quad (9)$$

$$N_{pri} = (L_m * I_D * 10^6)/(B_{sat} * A_e) = 34 \quad (10)$$

I_D is the current flowing through the drain, N_{pri} is the number of primary windings. B_{sat} is the value of the transformer core saturation flux. A_e is the area of windings in the transformer. P_{in} has been specified in Table I. V_{DCmin}, D_{max}, L_m have been explained at (5), (7), and (8).

3) Determine the Number of Secondary Loops (N_{sec}): The number of secondary windings will determine the value of the output voltage. The following equations are used to determine the number of secondary windings in order to obtain an output voltage of 3.3 V, 5 V, and 12 V.

$$N_{sec(n)} = \left(\left(V_{o(n)} + V_F\right)/V_{RO}\right) * N_{pri} \quad (11)$$

$$N_{sec(1)} = 2{,}58 \cong 3$$
$$N_{sec(2)} = 3{,}75 \cong 4$$
$$N_{sec(3)} = 8{,}5 \cong 9$$

V_o is the output voltage. V_F is the diode forward voltage output. V_{RO} was explained in (6). N_{pri} has been described in (10).

4) Determine the Ferrite Caliber Air Length (G): The air gap in the ferrite core is useful as a place for energy insertion. The air gap length is determined using the following equation.

$$G = 40\pi A_e\left(\left({N_{pri}}^2/1000L_m\right) - (1/A_l)\right) = 0{,}2 \text{ mm} \quad (12)$$

A_e Is the area of windings in the transformer. N_{pri} has been described in (10), L_m was explained in (9).

5) Determine the Size of the Wire Diameter (d_{pri}, d_{sec}, and d_{aux}): The main parameter for determining the wire size is the value of the rms output current that will flow through the wire. The following equations are used to determine the value of the output current to flow.

$$\Delta I = (V_{DCmin} * D_{max})/(L_m * f_{sw}) \quad (13)$$

$$I_{EDC} = P_{in}/(V_{DCmin} * D_{max}) \quad (14)$$

$$I_{DS} = \left(\left(\left(3 * {I_{EDC}}^2\right) + (\Delta I/2)^2\right) * D_{max}/3\right)^{1/2} \quad (15)$$

$$I_{sec(n)} = I_{DS}\sqrt{\frac{1-D_{max}}{D_{max}}\frac{V_{RO}}{V_{out(n)}+V_F}\frac{V_{out(n)}I_{out(n)}\eta}{P_{out}}} \quad (16)$$

$$I_{sec(1)} = 2{,}57\ A \text{ rms}$$
$$I_{sec(2)} = 1{,}34\ A \text{ rms}$$
$$I_{sec(3)} = 0{,}27\ A \text{ rms}$$

V_{DCmin}, V_{RO}, D_{max}, L_m, dan V_F have been described in (5), (6), (7), (8), and (11) respectively. P_{out}, V_{out}, I_{out}, η and f_{sw} have been specified before.

As a starting point, the intensity of the current that will flow on the winding is worth of $4A/mm^2$.

$$d_{pri} = \left(I_{pri}/\pi\right)^{1/2} = 0{,}44 \text{ mm} \quad (17)$$

$$d_{sec(1)} = \left(I_{sec(1)}/\pi\right)^{1/2} = 0{,}9 \text{ mm} \quad (18)$$
$$d_{sec(2)} = 0{,}65 \text{ mm}$$
$$d_{sec(3)} = 0{,}29 \text{ mm}$$
$$d_{aux} = 0{,}29 \text{ mm}$$

d_{pri} Is the diameter of the wire for the primary winding, d_{sec} is the diameter of the wire for the secondary winding, d_{aux} is the diameter of the wire for the auxiliary winding. I_{pri} and I_{sec} have been described in (9) and (18).

F. Control Circuit Design

Below are the step by step to design the control part.

1) Determine the Resistor Value on TL431: There are two resistors in TL431, R13 and R14 as shown in Fig. 1. The functions of these two resistors are described in reference (2). The resistor value of both resistors are determined using the following equations.

$$R_{13} < \left(V_{out2} - V_D - V_{KA}^{min}\right)/I_K \quad (19)$$

$$R_{14} < V_D/I_K^{min} \quad (20)$$

$$R_{13} < 1{,}5\ k\Omega$$

$$R_{14} < 1\ k\Omega$$

V_{out2} has been specified in Table I. V_D is a forward voltage diode optocoupler of 1V, V_{KA}^{min} is the minimum voltage value between the anode cathode required by TL431 as high as 2.5 V. I_K is the minimum current required TL431 that worth of 1 mA.

2) Calculate Resistor Value for Current Sensing: Current-sensing resistor or R8 in Fig. 1 serves to limit the current flowing through the drain MOSFET. The value of this resistor is determined using the following equation.

$$R_8 = V_{BE}/I_D = 0{,}5\ V/0{,}62\ A = 0{,}8\ \Omega \quad (21)$$

V_{BE} is the cut off voltage of the transistor be used in the circuit. I_D has been described at (9).

3) Determine the Resistor of Feedback Loop Value: This Resistor or R6 in Fig. 1 serves as feedback path [3]. The value of this resistor are determined by the following equations.

$$I_{emax} * (R_6 + R_8) \leq V_{BE} \quad (22)$$

$$5mA * (47\Omega + 0{,}8\Omega) \leq 0{,}7\ V$$

$$0{,}23\ V \leq 0{,}7\ V$$

I_{emax} is the value of emitor optocoupler current. V_{BE} is the cutoff voltage of the transistor.

4) Determine the Resistor Value for Phototransistor Power Limit: The value of this resistor is determined by the following equation. In Fig. 1, this resistor is R_7.

$$(V_{aux} - I_{emax} * R_7 - V_{BE}) * I_{emax} < P_{OK} \quad (23)$$

$$(5V - 5mA * 100\Omega - 0{,}7V) * 5mA < 200mW$$

V_{aux} Is the output voltage on an additional winding / auxiliary transformer. P_{OK} is the maximum power that can be dissipated by the optocoupler. V_{BE} and I_{emax} have been explained on (22).

5) Determine the Value of Capacitor C_3: Capacitor C_3 in Fig. 1 is suggested to be ten times greater than the input capacitor C_{ISS} MOSFET [3].

6) Determine the Value of Resistor R_4: Resistor R_4 serves to limit the power dissipation in the zener diode. The value of R_4 is determined using the following equation.

$$R_4 > \left(V_{pk\_max}\left(N_{sec(1)}/N_{pri}\right) - V_{DZ}\right) * V_{DZ}/P_{DZ} \quad (24)$$

$R_4 > 119\Omega$

V_{DZ} and P_{DZ} is the voltage and power dissipation of the zener diode.

7) Determine Resistor Start Up (R_5) Value: This resistor serves to charging MOSFET input capacitor. The value of this resistor is determined by the following equation.

$$R_5 > V_{pk\_max}{}^2/(1\% * P_{out}) \quad (25)$$

$$R_5 > 1{,}9\ M\Omega$$

V_{pk_max} and P_{out} have been specified in Table I.

G. Output Circuit.

Below is the step by step to design the output circuit.

1) Determine Diode Output: The main parameters in determining the output diode are maximum reverse voltage (V_{RRM}) and maximum forward current (I_F). Reverse voltage value of the diode is calculated using the following equations.

$$V_{RRM} = V_{out(n)} + \left(V_{pk\_max}\left(V_{out(n)} + V_F\right)/V_{RO}\right) \quad (26)$$

$$I_F = I_{sec(n)} \quad (27)$$

2) Determine the Output Capacitor: The main parameters in determining the output capacitor are ripple current (I_{cap}) and ripple output voltage (ΔV_{out}). The ripple current value of the capacitor and the ripple voltage of the capacitor are calculated by the following equations.

$$I_{cap(n)} = \left(I_{sec(n)}{}^2 - I_{out(n)}{}^2\right)^{1/2} \quad (28)$$

$$\Delta V_{out(n)} = \frac{I_{out(n)} D_{max}}{C_{out(n)} f_{sw}} + \frac{I_{pri} V_{RO} R_{c(n)} P_{out(n)}}{\left(V_{out(n)} + V_F\right) P_{in}} \quad (29)$$

C_{out} is the value of the used capacitor. R_c is the ESR value of the output capacitor. An additional LC filter is set to have a corner frequency for about 0.1 - 0.2 from switching frequency [4].

H. Protection Circuit

1) Transient Supressor: The component used is Metal Oxide Varistor (MOV). The parameters in selecting MOV are minimal clamp voltage. The minimum voltage of the MOV clamp (V_{clamp}) is calculated by the following equation.

$$V_{clamp} = 1{,}2 * V_{pk\_max} \quad (30)$$

2) Determine EMI Filters: EMI filters are not discussed in detail in this paper. References [5] and [7] describe how to specify components for EMI filters.

3) Determine NTC Resistor: NTC resistor value used is 5Ω. This value is chosen to make fewer loss of power.

4) Determine RCD Snubber: The main parameter in determining RCD snubber is the leak inductance value of the primary inductance. The snubber RCD should be able to dissipate the power of the leak inductance.

Leak Inductance energy (W_{LK})

$$W_{LK} = \left(L_{LK} * I_{pri}{}^2\right)/2 \quad (31)$$

L_{LK} is the leak inductance value. I_{pri} have been describe in (9).

The power that should be dissipated by the snubber

$$P_{LK} = W_{LK} * f_{sw} \quad (32)$$

W_{LK} have been explained in (31). f_{sw} have been specified in Table I.

Value of the snubber's resistor.

$$R_{sn} = V_{sn}{}^2/P_{LK} \quad (33)$$

V_{sn} Is the voltage in the snubber circuit. This value is the difference between stress voltage on MOSFET with V_{pk_max}. P_{LK} has been described in (32).

IV. Experiment Result

The SMPS for DVD player prototype has been built based on the design result as shown in Fig. 2.

Fig. 2 Photograph of the prototype.

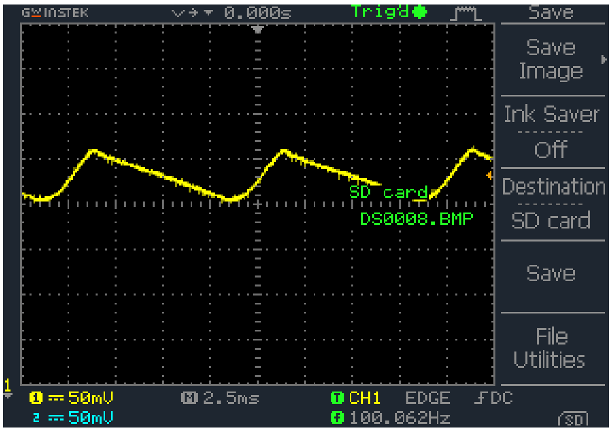

Fig. 3 Ripple wave voltage of the input section.

A. Ripple Testing Input Voltage.

Fig. 3 is a ripple voltage waveform at the input section. The ripple value of the input voltage of this SMPS circuit is about 15 V_{pp} with an input voltage value of 220 V_{rms}.

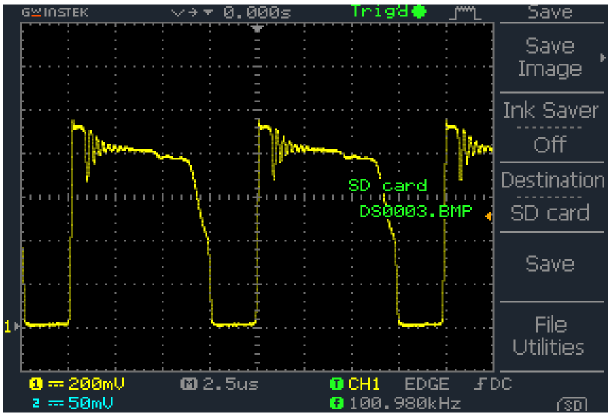

Fig. 4 Wave voltage on drain MOSFET.

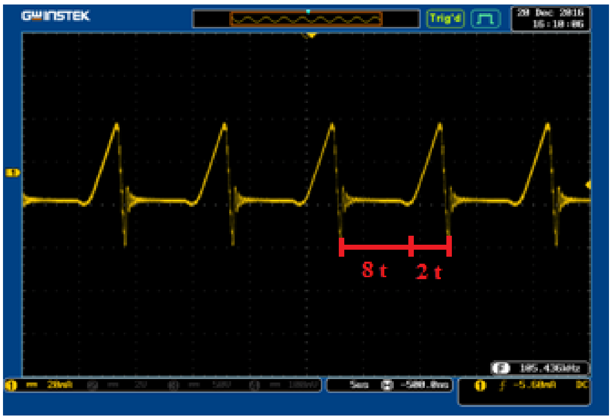

Fig. 5 MOSFET drain current wave.

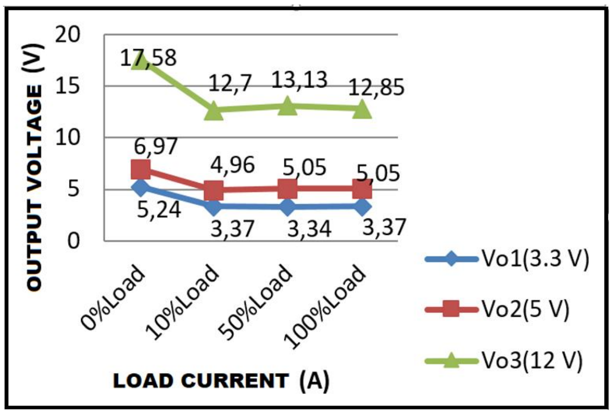

Fig. 6 Output voltage at input 85 V_{rms}.

B. Observation of MOSFET Drain Voltage.

Fig. 4 is the waveform of the drain MOSFET. The peak voltage value of this observation is 460V. It can be seen from the results, the stress voltage on the drain MOSFET is still below the maximum rating of the IRF840 MOSFET which is 500V.

C. Observation of MOSFET Drain Flow.

Fig. 5 is a current wave passing through the drain MOSFET. The peak value of the current passing through the drain is 60 mA with an average value of 20 mA. Duty cycle of the MOSFET in this circuit is 0.2 as expected.

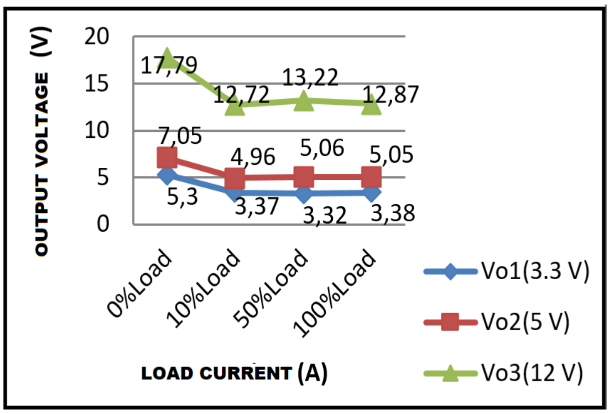

Fig. 7 Output voltage at 110 Vrms input.

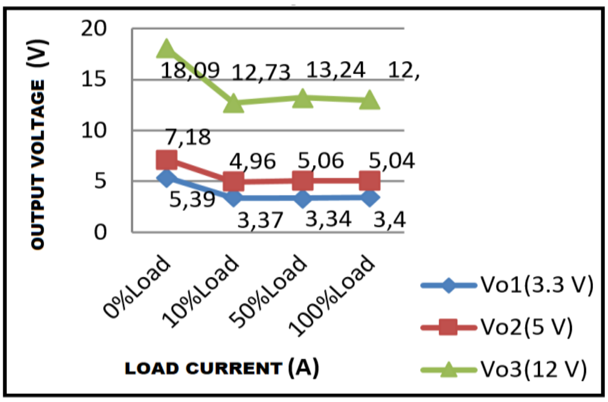

Fig. 8 Output voltage at 220 Vrms input.

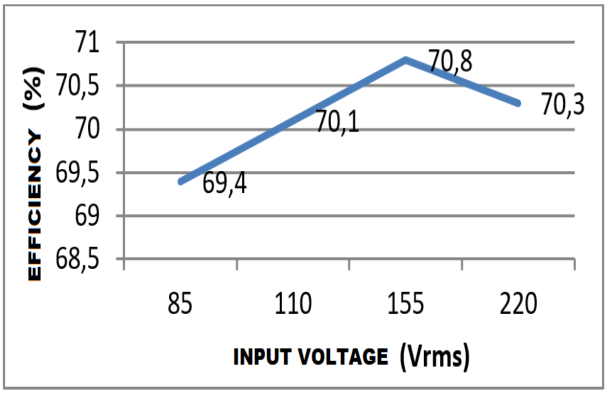

Fig. 9 Efficiency of the SMPS.

D. Test of Output Voltage Regulation.

This test is performed by giving a full load with input voltage varies. Fig. 6 shows the regulation of output voltage when input voltage is 85 V_{rms}. Observation were taken on the three outputs voltage which show a pretty good result because the output are relatively stable even though the load vary.

Fig. 7 and Fig. 8 show the output voltage data when input voltage are 110 V_{rms} and 220 V_{rms} respectively. Those figures show good stable output results.

E. SMPS Sequence Efficiency Testing.

The efficiency test is performed by giving full load while input voltage varies from 85 V_{rms}, 110 V_{rms}, 155 V_{rms}, and 220

V_{rms}. Fig. 9 shows the efficiency values of the SMPS circuit. These results prove that this SMPS has a good efficiency value of 70% in average.

V. Conclusion

In this paper SMPS with self oscillating flyback converter topology has been designed and discussed. The test results show that the designed SMPS has a high efficiency value of 0.7 with good voltage regulation and capable to supply 7.3 W continuously.

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