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DESIGN AND OPTIMIZATION OF A FLYBACK CONVERTER FOR SOLAR PUMP CONTROLLER

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Abstract: The fly-back converter is a popular power electronics converter for regulated power supply due to its simplicity and efficiency. This research paper concentrates on designing a flyback converter for a solar pump controller, considering input voltages from 400V to 1200V DC and output voltages of 15V, 5V, and 3.3V. Implementing the Cascode topology in the converter aims to increase controller performance, minimize losses, and improve voltage control. The Cascode technique improves overall efficiency by optimizing switching characteristics and reducing voltage stress on switching devices. The research analyses the behavior of a flyback converter in Discontinuous Conduction Mode (DCM) for a solar pump controller where the inductor current totally discharges after each switching cycle. The simulation results represent the converter in DCM using the Cascode technique is efficient, generating required output voltages and accurate voltage control over a broad range of input voltage changes. The results are beneficial for engineers and academics working on high-voltage isolated power supply, particularly for solar pump control applications. The paper has a sense on design considerations, simulations, and analysis of flyback converters, with a focus on improving the performance of solar pump controller.

***Key Words* – Isolated DC-DC converter, SMPS, Transformer, Power Electronics Switches**

I. INTRODUCTION

Solar pump controllers are essential components in solar-powered water pumping systems, which are increasingly adopted for their environmental sustainability and cost-effectiveness. These systems utilize solar panels to convert sunlight into electrical energy, which is then used to power the pump for water extraction [12], [13]. The flyback converter, with its galvanic isolation through a transformer, is an ideal choice for solar pump controllers as it ensures safety and protects sensitive electronic components from electrical disturbances [14], [15].

One of the key advantages of using the flyback converter in the discontinuous conduction mode (DCM) is its ability to minimize stress on the switches and diodes. In DCM operation, the current through these components becomes zero during the switching turn-off period, reducing their power dissipation and enhancing overall efficiency. This stress reduction not only improves energy efficiency but also enhances the reliability and durability of the converter components, thereby increasing the lifespan of the solar pump controller [13].

To construct a flyback converter for DCM operation in a solar pump controller, it is crucial to consider load changes and higher energy efficiency. Proper selection and sizing of the switch, output capacitor, diode, and transformer are vital for achieving optimal performance and reliable operation. Additionally, an in-depth understanding of the flyback converter's operation modes, efficiency concerns, component selection, and control strategies is necessary to ensure a successful design.

we provide a comprehensive reference for the design of a high-performance and dependable flyback converter for solar pump controllers. It will discuss the important design criteria, considerations, and factors that need to be taken into account during the development process. By following these guidelines, engineers and researchers can effectively design flyback converters that meet the specific requirements of solar pump controllers, enabling efficient and reliable water pumping systems powered by solar energy.

II. WORKING OF FLYBACK CONVERTER

A fly-back converter Fig.1 uses a switching transistor, generally a MOSFET for power flow regulation. The input DC voltage is first filtered before it's transmitted to the flyback transformer's primary winding. MOSFET quickly turns on and off, providing a square wave voltage across the primary winding of the transformer. During the "on" period, energy is stored in the magnetic field of the transformer [1]-[3]. When the MOSFET is turned off, the magnetic field decreases, causing a voltage to be generated in the secondary winding. Then, this voltage is rectified and filtered to provide the necessary DC voltage output. To manage the output voltage, feedback control changes the duty cycle of the MOSFET. Through the transformer, the flyback converter makes galvanic isolation, allowing for the effective conversion of energy and compact power supply designs.

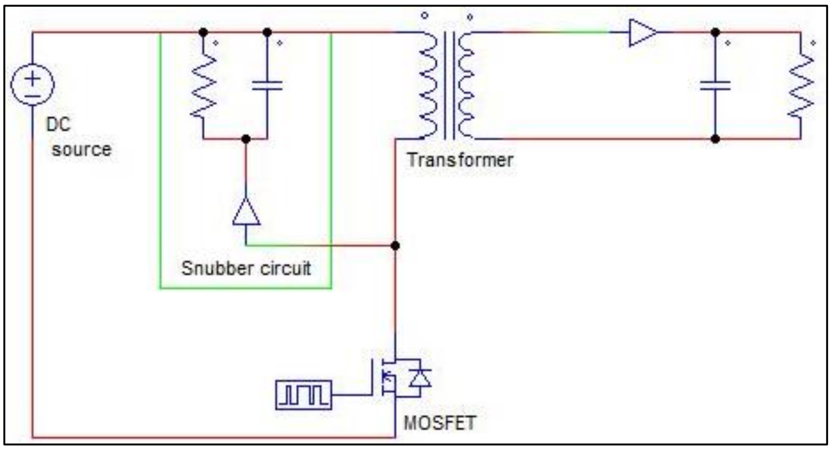


Figure 1: Flyback Converter Circuit Diagram

2.1 Application

A flyback converter is an essential component in a wide range of systems in industries. It is an essential element in power supply, providing efficient and regulated direct current (DC) power to electronic equipment. Flyback converters in solar pump controllers provide for component protection, galvanic isolation, regulation of voltage and efficient power conversion; all of these characteristics contribute to the overall performance, dependability, and durability of solar-powered water pumping systems. However, flyback converter is also used in industrial converters, automotive components, healthcare products, industrial automation, telecommunications devices, renewable energy systems, army and aviation systems, charging stations for electric car systems, information centers, robotics and automation equipment, and uninterruptible power supplies (UPS). It enables dependable and optimum operation across a wide number of industries by offering efficient power conversion, isolation, and voltage control [4]-[7].

III. TYPES OF FLYBACK CONVERTER

The flyback converter is Categorized into 2 different parts as per its mode of conduction [17].

3.1 CCM (Continuous Conduction Mode)

The CCM mode ensures that the current flowing across the inductor is not reduced to zero during any switching cycle. Benefits of this constant current flow include a steadier output voltage and less output distortion. However, CCM is less suitable for applications demanding high voltage or high power since it requires the use of a larger inductor to control the constant current.

3.2 DCM (Discontinuous Conduction Mode)

The DCM mode presents a non-continuous waveform with the inductor current decreasing to zero during each switching cycle. A smaller inductor can be used with DCM, which is advantageous for low-power or low-voltage applications. However, it can cause more output ripple and the need for further noise-reduction filtering techniques.

IV. SPECIFICATION OF FLYBACK CONVERTER

The requirement of the flyback converter to be used for solar pump controller application is as under.

- Input voltage- 400 to 1200V DC or 230 to 650V AC
- Output power- 50W
- Switching frequency ≤ 40khz
- Expected efficiency - 70% to 80%
- Output ripple voltage ≥ 500mv
- UVLO and OVLO protection
- Here, designs an example of a flyback converter that can convert the Input AC or DC supply into desired 15V, 5V, and 3.3V Isolated output voltage.

V. DESIGN A FLOW CHART OF THE FLYBACK CONVERTER

Now as per design requirements, the steps taken into consideration are as below Fig.2 [9]. Design steps of a fly-back converter which convert the Input AC / DC supply into desired 15V, 5V, and 3.3V Isolated output voltage (table-1) is demonstrated as under.

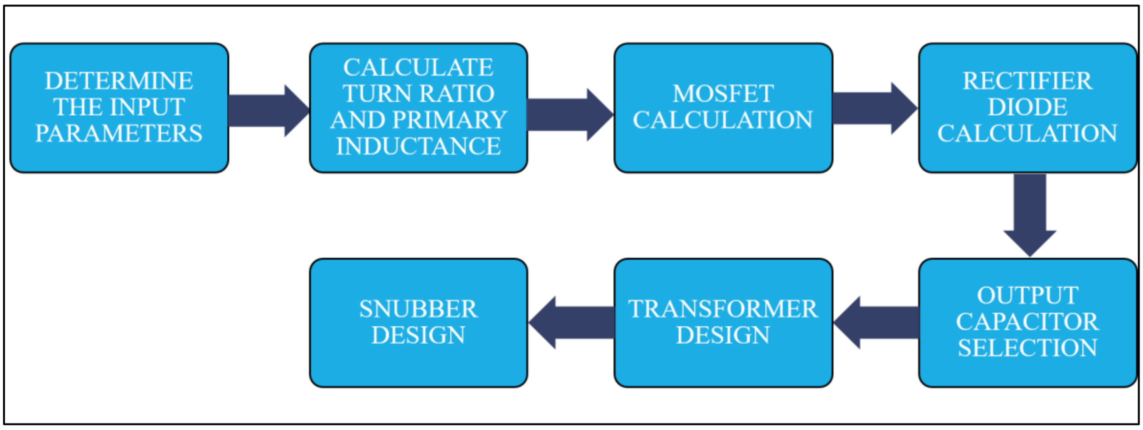


Figure 2: Steps to Design Flyback Converter

Step 1: Input Design Parameter

Table 1: Input Parameter

Input Voltage(V_{in})	400V to 1200V DC
Output Voltage(V_{out})	15V,5V, 3.3V
Output Power(P_{out})	50W max
Operation mode	DCM
Maximum Duty cycle	0.5
Switching Frequency	50kHz
Estimated efficiency(n)	80%
Input Power (as per our efficiency)	62.5W

Step 2: Calculation of Primary Inductance and Transformer's Turn Ratio

$$LP = \frac{\eta \times D_{max}{}^2 \times V_{in\_min}{}^2}{(2 \times f_{sw} \times ripple\ ratio\ (K) \times Po)}$$

$$= 6400 \text{ x} 10^{-6}$$

$$= 6400\text{uH}$$

Now, for the transformer's turns ratio,

$$N_{s1} = \frac{V_{IN_{Min}} \times D_{max}}{(1 - D_{max}) \times (Vo + VD)}$$

Multilevel winding transformers have considered for three different output voltage which has 1 primary, 3 secondary and 1 auxiliary winding.

Here, we have also considered the rectifier diode voltage drop is 0.7V. So, for 3 output levels for transformer, the winding ratios are,

- ✓ For 1st secondary winding (15V)- 20.63
- ✓ For 2nd secondary winding (5V)– 56.84
- ✓ For 3rd secondary winding (3V) – 79.024

Step 3: MOSFET Calculation

Cascode Topology For MOSFET

The Cascode method is a technique commonly used in electronic circuits to enhance the performance of MOSFET. It aims to overcome limitations such as restricted bandwidth, limited gain, and output impedance by employing a stacked configuration of two or more MOSFETs.

In the Cascode configuration Fig.3, MOSFETs are connected in series, typically using a common gate or common source setup. The lower MOSFET's output is connected to the upper MOSFET's input, combining the advantages of both transistors to address their limitations [16].

To implement the Cascode method with MOSFETs, follow these steps:

1. Start with a basic MOSFET circuit using a common source or common gate configuration. Connect a load resistor to the drain terminal and a signal source to the gate terminal.

2. Introduce a second MOSFET in a stacked configuration. Connect the drain of the lower MOSFET to the drain of the upper MOSFET. Ground or a bias voltage is connected to the lower MOSFET's source, while the upper MOSFET's source is connected to the load resistor.

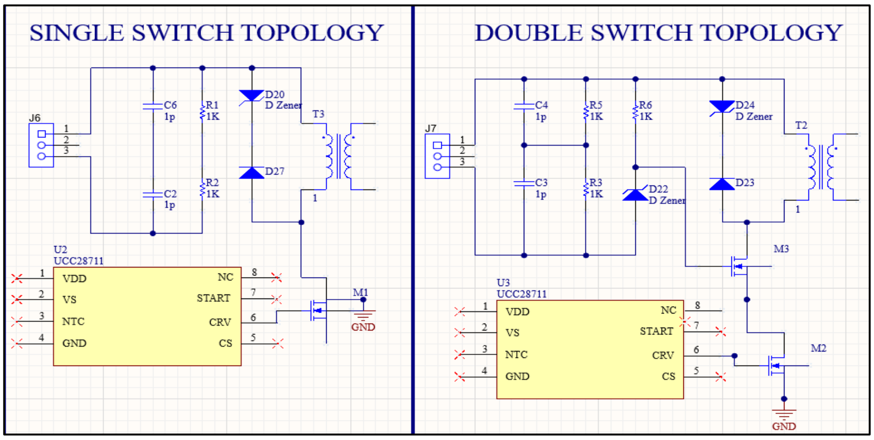


Figure 3: Cascode Topology for Single Switch and Double Switch

3. Connect the input signal source to the lower MOSFET's gate and apply a bias voltage to the upper MOSFET's gate.

4. Take the Cascode output from the drain of the upper MOSFET, which becomes the output for the Cascode configuration.

The Cascode method offers advantages for a flyback converter in a solar pump controller, including improved efficiency, higher voltage gains, reduced output impedance, and enhanced bandwidth. However, it comes with drawbacks such as increased complexity, higher component count and cost, potential increased power dissipation, and sensitivity to parameter variations. When considering the use of the Cascode method, it is crucial to carefully assess these factors and determine their impact on the specific requirements and trade-offs of the solar pump controller application.

The next step is to choose the right MOSFET for the application. Calculate the maximum current and voltage that the switch can handle. The equation can be used to calculate the maximum voltage which follows as

$$V_{DS\_max} = V_{In\_max} + \frac{D_{max} \times V_{In\_min}}{1 - D_{max}}$$

=1524V + 20% safety margin =1828.8V

Also, the maximum current passing through can be determined by,

$$I_{p\_peak} = \frac{P_{IN}}{D_{max} \times V_{In\_min}} + \frac{D_{max} \times V_{In\_min}}{2 \times f_{sw} \times L_{p\_max}}$$

= 628.4mA

So, we considered a MOSFET which has a voltage rating of 2000V and a current rating of 1A

Step 4: MOSFET Calculation Input and Output Rectifier Diode for calculations

For, the input diode bridge, the input current is determined by,

$$I_{In_{rms}} = \frac{P_{In}}{V_{ac\_min} \times \text{Cos} \propto}$$

Here, cos α is the power factor, which is assumed to be 0.6

So, $I_{In_{rms}}$ = 0.452 A

V_{dc_max} = (V_{ac_max} × 1.73) + 20% safety margin

=1432.44V

Considering the rise in dc bus voltage due to regenerative action, two diodes of 1000 V with a 1-A rating are used for the 3-phase bridge rectifier.

Now, for the Output diode

$$V_{ds} = \frac{V_{out} + V_{In\_max}}{N_{s1}}$$

$$= 15 + \frac{1200}{20.63}$$

$$V_{ds} => 73.16V$$

Also, the max current at the output side is 3.7 A
So, I have considered 100V, 5A diode for all 3 output levels.

Step 5: Output capacitor calculation

The calculation for selecting the output ESR is based on 90% of the allowable output ripple voltage.

$$C_{out} = 20u \times \frac{P_{out}}{2\times P_{in} \times V_{Ripple}}$$

$$= >180uF$$

Here, I have considered a 240uf capacitor for a filter, and for that two 120uf capacitors in parallel are connected.

Step 6: Flyback transformer design and calculation

The next step in designing a flyback converter for a solar pump controller involves selecting the appropriate transformer. This decision involves considering factors such as the core material and shape [11]. One commonly chosen option is a ferrite core with a double E shape, which effectively concentrates the magnetic flux Fig.4. To determine the transformer's size, the AP method is employed. This method calculates the combined area of the winding window and the core cross-section where the magnetic flux is concentrated. It is crucial to carefully evaluate the specific requirements of the application, including the input voltage range, desired output voltage, maximum power, and operating frequency. Additionally, calculating the turns ratio (Np: Ns) based on the desired output voltage and input voltage range is a critical step in the design process.

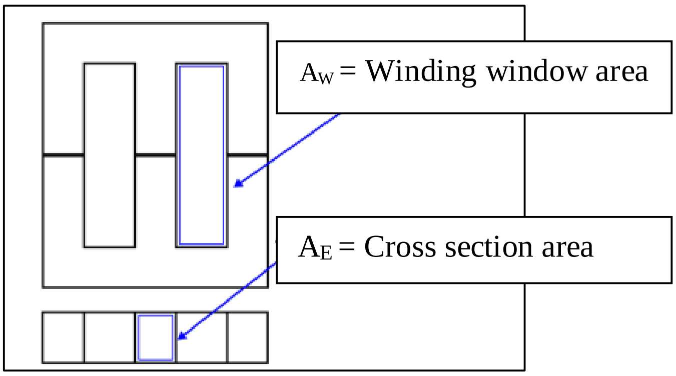


Figure 4: Transformer Internal Diagram

The transformer area can be estimated with Equation,

$$A_p = A_e \times A_w$$

From the equation, I have considered A_p as 164 mm^2 also the B_{max} is considered as 0.3T
The transformer ratio is as defined in step 2.

Step 7: Snubber design and calculation

The primary-side RCD snubber plays a vital role in flyback converter design by addressing various aspects. It protects sensitive components from voltage spikes and reduces noise, improving the overall reliability of the system. Additionally, it enhances efficiency by minimizing energy losses and helps reduce electromagnetic interference (EMI) generated during switching operations. The primary-side placement of the RCD snubber simplifies circuit layout, optimizing noise reduction and ensuring proper functionality [10].

The highest voltage that the capacitor can handle can be described as follows,

$$V_{c\_max} = V_{ds\_max} \times 0.1 + V_{In\_min} \frac{D_{max}}{1 - D_{max}}$$

$$= 476.4V$$

The power dissipated in the snubber resistor can be expressed as follows,

$$P_{R_{snubber}} = \frac{F_{sw} \times I_{p\_peak}^2 \times L_{leak}}{2}$$

$$= 12.62W$$

Now, determine the snubber resistance by using the following method,

$$R_{snubber} = \frac{V_{c\_max^2}}{P_{R_{subber}}}$$

$$= 18.9kohm$$

$$\approx 19kohm$$

And, the snubber capacitor can be calculated using the following approach,

$$C_{snubber} = \frac{1}{V_{o_{ripple}} \times I_{p\_peak^2} \times L_{leak}}$$

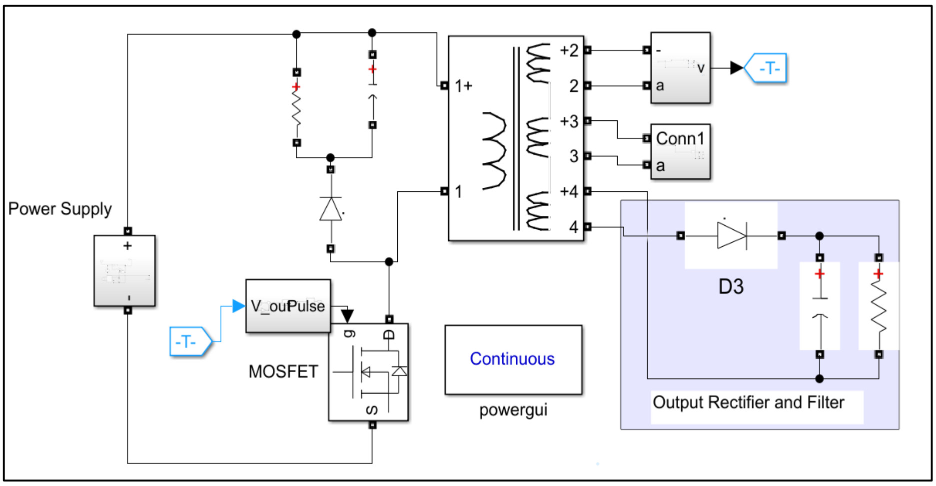
$$=> 106nF$$

Lastly, determine the maximum voltage across the snubber diode, following Equation,

$$V_{R_{snubber}} = 1.2 \times V_{DS\_max}$$

$$= 1828.8V$$

So, the diode with a 2000V 1A rating can be considered for design.

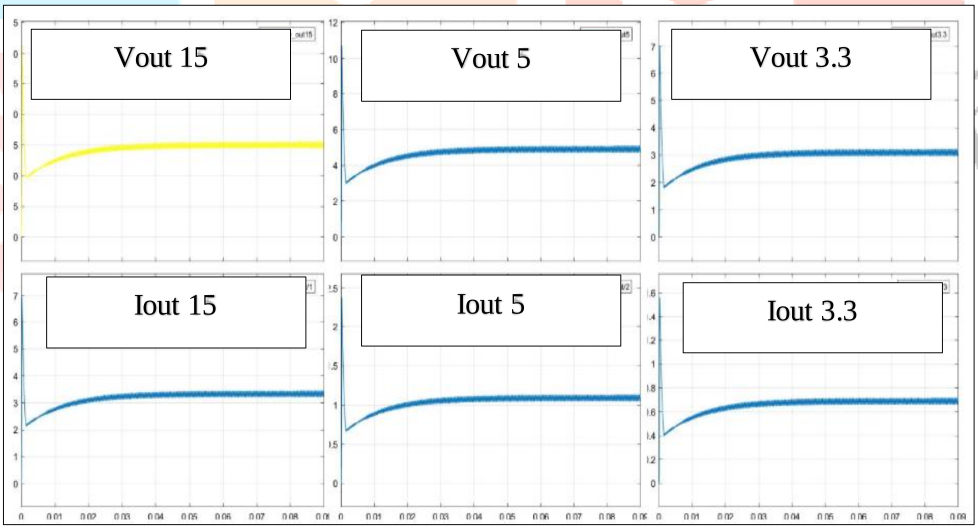


VI. SIMULATION AND PCB LAYOUT OF THE FLYBACK CONVERTER

With all the necessary calculations, it is mandatory to check whether the calculations are correct or incorrect before final production and to check this, we have simulated this fly-back converter into MATLAB Simulink and attached with PCB Layout Fig. 5 & 6. 3D layout of the fly-back converter is also depicted in Fig.7.

VII. CONCLUSION

The Cascode configuration improves the converters performance by enhancing its bandwidth, linearity and gain making it well-suited for high-frequency applications. Conducting simulations is essential for optimizing the design and assessing its performance, ensuring efficient power conversion and reliable operation. Accurate calculations such as snubber values and determining transformer parameters are crucial for achieving the desired output voltage and efficiency. By carefully considering these aspects and employing proper design techniques, the fly-back converter with Cascode method proves to be a dependable and efficient solution for solar pump controllers.



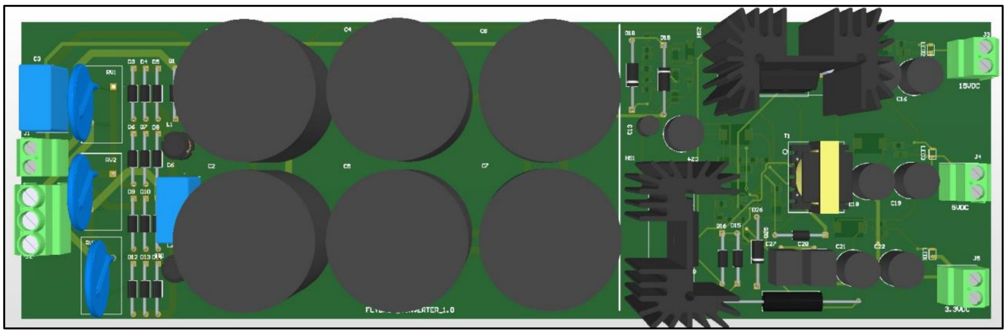


Figure 7: 3D Layout of The Flyback Converter

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