Factors to consider when designing a flyback

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1 Introduction

1.0.1 What is a Flyback Converter

A Flyback converter is a DC-DC converter that is mostly used in Low to Medium power applications. It is a Buck-Boost derived topology and it can be model it to a Buck-Boost equivalent and all the equations of a Buck-Boost can hold.
This form of converter has 2 operating modes

1. Continuos Conduction Mode (CCM)
2. Discontinous Conduction Mode (DCM)

The mode of operation is affected by

1. Value of primary inductance or magnetizing inductance
2. Ouput current.

With this in mind, a Flyback design to operate on the two modes can be made by selecting the primary inductance at Boundary Conduction Mode (BCM) $Lm_(BCM)$ where inductance values lower than this will render the converter to go into DCM and values greater than this will make the converter transit to CCM. Another design approach is by setting reference current output as the design starting point from which values of converter components are to be selected. Values below this sets the converter to DCM whereas values greater than this sets the converter to CCM.

1.1 Continous Conduction Mode Operation

A Flyback is said to be operating in CCM if its inductor current is decays to a value greater than zero.or the inductor current does not fall to Zero. Most CCM are used in applications that require high voltages and low currents. Generally any application that require ouput power of between 50 $\Leftrightarrow$ 150 Watts, this is the most suitable design.
Things to note while working on a Flyback to operate in CCM.

1. There is one Duty Cycle $D_(on)$. Unlike in DCM where one has to set $t_(on), t_(off), t_d$, in CCM once $t_(on)$ is set, $t_(off)$ is predefined.
   Where
   $$t_(on) = \frac{D_(on)}{f_(sw)}, t_(off) = \frac{1 - D_(on)}{f_(sw)}$$

2. As the load decreases(output power decreases or output current decreases) beyond a certain value, the converter transits into DCM operation.
3. As supply voltage decreases, the dutycyle tends to increase to keep ouput voltage constant (in voltage mode control) the reverse is true when supply voltage increases and therefore it is necessary to determine a limiting dutycyle from where we can determine the maximum primary inductance above or below which we transit from CCM to DCM. This also applies in designing DCM converter.

Advantages

1. High power ouput as the current does not drop to zero.
2. Components suffers from less Peak voltages and current stress.
3. Reduced Conduction and switching losses

1.2 Discontinous Conduction Mode Operation

In DCM, primary and secondary inductor current reaches Zero before the next charge cycle begins. DCM Flyback is suitable for Low power application usually < 50 Watts.
A typical DCM waveform is as shown below
Things to note while working on a Flyback in DCM

1. There are 2 Duty Cycles
   (a) $D_(on)$ and $D_(off)$
   (b) There is a time delay t_d between when the secondary current reaches 0 and the begininning of a new charge cycle
   (c) The total switching period T is the sum of $t_(on) + t_(off) + t_(d)$ where

$$t_(on) = \frac{D_(on)}{f_(sw)}, t_(off) = \frac{D_(off)}{f_(sw)}, t_d = T - t_(on) - t_(off)$$

2. As Power demand increases there is a likelihood for the converter to switch from DCM to CCM , thus one has to set maximum limit of Duty Cycle to prevent this transition.

1.3 Forced Continous Mode Operation

2 Component Selection

2.1 Introduction

A flyback can get its supply from either DC source or an AC Source. Getting power from AC sources means one has to perform necessary steps to keep the input voltages within specified voltages. Having very high input values i.e drawing power from mains without performing steps such as stepping down is possible but have its own limitation. I am going to discuss some of the limitations one can face

1. Very low values of Duty cycle to keep the output voltage within the design range Say for example one needs to supply a load with 24V 5A from a $240V_(ac)$. Here it is clear that one has to maintain very low dutycyle ratio within the range $0.1 \Leftrightarrow 0.3$ giving less output voltage variations.

2. One will find out that there is numerous losses in supplying the Controller IC as there is a need to step down the voltages from around $339V_(dc)$: this is for a $240V_(ac) Supply$, to around $5 \Leftrightarrow 15V_(dc)$. This losses are due to resistor diveder network as resistors dissipate energy inform of heat. This heat in turn will in turn reduce the saturation level of the core, increased conductor resistance and evaporation of capacitor electrolyte.

3. Strain in electronic components such as capacitor and switch

Before the starting the converter it is necessary to determine the load requirement as this will guide you on what converter configuration you will use, the size of components to be used and other factors such as PCB traces thicknesses. In this paper, my focus is on a Flyback converter and therefore the maximum power power for optimal result I can design is 150 Watts. It is worthwhile to further note that for power requirements less than 50 Watts, a Flyback operating in DCM is the optimal option. Values greater than 50 but less than 150 Watts, a CCM design is the optimal option.
As mentioned earlier we can start our design by choosing the reference current or reference inductance all these operate in BCM such that values greater than the reference will make it transit to CCM and less to DCM.

$$DCM \Longleftarrow I_(ref) \Longrightarrow CCM$$

$$DCM \Longleftarrow Lm_(ref) \Longrightarrow CCM$$

In this paper I am going to design a Flyback converter for 12V 45Ah Lead Acid battery. The Charge requirements are 4.5A and 14.4V. This is our Flyback converter outputs.
The power output $P_(out) = V * I \Longrightarrow 14.4 * 4.5 \approx 65$ Watts.
For a universal supply its the supply ranges from $110 \Leftrightarrow 240$ VAC giving some derating of 10VAC for regulation we have a range of $100 \Leftrightarrow 250$ VAC as our supply.
Having 65 Watts as our demand, it is clear that for optimal performance I need to use a CCM Flyback. In the next section I am going to start the core design process.

2.2 Core Design

The core should be able to supply the demand without going into saturation. Our core therefore, needs to reset after every cycle i.e volt-seconds must balance. In order to select or design a core , one has to know the following parameters:

1. Input Power $\eta_(in)$
2. Input peak current $Ip_(peak)$
3. Input Voltage range $Vin_(min) \Leftrightarrow Vin_(max)$
4. MOSFET rating $V_(mos)$
5. Primary inductance $L_p$which is the same as magnetizing inductance L_m
6. Secondary inductance L_s
7. Secondary peak current $Is_(peak)$
8. Ouput current I_o
9. Ouput Voltage V_o
10. Turns ratio n
11. Primary turns N_p
12. Secondary turns N_s

Deriving equation for the peak primary current.
Energy stored in an inductor can be calculated using

$$E = \frac{1}{2} * LI^2 \tag{1}$$

Power can be calculated using

$$P = \frac{E}{t} \Longrightarrow \frac{1}{2T} * LI^2 \Longrightarrow P = \frac{1}{2} * LI^2 f_(sw) \tag{2}$$

Voltage on primary can be calculated using

$$V = \frac{L\Delta I}{\Delta t} \Longrightarrow Vin \frac{L_p * I_p * f_(sw)}{D_(on)} \tag{3}$$

Now $\Delta t = t_(on) = \frac{D_(on)}{f_(sw)} = T * D_(on)$ substituting in 3 we get

$$V = \frac{LI_p}{T * D_(on)} \Longrightarrow V * D_(on) = \frac{LI_p}{T} \Longrightarrow V * D_(on) = LI_p f_(sw) \tag{4}$$

Substitung into 2 we get

$$P = \frac{1}{2} * LI_p f(sw) * I_p \Longrightarrow V * D_(on) * I_p \tag{5}$$

Putting I_p as a reference we get

$$I_p = \frac{2P_(in)}{Vin_(min) * D_(on)} \tag{6}$$

Here $D_(on)$ is dutycyle at boundary between CCM and DCM.
Calculating Primary Inductance.
Now since the value of I_p can be readily obtained, we can now use 3 to obtain the primary inductance by

$$L_p = \frac{Vin_(min) * D_(on)}{I_p * f_(sw)} \tag{7}$$

This is the reference value of selected inductance, values greater than this will be in CCM and less than this in DCM.
Calculating the secondary Inductance.
Secondary inductance I_s can be calculated using 6 by replacing $P_(in)$ with $P_(out)$ and $D_(on)$ with $1 - D_(on)$.This will look like this

$$I_s = \frac{2P_(out)}{V_(out) * (1 - D_(on))} \tag{8}$$

Secondary inductance can also be calculated as 7 but replacing values of $D_(on)$ and V_in to look like this

$$L_s = \frac{V_(out) * (1 - D_(on))}{I_(out) * f_(sw)} \tag{9}$$

Once the Primary and Secondary inductances and peak current have been determined, the next parameter is the turns ratio n. We know that

$$L_p = \frac{L_s}{n^2} \tag{10}$$

substituting L_s with 9 and L_p with 7 we get

$$n^2 = \frac{L_s}{L_p} = \frac{V_(out)(1 - D_(on) * I_p)}{I_(out) * Vin_(min) * D_(on)} = \left(\frac{N_s}{N_p}\right)^2 \tag{11}$$

Having the turns ration n we can now calculate the primary and secondary turns. This is not that staightfoward since depending on the core selected, the number of primary turns vary but always the turns ratio remains the same. Therefore it is vital to know the properties of the core that one select for any given application. This properties are readily available in the datasheet whether you are designing your own transformer or selecting an off-shelf transformer. Some important parameters to check are :

1. Maximum flux density
2. Inductance index
3. Whether the core is gapped or ungapped
4. Effective area
5. Effective length
6. Effective Volume
7. Relative permeability
8. Area Product
9. Window area for Copper $W_(cu)$
10. Window Bobbin area

To get the required wire diameter

$$cmils * Area_(wire) = I_(avg)$$

where $cmils$ is the acceptable current density, usually the optimum is around $4A$ per mm^2 or it can be represented as $400cmils$.We know area of circle $\Pi * \left(\frac{d}{2}\right)^2$.Making d the subject we get

$$d = 2\sqrt{\frac{I_(avg)}{cmils * \Pi}} \tag{12}$$

There are 2 methods to select a core namely

1. Core by power handling capacity
2. Core by Area Product

In each of the above method, one is presented with a chart that matches or ranges within the calculated Area product or power.
Core selection by area product

$$AP_(cm^4) = \frac{P_(out) * Cmils}{K_t * B_(max) * f_(sw)} \tag{13}$$

where $AP_(cm^4) = Wa * A_e$,K_t is the topology constant

Topology	ValueK_t
Full Bridge	0.0014
Half Bridge	0.0014
Push Pull	0.001
Flyback One winding	0.00033
Fylback multiple winding	0.00025
Forward	0.0005

Once that is calculated you can refer to a chart to help you selet a core within the $AP_(cm^4)$ range. Now, the total area of copper windings should be less the window area for copper winding i.e $Area_(windings) < Wac_(cu)$, if not so select another core. The inductance index can also be calculated using

$$A_L = \frac{L_p}{N_p^2} \tag{14}$$

this calculated value should be less or equal to the selected core A_l value.
To calculate the number of primary turns we use the following equation:

$$N_p \geq \frac{L_p * I_p}{B_(max) * A_e} \tag{15}$$

Where $B_(max)$ is the maximum permissible Flux density, A_e is the effective area of the selected core.

2.3 Snubber Circuit Design

Selecting values for RC,RCD or DZ snubbers

2.4 EMI Filter Design

2.5 Rectifier Circuit Design

3 Calculating Losses

Switching losses, Conduction Losses

3.1 Switching Losses

3.2 Conduction Losses

3.3 Core Losses

3.4 Simulating Losses

4 Modelling A Flyback Converter

4.1 Modelling with MATLAB

MATLAB is a great tool for Electrical Engineers

4.2 Modelling with PSIM

PSIM is the best option to simulate Power electronics circuits

4.3 PSIM - MATLAB Co-simulation

Integrating PSIM with MATLAB

4.4 Other Simulation Tools

5 Direct Offline vs Step Down, DCM vs CCM Comparison

In this section I am going to design both Direct Offline Feed and another converter that involve stepping down of Mains voltages, then compare the results and efficiencies.
The Following are the Power requirements

Output	Minumum	Maximum
Voltage	12	24
Current	$2A$	$5A$
Switching Frequency	$150kHz$	-
Supply Voltage	$110V_(ac)$	$260V_(ac)$
MOSFET	$600V$	-
Estimate Efficiency η	97%	-

5.0.1 Direct Offline Design

5.1 Direct Offline Flyback CCM

5.2 Direct Offline Flyback DCM

5.2.1 Step Down Offline Flyback Design

5.3 Step Down Offline Flyback CCM

5.4 Step Down Offline Flyback DCM

6 Conclusions

6.1 Offline Flyback Supply Voltages

In countries having supply voltages of 115 $\Leftrightarrow$ 120 VAC, Direct Offline method is suitable anything above this calls for a step down operation or use of other configurations such as Full Bridges.