

ALNT 1440, Revision 1 FLYBACK CONVERTER DESIGN

TYPICAL APPLICATIONS

The flyback converter has a number of advantages which make it one of the most widely used topologies for low power (< 200 W) designs. The flyback converter provides DC isolation of up to 5000 volts and it is much more failure tolerant than a non-transformer isolated topology. When compared to other transformer isolated topologies like the forward converter or push-pull converter the major advantage is simplicity. It is very easy to have more than one output on a single transformer and the outputs can be both positive or negative in voltage. Additionally very few components are needed to build a flyback converter (only one switching device is required and output inductors are not needed). Input voltage range is typically 3 to 1 and special designs can even accommodate ratios as high as 6 to 1.

The flyback also has some disadvantages which will favor other topologies in many applications. The input and output current ripple is high compared to other topologies. Cross regulation also is generally high with values on the order of +/-5% being typical. These problems can be addressed by adding other components to the supply however with the addition of more components the essential advantage of the flyback design (simplicity and cost) is lost. Therefore it may be preferable to look at a different topology when output ripple and cross regulation are very important.

Due to the high ripple currents the flyback is less efficient than other designs and therefore is generally not used for high power applications. Also the flyback can have voltage spikes on the primary which will tend to stress other components and can lead to reliability problems if the design and build process is not controlled carefully.

Despite these disadvantages the flyback topology is very widely used for low power switch mode designs and a large selection of switching transistors are available. With careful and thorough design, and good manufacturing control the flyback transformer will perform efficiently and reliably.

OPERATION DESCRIPTION...GENERAL

The basic circuit for a flyback transformer with a single output is shown in Figure A. The operation of the flyback can be described by breaking the operational cycle into two parts: the on-time and the off-time of the switch. During the on-time, a constant voltage is applied across the primary winding of the transformer

which is equal to V_{in} minus V_t . During this time the current will ramp in a linear fashion with a slope equal to $(V_{in}-V_t)/L_{pri}$ where:

V_{in} = DC input voltage

V_t = Switching transistor voltage drop

L_{pri} = Transformer primary winding inductance.

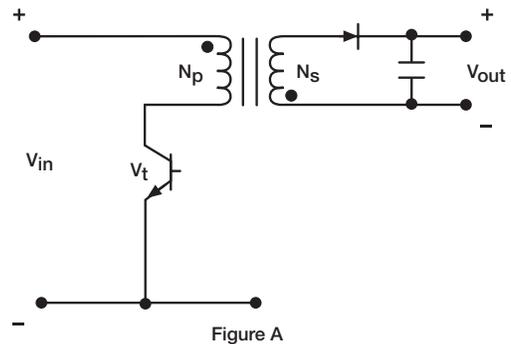


Figure A
TYPICAL FLYBACK
REGULATOR CIRCUIT

When the power switch turns off the input voltage drops to zero and the energy stored in the core flies back to the secondary of the transformer and to the load. The voltage on the secondary of the transformer during the flyback time is then determined by the turns ratio, (note that the actual power supply output voltage will be lower than the transformer secondary voltage due to the diode drop). The flyback period will continue until the core is depleted of energy and the output current drops to zero (discontinuous operation) or until the power switch is turned on again (continuous operation).

Because the transformer never operates with both windings conducting at the same time it can be modeled as two separate inductors. Looking at the transformer in this fashion it is apparent that the designer can choose the primary to secondary turns ratio based on factors besides the voltage ratios and in fact a 2:1 turns ratio can create 3.3 volts just as easily as 5 volts from the same input voltage. On and off times are rarely equal due to variations in input and output voltages and the turns ratio.

OPERATIONAL DESCRIPTION...DISCONTINUOUS

Most flyback designs are discontinuous because the transformer is typically smaller and because the power supply is more stable. The power switch voltage

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and input and output currents are shown for the discontinuous mode of operation in Figures B, C, and D.

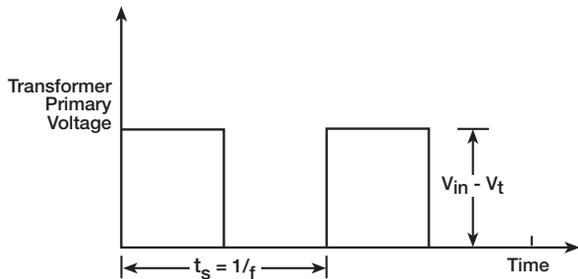


Figure B

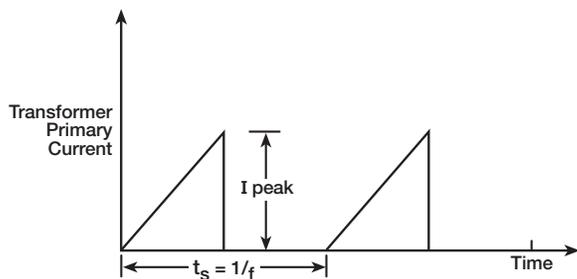


Figure C

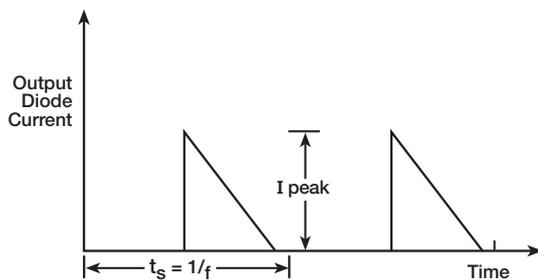


Figure D

In the discontinuous mode of operation the output current drops to zero before the power switch turns on and the current ramp starts up. In this case the secondary current ripple starts from a zero base on each cycle and the core only stores energy during the switch on-time and during the flyback period. Every cycle will have a small dead time in which nothing in the transformer is energized. It is this shut down time which is unique to the flyback and which allows the flyback to regulate over a wide range of input voltages and over a wide range of output currents.

The discontinuous mode of operation can be distinguished from the continuous mode by examining the output current waveform across the transformer (Figures E and F).

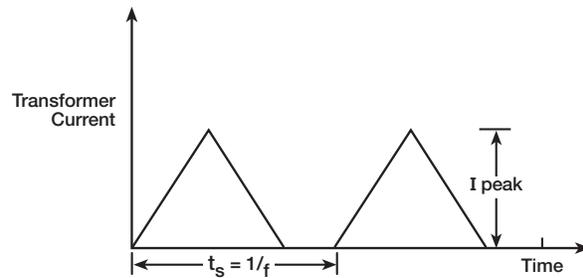


Figure E
Discontinuous Operation

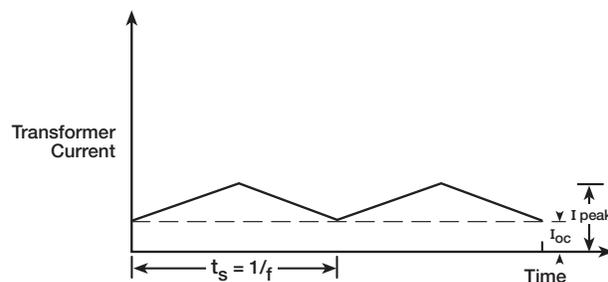


Figure F
Continuous Operation

It should be noted that with a discontinuous design it is possible to deliver more power to the load by reducing the primary inductance of the transformer. This will also reduce the size of the transformer. The degree to which this is possible will be governed by reliability concerns as high peak currents will cause the power supply semiconductor devices to fail. The disadvantage of the discontinuous mode is that peak currents are higher than in the continuous mode of operation.

Even when the design is based on a discontinuous mode of operation it is not unusual for a flyback to revert to continuous mode of operation when the input voltage drops too low. In the continuous mode energy must be stored in the core.

OPERATIONAL DESCRIPTION...CONTINUOUS

If efficiency and reliability are a driving concern, and the flyback topology must be used it is better to operate in the continuous mode. Lower peak currents will not only improve the reliability of the power supply, they will reduce switching losses and improve the efficiency of the power supply.

In the continuous mode of operation the output current never drops to zero (Figure F). The current ripple essentially rides on a pedestal of continuous DC current, thereby creating a strong DC bias in the core. The

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converter designer must allow for this DC bias and determine the magnetizing force under high load conditions. Adequate margin must be allowed to insure against saturation due to the magnetizing force.

It is very important to note that operation in the continuous mode introduces a control problem for the designer. Because of a negative zero in the small signal control to output voltage transfer function located in the right half plane of the frequency plane the flyback converter is subject to unstable operation in the continuous mode. While this problem rarely leads to converter failure it does create problems with stability and transient response.

Therefore when designing a continuous mode converter compensation should be introduced to minimize the problem. Typically this problem is addressed by adding of current mode control to the circuit topology.

DESIGN INPUT VARIABLES

In order to minimize the design cycle time it is preferable to fully specify the transformer design variables before undertaking a design. A complete set of design variables would include the following:

- **Efficiency:** The target design efficiency of the entire power supply is utilized in order to generate a maximum loss value for the transformer. By estimating losses from each component in the power supply a loss budget can be generated for the transformer. This loss value (expressed in Watts) then becomes a part of the iterative transformer design process. Alternatively the transformer may be designed around an allowable temperature rise specification.

- **Minimum Input Voltage:** The minimum voltage is very important as most flyback designs are based on this variable and therefore it should be specified very carefully. If an AC voltage is used as a design variable, specifications on the rectification circuit are required.

- **Maximum Input Voltage:** The maximum voltage is important because it will effect the switch on-time. At maximum line input voltage the switch on-time will be at a minimum. At high input voltages the on-time of the PWM can become so short that the special control techniques are required. Typically the flyback can accommodate a 3:1 input voltage range. For greater input voltage ranges special control circuits will allow input voltage ranges in excess of 6:1.

Most flyback topologies utilize a fixed frequency current mode type of control. Under these conditions the controller attempts to maintain a constant peak current over the range of input voltages. See figure G. The problem that arises is that at high input voltages the

on-time of the power switch is very short and it is not possible to source enough output current to drive the switch into a saturated state before turning it off again. This creates a big reduction in efficiency and can lead to a runaway failure mode.

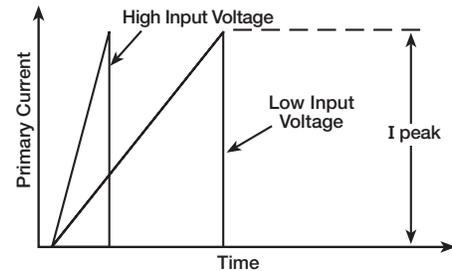


Figure G

PRIMARY CURRENT vs TIME
for Differing Input Voltages

- **Output Load:** Amperage and voltage should be specified for each output. Typically the amperage is specified as a DC value. This value must be converted to RMS AC by the designer for loss calculations. Maximum or design load conditions must be known to complete a design. It is also beneficial to know minimum load conditions as this will effect cross regulation and will influence aspects of the transformer design.

- **Output Diode(s):** A flyback converter will require a diode for each output. The voltage drop across each diode is required in order to accurately specify the primary to secondary turns ratio from the DC transfer function. The voltage drop will vary with output current and typically a design value is chosen at high load to allow some margin.

The output diode drop is also the primary factor effecting load regulation. Therefore an accurate prediction of load regulation will require specification of the relationship between current throughput and diode voltage drop for each diode.

The final specification which is important is an estimate of diode losses. The diode loss value is used as part of the power supply loss budget and can effect the transformer design efficiency.

- **Other Design Variables:** The maximum duty cycle and the voltage drop across the switching transistor are also required to optimize the flyback design output inductor is used it may be necessary to include the inductor voltage drop in the input/output transfer function to determine the turns ratio.

- **Output Inductor:** Output inductors are not needed with a flyback converter but they are often used to minimize output ripple. The starting point for the design of

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the output inductance will be a calculation of the desired inductance value. This inductance value will be derived from a choice of how much attenuation of ripple is desired. Then the design will take into account the level of DC to predict magnetizing force, AC input to predict flux density and the loss budget for the component.

- **Switching Transistor:** The selection of a switch for the flyback regulator must be made carefully because it will define the requirements for much of the power supply circuit.

For the transformer design the voltage drop across the transistor should be specified to determine the correct turns ratio.

The other critical design variable which comes from the PWM is the maximum duty cycle, typically 45% to 50%.

The current rating for this component will depend on a number of variables including mode of operation, input voltage and load. The maximum voltage is also very critical and can be determined from the transformer specifications and the snubbing method.

As discussed before a large voltage spike will destroy the PWM. This can be avoided by the addition of a snubber across the primary winding of the transformer. A typical snubber schematic is shown in Figure H. However this will add cost and complexity, and will reduce the efficiency of the power supply significantly. The use of a snubber can be avoided in most cases by the careful design and controlled manufacture of the transformer.

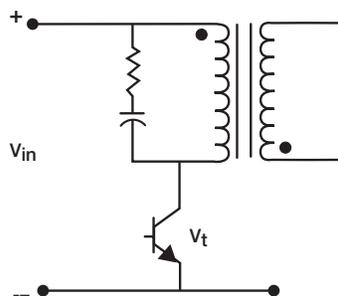


Figure H
SNUBBER SCHEMATIC

FINAL DESIGN PARAMETERS

- **Inductance:** The inductance of the primary winding of the transformer will govern the mode of operation (discontinuous vs. continuous). Inductance is typically determined at high output current and low line input voltage as this is the most severe loading condition. A typical inductance specification for a flyback transformer

would be 50 microhenries +/- 10%.

- **Geometry:** A number of core geometries are suitable for flyback transformers including pot cores, E cores, EP cores and RM cores. West Coast Magnetic's 401, 402, 403, 404, 405, 406 and 407 series are ideal for flyback applications. The choice of size will be a function of frequency, throughput power, allowable losses (temperature rise), and safety agency requirements.

- **Core Material:** Flyback transformers are typically constructed from high quality power ferrite materials. Material permeability should be selected based on frequency of operation. For operation below 500 KHz most designers will use a core material with a permeability of 2000 to 2500. Permeability varies significantly with temperature rise and operating flux density. In general however this will not effect operation of the converter as long as the core is not close to saturation as the inductance (which controls the mode of operation) is primarily determined by the air gap. However temperature rise and operating flux density will effect core losses and this must be taken into account to ensure reliable operation.

- **Core Gap:** The core gap will be determined by the number of primary turns and the inductance specification. The designer will verify that the gap is sufficient to prevent core saturation resulting from DC bias.

- **Windings:** The number of primary and secondary turns, wire type, gauge and winding pattern will also be specified. The manner in which the windings are placed on the bobbin is very important.

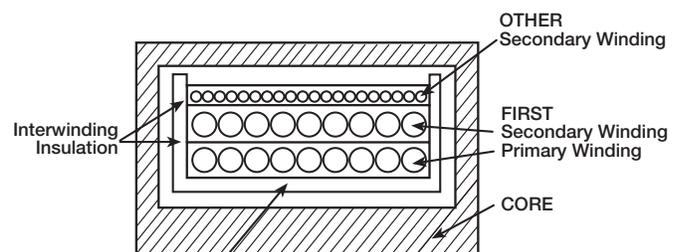


Figure I
FLYBACK TRANSFORMER
Cross Section

In particular the coupling between the primary and secondary windings and between the windings and the core is very important. This will effect the magnitude of the voltage spikes across the transistor. This coupling can be measured by testing leakage inductance and interwinding capacitance. It is controlled by designing the windings of the transformers carefully. Techniques used to minimize leakage inductance and capacitance

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include the use of multistranded layered windings, copper foil windings, and bifilar windings. It is also effected by the order in which the windings are placed on the transformer. It can be controlled in a production setting through the use of automated winding and testing equipment.

Figure I shows a cross section of a typical flyback transformer winding used in a low voltage application.

• **Safety Agency Requirement:** Flyback converters may have special build and test requirements to meet safety agency requirements. These requirements may include one or more of the following:

1.) Hipot - expressed in applied VAC or VDC between selected windings and other windings and between the core and selected windings.

2.) Creepage and clearance - distance between uninsulated portions of selected windings measured according to UL or IEC guidelines. Similarly distance between the core and uninsulated portions of selected windings.

3.) Insulation system - in most cases a UL recognized transformer with a temperature rating of class B (130 degrees C) and higher will require a UL approved insulation system.

4.) Insulating materials - many UL and IEC specifications will have specific requirements for the thickness and number of layers of insulation which will be required between selected windings.

THERMAL CONSIDERATIONS:

Most power supply designs have a goal of compactness, cost effectiveness, and a goal of reliability. These goals often conflict and the power supply design engineer must balance these considerations during the design process. The magnetics typically end up being the largest components on the board and for this reason the tradeoff between compactness and reliability is acute.

The reliability of the power supply is directly related to temperature rise. Reliability will also effect the safety of the power supply, particularly in the case of the transformer.

Temperature rise for magnetic components comes from two sources: core losses and copper losses. Typically the magnetics designer will estimate core losses and copper losses. Then these loss values will be used along with a thermal resistivity coefficient which is specific to the transformer geometry to predict a temperature rise for the part. Temperature rise due to operation may be as low as 10 degrees C and as high as 60 degrees

C, depending on the application.

It is very important to bear in mind that theoretical temperature rise calculations are not a substitute for thermocouple measurements under actual load conditions in the design circuit. Thermocouple measurements are recommended in all cases, especially if safety agency approval is required.

• **Core Losses:** Core losses can be determined with a high degree of precision once the core geometry and material type, operating frequency, number of turns and primary voltage are known. This information is used to estimate the operating flux density of the transformer under max load conditions. Flux density and frequency of operation determine the losses (typically expressed in mW/cm³).

Flyback transformers operate in the first quadrant of the hysteresis loop (Figure J). As such, peak operating flux density is typically limited to 2000 gauss at 50 KHz. This will vary depending on core geometry with smaller sizes having an ability to effectively dissipate more power per unit of volume.

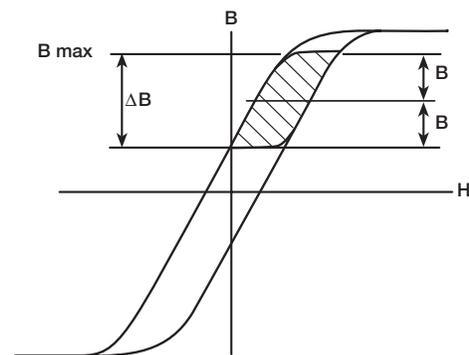


Figure J
HYSTERESIS LOOP of MAGNETIC CORE
in Flyback Circuit

As operating frequency increases, lower flux levels are required to hold losses constant (Figure K).

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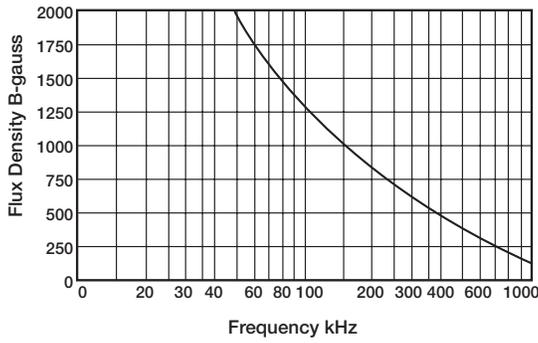


Figure K
OPERATING FREQUENCY vs. FLUX DENSITY
Core Losses Constant - Typical Ferrite
Power Material

Core losses also vary with operating temperature. This relationship is expressed in (Figure L), for a typical ferrite power material. In general, for a given material, core losses will decrease with increasing temperature up to a transitional point, and then they will start increasing again. Every ferrite power material will have a unique set of loss characteristics. It should not be assumed that one material can be substituted for another merely because it has a similar permeability. It is imperative to estimate core losses using the manufacturers loss curves for the material used in the design.

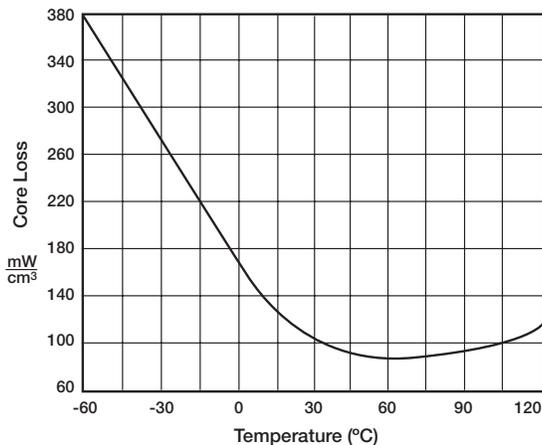


Figure L
CORE LOSS vs. TEMPERATURE:
Typical Ferrite Power Material

- **Copper Losses:** Magnetic components used in flyback converters will also have losses associated with the copper wire or copper strip used to form the winding.

These losses include DC losses and AC losses. AC losses are created from eddy currents which circulate on the surface of a conductor. See (Figure M) and from proximity effects generated from other windings.

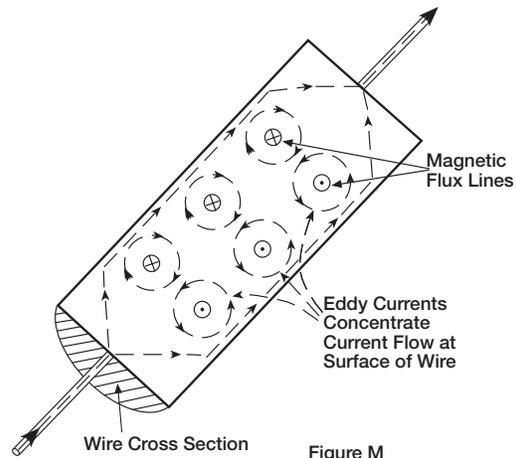


Figure M
EDDY CURRENTS
Contributing to AC Resistance

AC losses will dictate the use of finer gauge wires or copper foil windings as the operating frequency increases. This tends to result in less copper area per unit of bobbin window area.

Higher temperatures will also give rise to higher copper resistivity. (Figure N) shows a normalized copper resistance factor as a function of temperature.

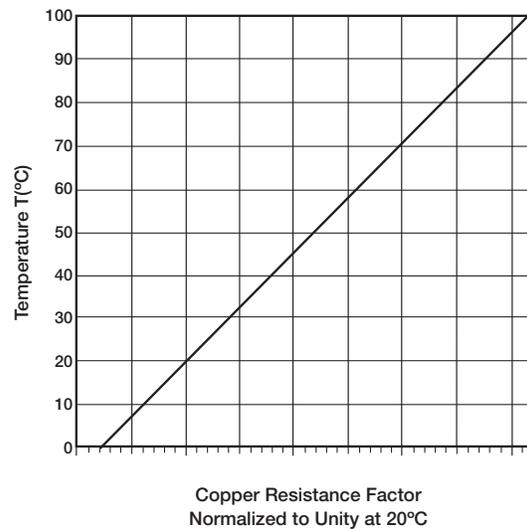


Figure N

Final design calculations must consider the effects of AC and DC resistance and the temperature rise of the wire when determining copper losses for the transformer.

West Coast Magnetics typically utilizes Class B (130 degrees Centigrade) materials in the construction of its parts. A good rule of thumb for thermal considerations is to allow for a 40 degrees Centigrade operating temperature rise at maximum load. In most cases this will allow adequate margin given ambient conditions to remain safely below the 130 degrees Centigrade temperature rating on the materials used in construction.