FLYBACK-CONVERTOR POWER SUPPLY DESIGN AND THEORY

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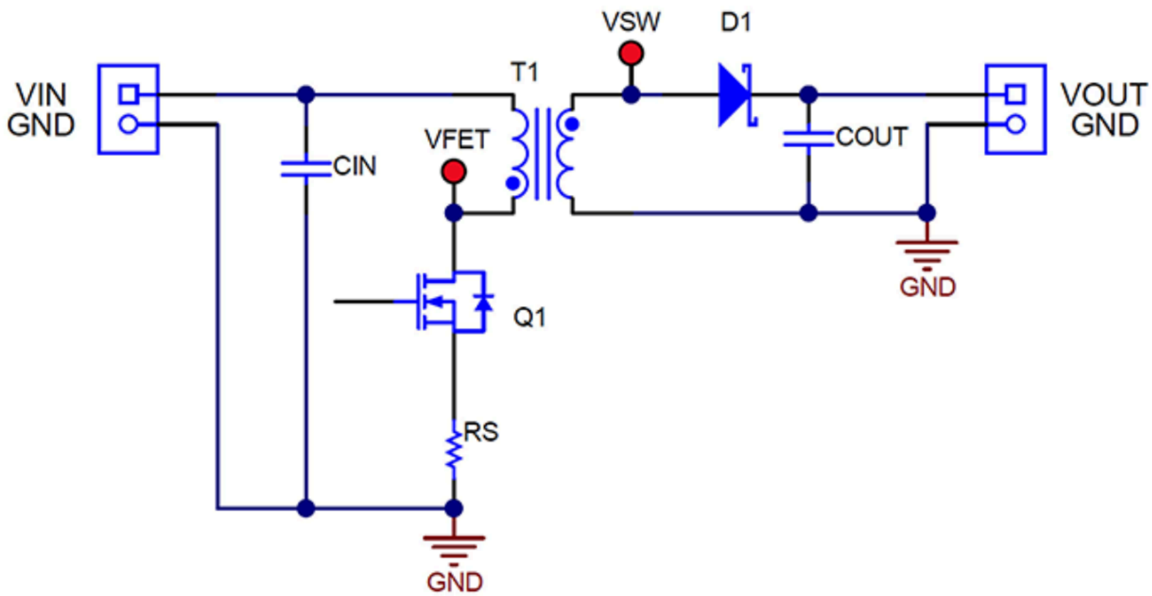
Flyback Converter Topology

Flyback converters are versatile power electronics devices used in applications such as medical devices and laptops. Also known as isolated buck-boost converters, these converters are simple circuits that can regulate a system's output voltage (V_{OUT}) while minimizing electromagnetic interference (EMI).
The basic flyback converter topology consists of the following circuit : ->



Here the MOSFET Q1 is switched ON and OFF through a control signal.The inductor also provides an isolation between the input and the output side of the converter.

The general principle of operation is that when the MOSFET is turned ON, current flows through the primary winding of the transformer (T1), and energy is stored in the magnetic field of the transformer core. Unlike a traditional transformer that transfers energy instantaneously from primary to secondary, a flyback transformer stores energy during the ON phase and delivers it during the OFF phase.

When the MOSFET is turned OFF, the sudden interruption of current causes the magnetic field in the transformer core to collapse. This induces a voltage in the secondary winding

This process repeats continuously:

- **During the ON time**, energy is stored in the core;
- **During the OFF time**, energy is released to the output.

The output voltage of such a flyback converter depends on various factors such as input and output capacitors, the transformer turn ratio ,duty cycle of control signal etc.

Role of Input Capacitor

The input capacitor in a flyback converter, often referred to as Cin, plays a role in providing a stable and clean DC input voltage negating any ripples that might occur, especially when the input to the converter is from a rectified source.

Role of Output Capacitor (has to be added later)

The output capacitor is needed to supply current to the load during the times at which the MOSFET is ON and the diode is reverse biased.

Selecting Duty Cycle of MOSFET Control

The duty cycle of the mosfet control signal plays an important role in the design of a flyback converter. It directly affects the amount of energy that is transferred from input to output of the converter.

A higher duty cycle means that the Mosfet is ON for a longer duration, which allows more energy to be stored and thus more to be transferred to the output.However the maximum energy that can be stored in the input side inductor is also limited by other factors.A lower duty cycle means less energy storage → lower output voltage.

Duty cycle also helps regulate circuit behaviour at different input voltages.When input voltage drops, increasing the duty cycle compensates to maintain constant output.On the other hand input voltage rises, reducing the duty cycle prevents overvoltage at the output.

The duty cycle is chosen according to the input voltage value and the output voltage to be maintained.

Selecting Frequency Of MOSFET control

The effect of frequency has been explained below : ->

Increasing the frequency allows the use of smaller transformers and output capacitors since energy is transferred more frequently, which improves transient response and reduces the overall size of the converter. However, higher frequencies also result in increased switching losses in the MOSFET and diode due to more frequent transitions, and they generate more electromagnetic interference (EMI), requiring careful layout and additional filtering.

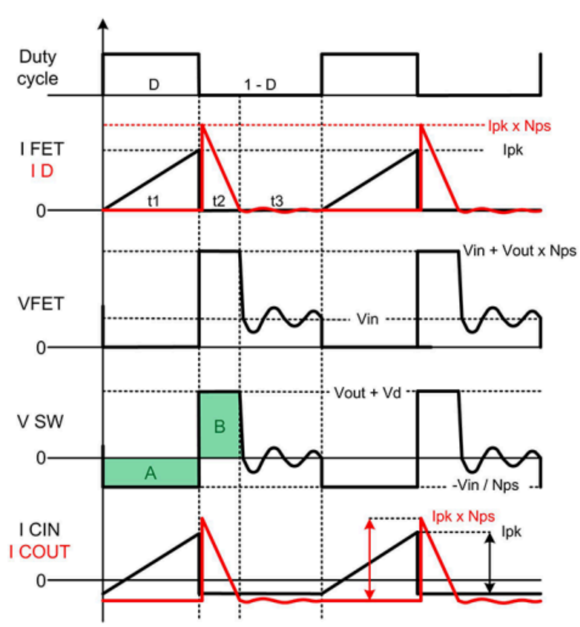
On the other hand, operating at lower frequencies reduces switching losses and EMI, leading to higher efficiency, especially at high loads, but it requires larger magnetic components and capacitors to store and transfer more energy per cycle.

Therefore, selecting the optimal switching frequency is a trade-off between efficiency, size, EMI performance, and thermal considerations, with typical values ranging from 50 kHz to 300 kHz depending on the application.

Voltage And Current Waveforms in A Flyback Converter

Operation starts when FET Q1 turns on for duty cycle period D. The current in T1's primary winding, which always starts at zero, reaches a peak set by the primary winding inductance, the input voltage, and on-time t1. During this FET on-time, diode D1 is reverse-biased because of T1's secondary winding polarity, forcing all output current to be supplied by output capacitor COUT during time periods t1 and t3.

When Q1 turns off during period 1-D, T1's secondary voltage polarity reverses, which allows D1 to conduct current to the load and recharge COUT. Current in D1 decreases linearly from its peak to zero during time t2.Once T1's stored energy is depleted, only residual ringing occurs during the remainder of period t3. This ringing is primarily due to T1's magnetizing inductance and to the parasitic capacitances of Q1, D1, and T1. This is easily seen in Q1's drain voltage during t3, which drops from VIN plus the reflected output voltage back to VIN, since T1 cannot support a voltage once current flow stops. (Note: Without an adequate dead time for t3, CCM operation may occur.) Currents in CIN and COUT are identical to those in Q1 and D1, but without a DC offset.

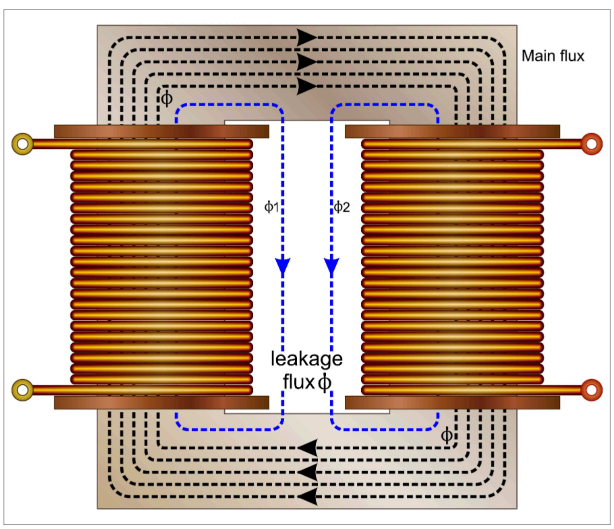


The Concept Of Leakage Inductance and Primary Inductance

Leakage inductance is inherent characteristic of coupled inductors, in which an imperfect coupling between the primary and secondary inductor causes a reduction in the energy transfer efficiency.Various factors—including winding and core geometry, the number of turns, and gaps between windings—significantly impact the level of leakage inductance in a transformer or inductor.

A transformer works on the following principle, when an Alternating Current passes through the primary inductor, it produces a time varying magnetic field around it.This time varying magnetic field then passes through the secondary inductor windings creating a time varying magnetic flux through it. Now according to Faraday's law -> Voltage across the secondary winding is directly proportional to the rate of change of flux through it.

However, not all of the magnetic flux generated by the primary winding links with the secondary winding. Some of it escapes or "leaks" into the surrounding environment.This is known as leakage inductance.This reduction can be modeled electrically as a self-inductance component in series with the primary windings, and this component is referred to as "leakage inductance.”



Some methods for modifying leakage inductance are given below ;

Source -> https://resources.pcb.cadence.com/blog/2023-leakage-inductance-an-introduction

Method	Description
Increase Core Material Permeability	Utilize core materials with higher permeability to concentrate magnetic flux and reduce its escape.
Improve Winding Techniques	Use techniques like interleaved or bifilar windings to enhance magnetic coupling between windings.
Utilize Magnetic Shields	Place magnetic shields (e.g., mu-metal) strategically around windings to confine magnetic flux within the core.
Reduce Air Gaps	Minimize air gaps within the core, which can lead to higher leakage inductance.
Optimize Core and Winding Geometry	Carefully design the physical geometry to concentrate magnetic flux lines within the core. Examples include reducing the number of turns and layers, reducing the insulator layer thickness, shortening the mean turn length, widening the core window, and lowering the core window height.
Insert Magnetic Shunt	For applications requiring higher leakage inductance, insert a magnetic shunt between layers.
Use Fractional Turns	Employ fractional turns to achieve the desired level of leakage inductance when necessary.

Primary inductance refers to the inductance of the primary winding of a transformer, representing its ability to store energy in the magnetic field created by the current flowing through it.
In the context of a flyback converter, the primary inductance plays a pivotal role in determining the mode of operation—either continuous conduction mode (CCM) or discontinuous conduction mode (DCM). A higher primary inductance allows for more energy storage during the switch-on period, which is essential for maintaining CCM, especially under varying load conditions. Conversely, a lower primary inductance may lead to operation in DCM, which can be beneficial for certain applications requiring rapid response times

EMI and Filtering

Electromagnetic interference (EMI), also called radio-frequency interference (RFI) when in the radio frequency spectrum, i**s a disturbance generated by an external source that affects an electrical circuit by electromagnetic induction,** electrostatic coupling, or conduction.The disturbance may degrade the performance of the circuit or even stop it from functioning.
In the case of an EMI in the data path, these effects can range from an increase in error rate to a total loss of the data.

EMI can be of the following 4 types :

1) Conducted (Electric Current)
2) Radiated (Electromagnetic field)
3) Inductively Coupled (Magnetic Field)

4) Capacitively Coupled (Electric Current)

The EMC or electromagnetic compatibility is a devices potential to create and respond to the interference in an electromagnetic environment,

In the context of EMI (Electromagnetic Interference), filtering refers to the **process of using electronic components, primarily capacitors and inductors**, to attenuate or suppress unwanted electromagnetic noise while allowing desired signals to pass through. EMI filters are commonly placed in power supply lines to protect sensitive circuits from noise.

In power electronics, EMI filters are used to suppress and filter out unwanted high-frequency electromagnetic noise generated by the switching operations of power electronic circuits

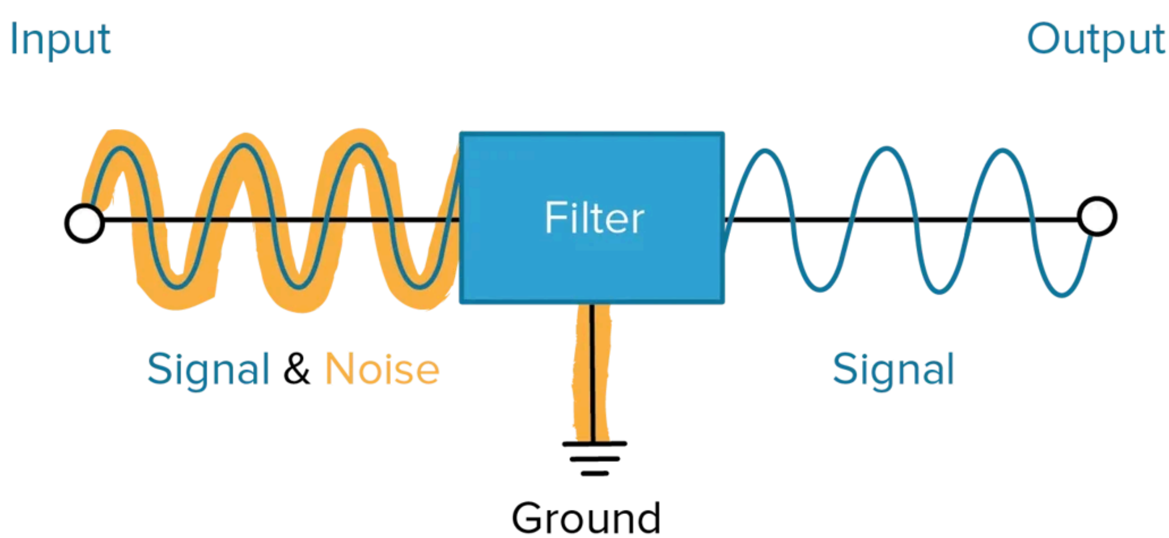


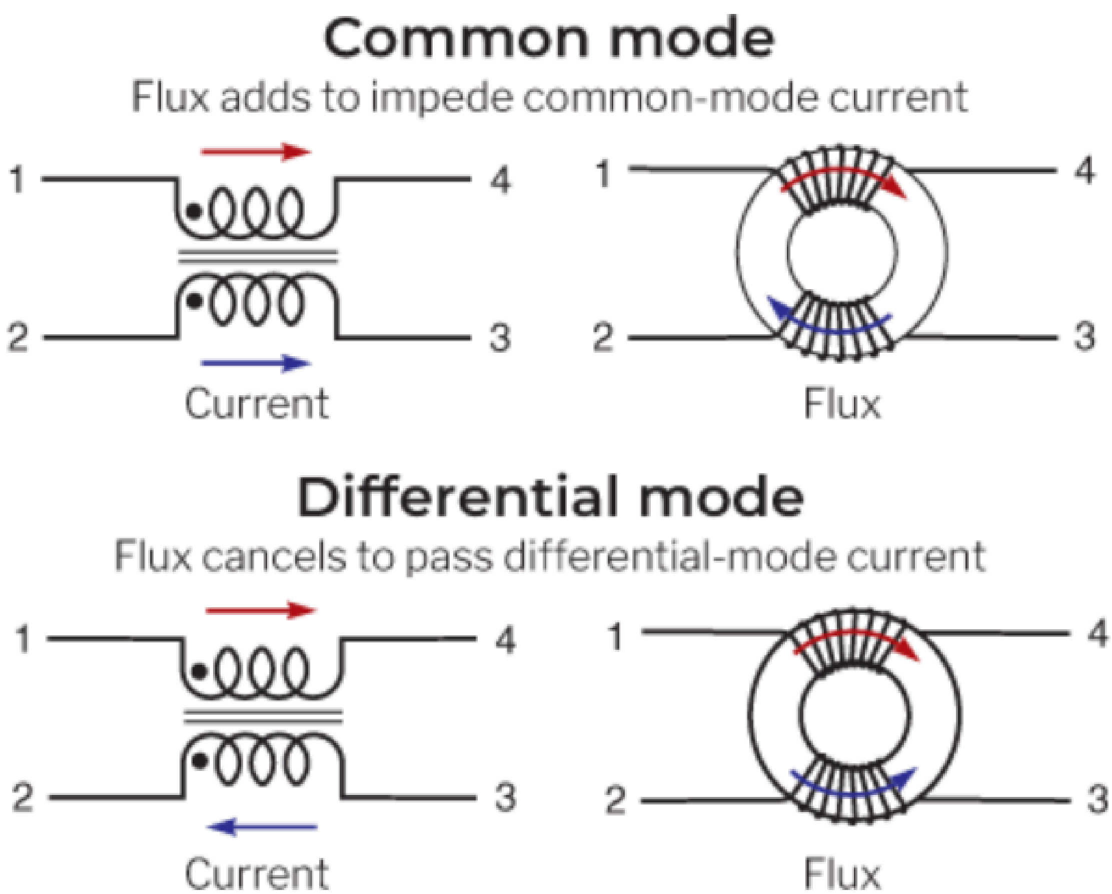
Figure 1. An illustration of the basic concept of how an EMI filter works.

Common Mode Choke

A common mode choke is an electrical filter that blocks high frequency noise common to two or more data or power lines while allowing the desired DC or low-frequency signal to pass Common mode (CM) noise current is typically radiated from sources such as unwanted radio signals, unshielded electronics, inverters and motors. Left unfiltered, this noise presents interference problems in electronics and electrical circuits.

In **normal or differential mode (single choke)**, current travels on one line in one direction from the source to the load, and in the opposite direction on the return line that completes the circuit. In **common mode**, the noise current travels on both lines in the same direction

In common mode, the current in a group of lines travels in the same direction so the combined magnetic flux adds to create an opposing field to block the noise.



X-Cap and Y-Cap

Capacitors are essential passive components used in every modern circuit and electronics applications for smoothing and filtering power lines. In AC/DC filter applications two special classes of capacitors are used : Class X and Class Y are used to filter AC power-source noise and are commonly referred to as safety capacitors.

Class X capacitors ->

These are known as 'line to line' or 'across the line' capacitors and are used to minimise EMI that may be caused by differential mode noise in the power supply.These are commonly placed between Live and Neutral

Class Y capacitors->

These are known as ‘line to ground’ or ‘line by-pass’ capacitors.They are placed between AC supply and ground to handle common mode noise.

Differential Mode Noise : Noise that appears **between two conductors** carrying a signal or power.

Common Mode Noise : Noise that appears **equally on both lines** (line and neutral, or signal and ground) **relative to a common reference** (usually earth ground or chassis).

Snubber Circuits

A snubber circuit in a flyback converter is used to **protect the switching MOSFET from high-voltage spikes and reduce electromagnetic interference (EMI) caused by those spikes**. These spikes occur when the MOSFET turns off, and the energy stored in the transformer’s leakage inductance (the part of magnetic energy that doesn’t transfer to the secondary winding) has nowhere to go. As a result, it generates a sharp voltage spike across the MOSFET, which can damage the device or cause unwanted oscillations and EMI.

The diagram of a flyback supply with an input snubber circuit is given below :

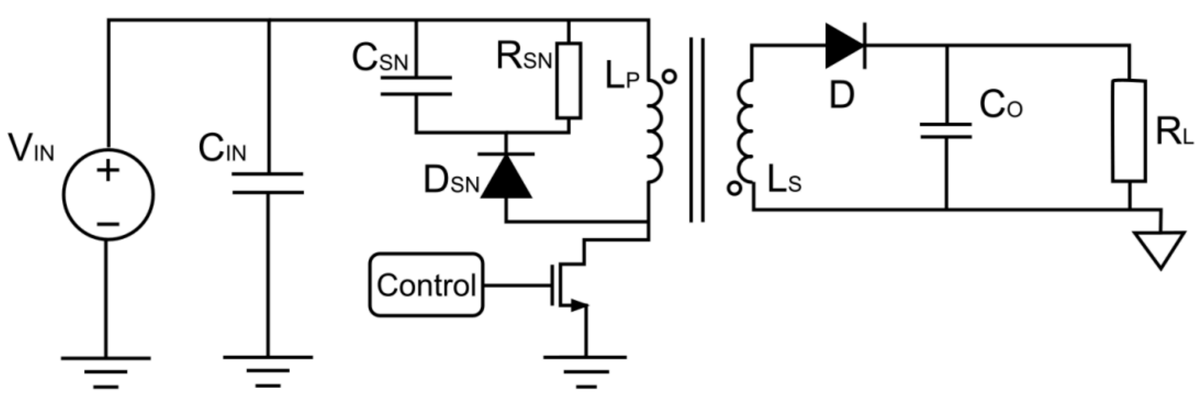


Figure 7: Flyback Converter with an Input Snubber Circuit

CCM and DCM Supplies

Flyback converters have two modes :->

1) **Continuous Conduction Mode :**

In CCM, the current in the transformer's primary and secondary windings never falls to zero; energy is continuously stored and transferred, making it suitable for higher power levels with lower peak currents and better efficiency at full load. However, CCM requires a larger transformer and more complex control circuitry.

2) **Discontinuous Conduction Mode:**
DCM operates such that all the energy stored in the transformer during the ON-time is fully transferred to the output during the OFF-time, causing the current to fall to zero before the next cycle begins. This mode is simpler to control and allows for smaller magnetics, but it results in higher peak currents, increased switching losses, and lower efficiency at high loads.

Concept of Ringing in A Power Supply

Radiated and Conducted Emissions

Radiated emissions are electromagnetic waves that are transmitted wirelessly from a device into the surrounding environment, while **conducted emissions** are electromagnetic disturbances that travel through conductive paths, like cables or power lines, from one device to another. Both can cause interference and affect the performance of other electronic devices.