Popular Topologies in Offline Power Supplies

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Offline switched−mode power supplies (SMPS) are ubiquitous in our daily life and are used in every corner of industrial applications, which have been discussed and studied since last century. Offline SMPS is defined as a switching power supply with an isolation transformer powered by the grid. When it comes to mass production of SMPS, the most important thing is to achieve the happy medium of cost and performance, while considering other aspects such as size and safety.

Figure 1. SMPS with Different Power Level

Long−term use and continuous validation have fixed several excellent topologies for offline switching power supplies. Learn and understand these topologies can help in the development of SMPS that is suitable for your use cases.

Standards

Before we get to the different topologies, it is necessary to understand the relevant standards in your regions before designing a SMPS. There are mainly 3 types of standards:

- Safety standards

The primary goal of safety standards for power supplies used in electrical equipment is to protect against fire, electric shock and injury. The 2nd edition of IEC 62368−1 is the latest revision that has been accepted by the US, Canada, and EU. This new standard currently coexists with 60950−1 and 60065 to aid designers in the transition and includes several clauses to help companies manage legacy inventory of subsystems and components. IEC 62368−1 has clear definitions of insulation and isolation, clearances, creepage distance, etc.

- Emissions standards

With the emergence of large scale distributed electronic devices, first the radio with electronic valves, and later TV and personal computers, there has been a fundamental problem with mains pollution by harmonic currents. IEC 61000−3−2 is an international standard that limits mains voltage distortion by prescribing the maximum value for harmonic currents from the second harmonic up to and including the 40th harmonic current. It applies to equipment with a rated current up to 16 A while for equipment above 16A, IEC 61000−3−12 should be followed.

- Efficiency standards

There is a wide variety of regulations covering energy efficiency around the world, from the California Energy Commission (CEC) to Energy Star and Energy−related Products (ErP). Specific to external power supplies (wall mount or desktop), the US Department of Energy (DoE) publishes a standard described in levels (Level VI is the most recent and most stringent), while in Europe, the European Union (EU) Code of Conduct (CoC) on External Power Supplies (EPS) is prepared by the Joint Research Centre, the European Commission's science, and knowledge service.

The 80 PLUS® program promotes 80% efficiency or greater, between 20% and 100% loading and a power factor of 0.9 or higher at 100% loading. The highest level in this program (known as the 80+ Titanium standard) specifies a minimum efficiency of 92% at 20% loading and 94 % efficiency at 100 % loading.

Topologies

PFC Converter

Power Factor Correction (PFC) is a crucial stage for industrial offline power supply. The key mission of PFC is to shape the input current to maximize the real power available from the mains, reduce the high−frequency harmonic current to minimizes losses and costs associated not only with the distribution of the power, but also with the generation of the power and the capital equipment involved in the process. Total Harmonic Distortion (THD) is an important method in determining the quality of line current in any system and is often mentioned in place of the power factor. Another important value is PFC stage can provide regulated DC output voltage, optimizing the design of the following isolated DC/DC converter with a narrow DC input.

$$THD(\%) = 100 \cdot \sqrt{\sum_{p=2}^{\infty} \frac{Ip^2}{I_1{}^2}} \qquad \cos\theta = PF = \sqrt{\frac{1}{1 + THD^2}}$$

Figure 2. THD Definition

Boost PFC

Boost is most widely used PFC topology covering output power from below 100W to more than thousands of watts for its simple structure and easy control strategy. Comparing with the other classical DC−DC topologies (Buck and Buck−boost), boost is preferred in PFC for continuous inductor current, less distortion of current waveform and less RFI and EMI noise. Besides, usually a single−phase boost circuit will boost the DC bus to 380 V – 400 V, it allows the regulation operating in all conditions, while buck converter will have dead time when input voltage is lower than bus voltage.

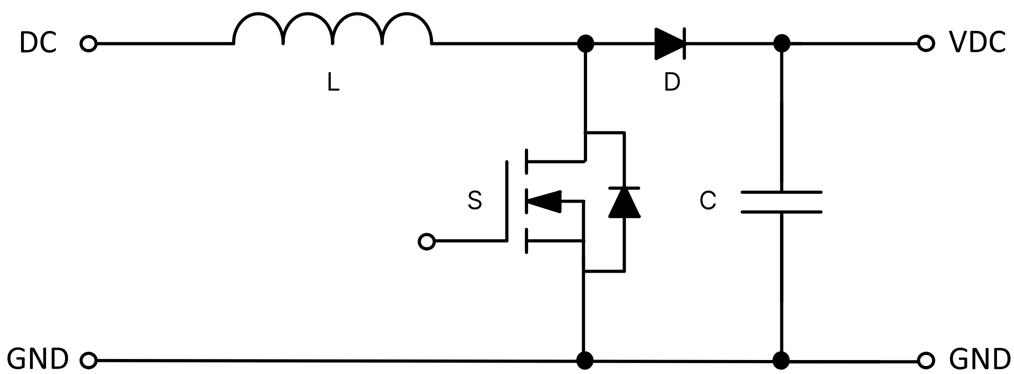


Figure 3. Single Boost

As just mentioned, boost is preferred for its simple configuration, however at high power, it doesn't have a good performance in terms of efficiency as expected because the unavoidable switching losses from the rectifiers.

Operating Mode

It's necessary to repeat the classical operating modes as they can completely affect not only the choice of topology, but the entire system design.

CCM (Continuous Conduction Mode) is more popular at higher power levels as it has minimal peak and rms currents. In CCM the controller can initiate a new switching cycle even if the inductor current is not zero. Therefore, the inductor current ripple is reduced, but now the MOSFET turns on while the boost diode is conducting. Low t_{rr} diodes are now necessary to avoid excessive losses and stress at MOSFET turn on. In comparison with the CrM operation, the peak currents can be 50% lower and rms currents can be 25% lower. This reduces the stress in power switch, diode and inductor. In addition, the filtering is easier as the current through the boost inductor is more continuous. Finally, the switching frequency remains constant for the CCM operation, so the boost inductor design and EMI filter design are easier.

Critical Conduction Mode(CrM) is very popular for low power applications. In this mode the inductor current reaches zero before the start of the next cycle and the frequency varies with line and load conditions. One benefit of CrM is that the current loop is intrinsically stable and there is no need for ramp compensation. In addition, the inductor current reaching zero every cycle causes the diode to turn off without reverse recovery losses and enables the use of a less expensive boost diode without performance penalties. Similarly, the MOSFET turn−on can be at a low voltage, which reduces switching losses.

Discontinuous Conduction Mode (DCM) is usually active at light loads of a CrM/CCM system to ensure power factor and limit the EMI generation because of the significant rising frequency near the zero crossing.

Frequency−Clamped Critical conduction Mode (FCCrM) is an approach introduced by onsemi to limit the switching frequency spread of CrM circuits. A maximum frequency clamp forces DCM when the converter operates in light−load and/or near the line zero crossing. Without this circuitry, the CrM switching frequency would exceed the upper clamp threshold, naturally increasing switching losses. A circuitry is added to compensate the DCM−engendered dead−times so that the line current keeps being properly shaped.[1][2]

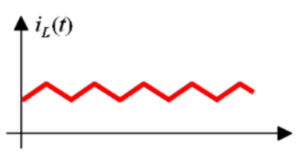
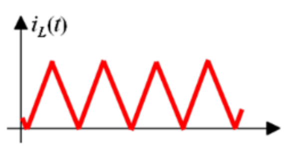
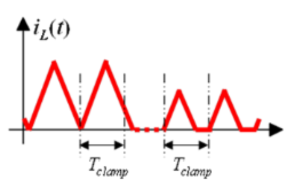
	Operating Mode	**Main Features**
	Continuous Conduction Mode (**CCM**)	Always hard-switching Inductor value is largest Minimized rms current
	Critical conduction Mode (**CrM**)	Large rms current Switching frequency is not fixed
	Frequency Clamped Critical conduction Mode (**FCCrM**)	Large rms current Frequency is limited Reduced coil inductance

Figure 4. Current Control Modes

Interleaved Boost PFC

Interleaved boost is an easy approach to reach higher output power in a small form factor, it consists in paralleling ≥ 2 small stages instead of a bigger one, which are operated 180°/120° out of phase from each other. We can see this approach almost in every power level, basically when the required current is higher than the rating of your current components, instead of adding one more switch/diode, add another boost circuit in parallel can easily solve the problem.[3]

This approach offers several merits such as ease of implementation, use of more but smaller components and a better heat distribution limiting the risk of hot spots. Also, interleaving extends the power range in an efficient and cost−effective way, eliminating the need for low trr diodes. Though the ripple current in each inductor is still high, the total input current ripple is much smaller due to ripple cancellation. As a result, compared to a single−phase PFC, differential−mode EMI filtering design is easier and the significantly lower rms current it produces extends the bulk capacitor life.

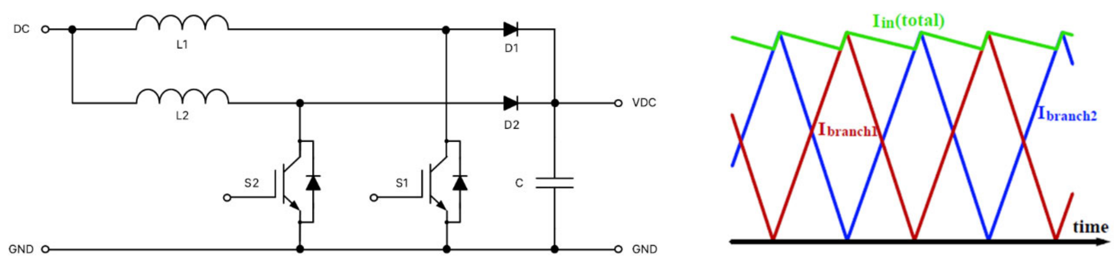


Figure 5. 2ch Interleaved Boost and Reduced Total Inductor Current

Totem Pole PFC

The need for higher efficiencies from the PFC stage has led the circuit designers to look closely at all sections of the circuit and develop possible lower loss alternatives. One section that contributes significantly to the losses is the input bridge rectifier (about 1% efficiency wasted). As a result, the alternatives to eliminate the diode bridge or convert it into a dual−use circuit have been explored for many years. This elimination/conversion of diode bridge brings about its own set of challenges.

Totem pole PFC is nowadays a preferred topology in systems with high power density requirements. An interesting aspect of this structure is that the body diodes of switches S1 and S2 are used as boost diodes, only 2 components are in the conduction path during each half cycle. Before mass production of WBG switches, S1 and S2 used to be MOSFETs and hence, their body diode has relatively poor performance. That is why, this architecture seemed reserved to critical or discontinuous conduction mode operation. Now this structure could become more popular with the recent emergence of SiC/GaN switches that could enable its use in continuous conduction mode.

However, there are still several points need to paid attention such as EMI/EMC issue because of the direct connection between AC input and switches and current spikes at AC zero crossing caused by the reverse recovery of slow switches.

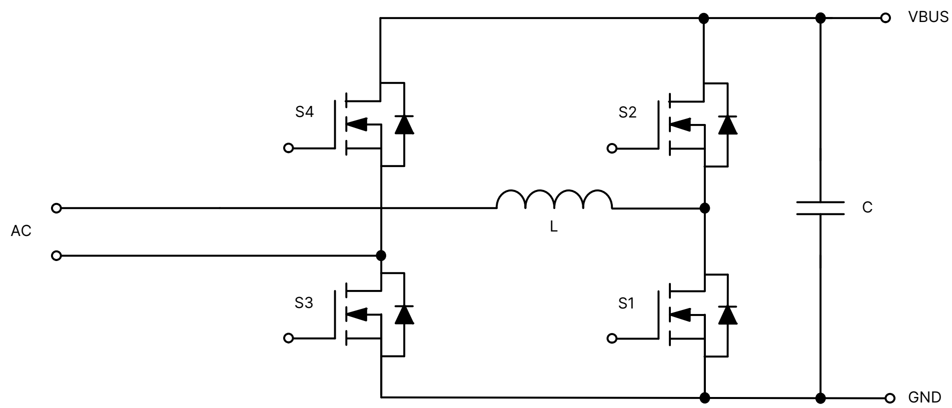


Figure 6. Totem Pole PFC

Isolated DC−DC Converter

Industrial offline PSU (Power supply unit) is always designed to incorporate a transformer between input and output for isolation in terms of safety and signal immunity. By changing the turns ratios, output voltage can be easily adjusted for a large step−up or step−down. It can also realize multiple outputs by adding secondary windings and output circuits. However, designers need to face the challenges like space management, transformer evaluation and customization, high frequency issues such as skin effect and proximity effect.

Flyback

The well−known flyback converter is usually used at low power level ranging from 50−100 W , it has simple BoM, low cost and flexibility for multiple output and easy voltage regulation. On the other side, flyback converter has more ripple current in the input and output circuit, which requires larger capacitors and causes higher losses. The leakage inductance is another issue, usually an extra snubber is placed in the primary side. Lastly, it produces more electromagnetic interference (EMI) due to the gap in the transformer core and the high di/dt of the switch.

QR Flyback

Instead of changing topologies or components, a new control mode can also contribute a better efficiency and a higher output power. Quasi−resonant flyback is a flyback converter working in DCM and having a valley switching turn on, it extends the power range to around 200W and suitable applications such as auxiliary power supplies for sever and adaptors. The working principle of a QR flyback is when the secondary current reaches zero in DCM, there's oscillations occurred on V_{DS}, and the oscillations form valleys. The QR controller seeks the lowest valley point for the next turn on to minimize the power losses.[4]

Figure 7. Valley Switching at 6th Valley for Improved Efficiency (Green: Drain voltage, Purple: Drive)

ACF

A RCD snubber is usually put in the primary side to prevent the excessive ringing caused by leakage inductance, which might destroy the switch. The leakage energy will be finally dissipated as heat by parallel resistor.

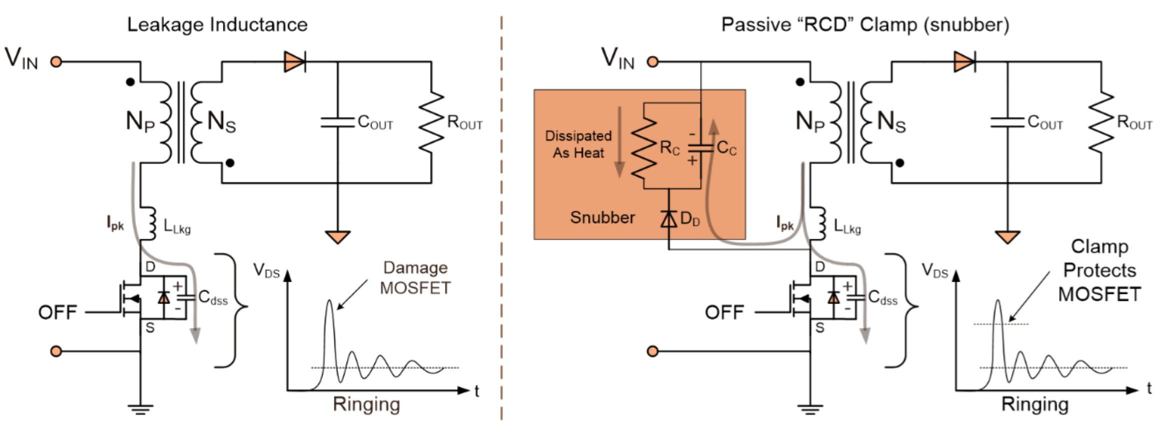


Figure 8. Passive RCD Clamp

System efficiency can’t be improved by adding a RCD snubber but can be realized by replacing diode with another MOSFET. ACF (Active clamp flyback) utilizes the energy stored in the parasitic elements to achieve ZVS instead of dissipating it in the snubber circuit. It allows an even higher operating power level for flyback.

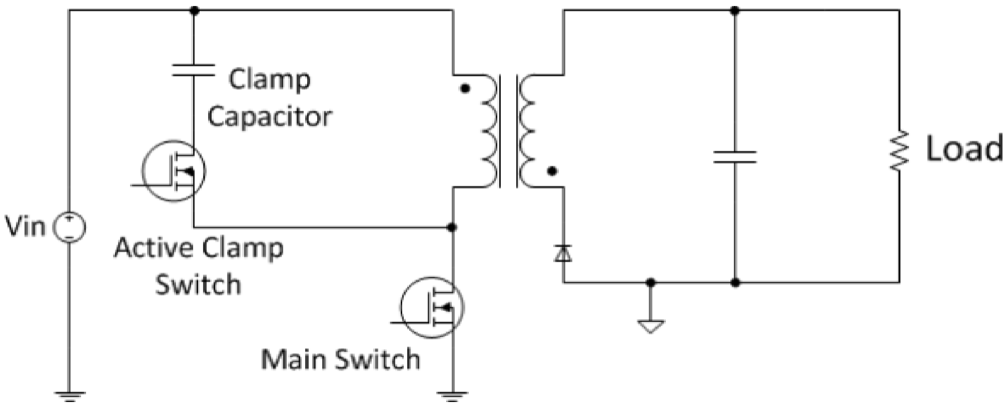
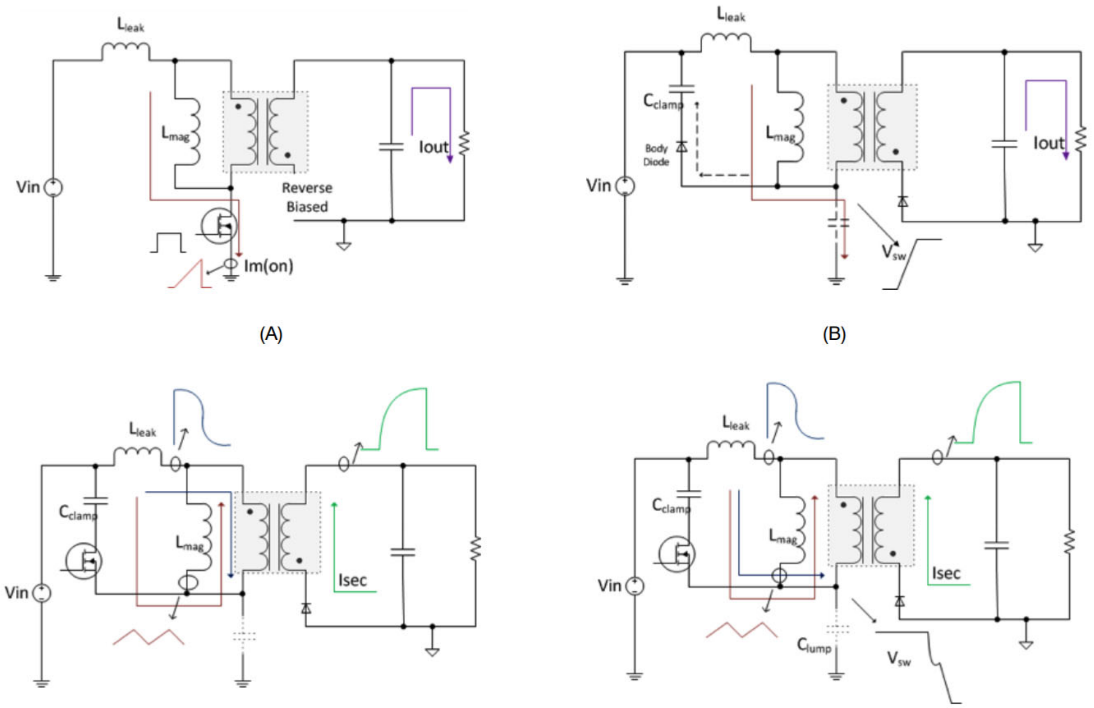


Figure 9. Active Clamp Flyback Circuit Diagram

The entire operation can be simplified into 4 stages. In stage A, it runs just like a standard flyback. When the main switch is turned on, the energy is stored in the transformer. The diode in the secondary side is reverse biased and hence no power transfer occurs. When the main switch is turned off, the current that is flowing in the primary of the transformer continues to flow and charges the output capacitance of the main switch. Once the switch node voltage raises above the clamp capacitor voltage, it forward biases the body diode of the active clamp switch. Activating the active clamp switch at this instant results in ZVS turn−on. The activation of the active clamp switch at the end of charging starts the resonant power delivery mode. During the resonant power delivery mode, the secondary diode/switch is conducting and power is delivered to the load. In stage 4, the active clamp is turn−off, power delivery is terminated.[5]



(A) Energy Storage Mode.
(B) Transition from Energy Storage Mode to Resonant Power Delivery Mode.
(C) Resonant Power Delivery Mode.
(D) Transition from Resonant Power Delivery Mode to Energy Storage Mode.

Figure 10. ACF Working Principle

LLC

Unlike the PWM converter mentioned above, resonant converter is regulating the output voltage through changing the operating frequency of the resonant tank to achieve soft switching, which eventually bring a series of benefits like higher efficiency, better EMI, smaller passive, etc. The LLC resonant converter is preferred to the other resonant convertors for its wider range of soft switching, narrow frequency range with entire load change and smaller circulating current. Now LLC is becoming the no.1 popular topology in medium and high-power range. It saves power losses by achieving Zero Voltage Switching (ZVS) for the primary side switches and Zero Current Switching (ZCS) for the secondary side rectifiers over the entire operating range. In addition, the resonant inductance can be integrated with the transformer into a single magnetic component to save space.

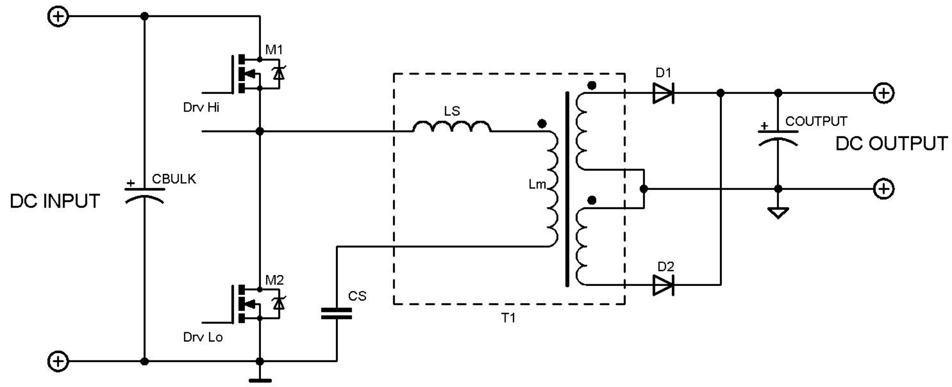


Figure 11. LLC Converter

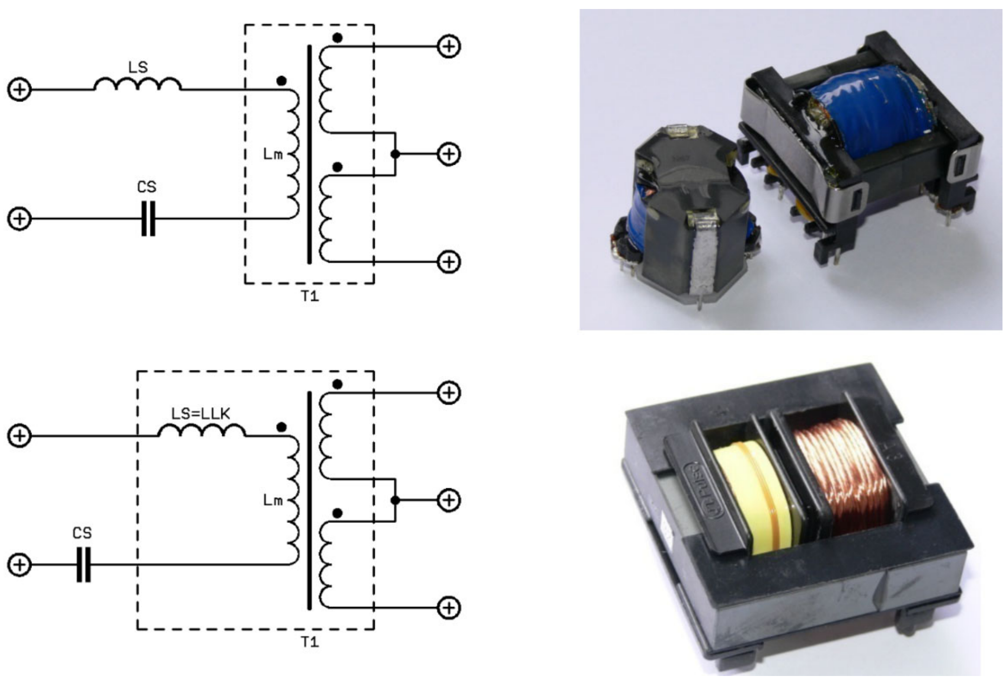


Figure 12. Integrated Transformer vs. Discrete Transformer

The resonant tank design is part of the design challenges of a LLC converter. Like mentioned above, it is common to implement the magnetic components (series inductor and shunt inductor) using an integrated transformer, where the leakage inductance is used as a series inductor while the magnetizing inductor is used as a shunt inductor. However, when building the magnetizing components in this way, the leakage inductance from the secondary side should be taken into considerations, or it will result in an incorrect design. When implementing the magnetic components with the integrated transformer, the gain at the resonant frequency will be higher than unity due to the changed gain caused by the leakage inductance in the transformer secondary side. [6][7]

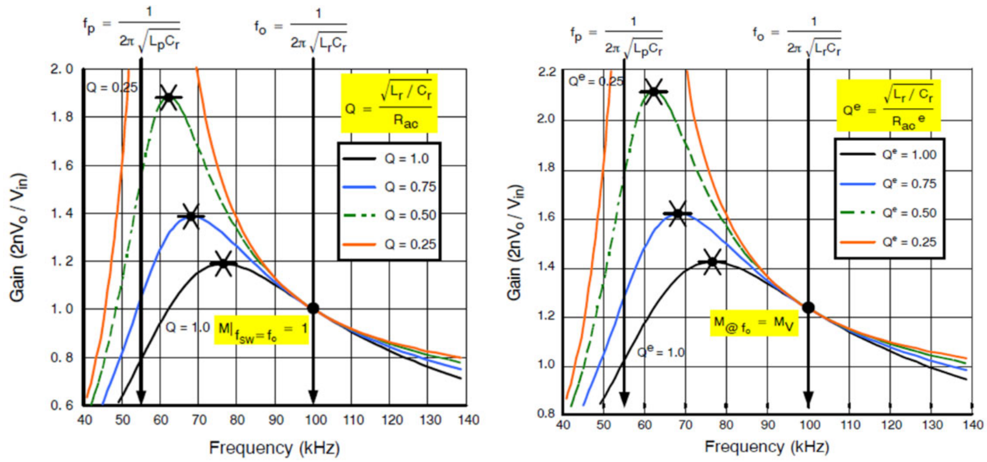


Figure 13. Gain Difference with an Integrated Transformer

Synchronous Rectifier

Replacing the freewheeling diode with a MOSFET improves the secondary side efficiency especially in low voltage and high current system because the $R_{DS(ON)}$ of a MOSFET dissipates much less power than a diode. A self−driven approach by monitoring the drain voltage changes is usually used to control the secondary MOSFET. It doesn't need additional communication with primary side, which saves the BoM and control complexity.

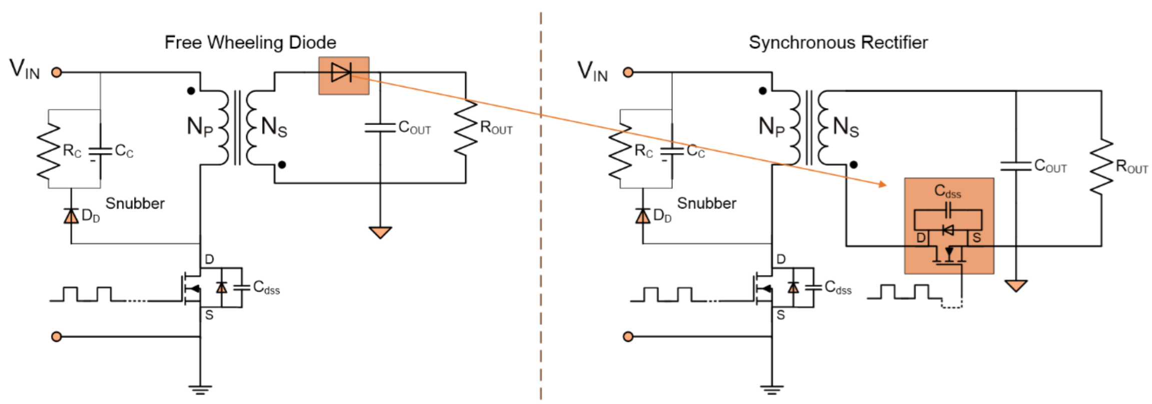


Figure 14. SR in a Flyback Converter

When choosing a proper secondary MOSFET, don't stick only to the lowest $R_{DS(ON)}$ requirement. The lower $R_{DS(ON)}$ device is selected the more significant role the lead parasitic inductances play in tum−of threshold sensing, the more premature turn−off will happen. The lower $R_{DS(ON)}$ switch also usually features higher input capacitance that increases driving losses. The higher output capacitance and higher reverse recovery charge of body diode then results in higher drain−to source voltage peaks in CCM applications.

In a high di/dt system, the parasitic inductance of MOSFET (leads, bonding) and PCB layout will produce unwanted voltage ringing. It might impact the current sensing pin, lead to a premature turn−off while big current is still passing through the MOSFET, reduce system efficiency which is contrary to the original purpose of using SR. [8]

Sources

[1] AN42047−Power Factor Correction Basics
[2] TND6278−Power Factor Correction – Optimization Options
[3] AN4165−Design Guideline for 3−Ch Interleaved CCM PFC Using the FAN9673 5kW CCM PFC Controller
[4] NCP1345 Datasheet
[5] TND6279−High−Density AC−DC Power Supplies using Active−Clamp Flyback Topology
[6] AND90061−Half−Bridge LLC Resonant Converter Design Using NCP4390/NCV4390
[7] AND8311−Understanding the LLC Structure in Resonant Applications
[8] NCP4306 Datasheet