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Synchronous rectifier reduces conduction loss in LLC resonant power supplies

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With increasing drive to shrink electronic solutions, the merits of resonant power converters are now attracting increased attention among power supply engineers. This will especially affect the LCD TV 80PLUS[®] Silver or the more recent 85PLUS[®] ATX power supplies segment, where there is more and more pressure to shift towards higher switching frequencies in an attempt to reduce the physical size and cost of key system elements, such as the power transformer, filtering capacitors and heat sinking component. Resonant LLC converters can enable higher frequency through minimization of the primary switches' switching loss. Critically, the rectifier stage can constitute a significant source of conduction loss, since even the Schottky will have a relatively large voltage drop at high current ratings. This article discusses the limitations of using a diode and shows that the ultimate efficiency could be realized by the more elaborate scheme of using synchronous controller in conjunction with low resistance MOSFET as the output rectifier.

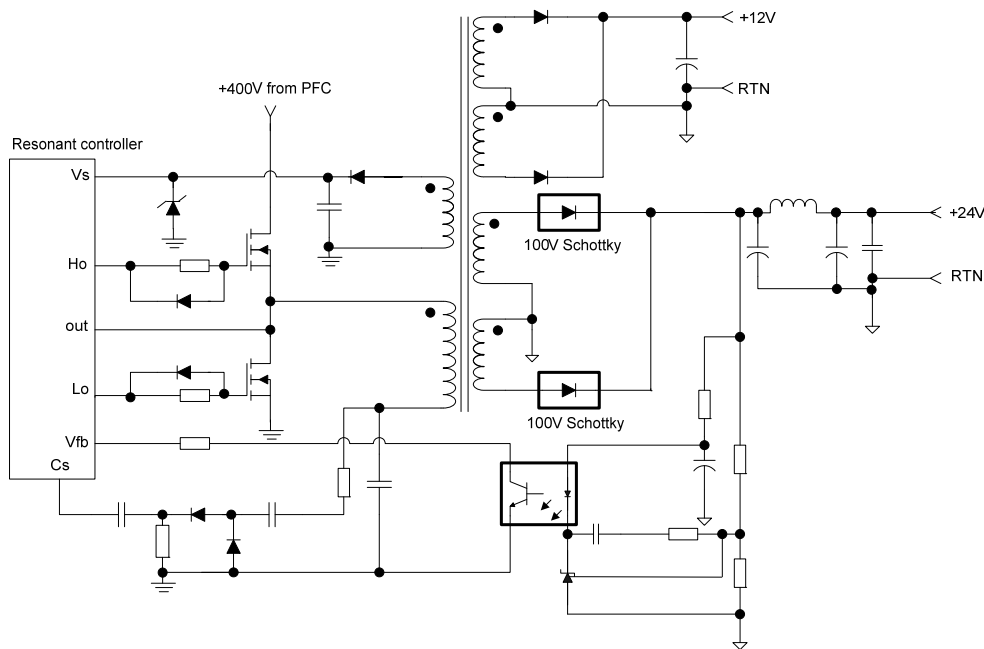


Figure 1 Power supply with LLC resonant downstream DC-DC converter

Resonant converter and limitation of existing rectifier technology

Although migration from the 65kHz typical of both Flyback and Forward PSU to the 100's of kHz allows smaller reactive components to be employed in designs, the resulting supplies are often more susceptible to the effects of parasitic capacitance and leakage inductance. Such effects manifest themselves as high-frequency ringing and large current spikes and switching loss, and unwanted electromagnetic interference. If used in a LCD TV, the EMI pollution could then severely distort the image and sound quality as the panel, the power supply and audio card are in close proximity to each other.

In a resonant converter, the input switching devices as opposed to hard-switched counterparts, can be configured to operate in ‘zero voltage’ (ZVS) switching modes, thereby greatly reducing levels of edge losses. Another advantage is the reduction of EMI, converters designed to exhibit ZVS do not generate this type of EMI. Furthermore, the sine-wave characteristics of resonant tank voltages and currents reduce the generation of high frequency harmonics.

Figure 2 shows the efficiency curve of a nominal 24V, 4A output LLC resonant DC-DC converter with diode rectification. Generally, the converter will accept its supply from an active power factor correction (PFC) pre-regulator that ensures compliant with the IEC1000-3-2 class D standard. In this design example, the magnetizing L_m and leakage inductance L_{lk} of the integrated magnetic approach transformer—810 μ H and 180 μ H respectively, and a 630V 22nF double metalized film pulse resonant capacitor C_s make up the resonant tank. No additional coil is required for resonance. The converter’s secondary side is configured in a centre-tapped manner for half wave rectification. 100V 20A rated Schottky diodes are used.

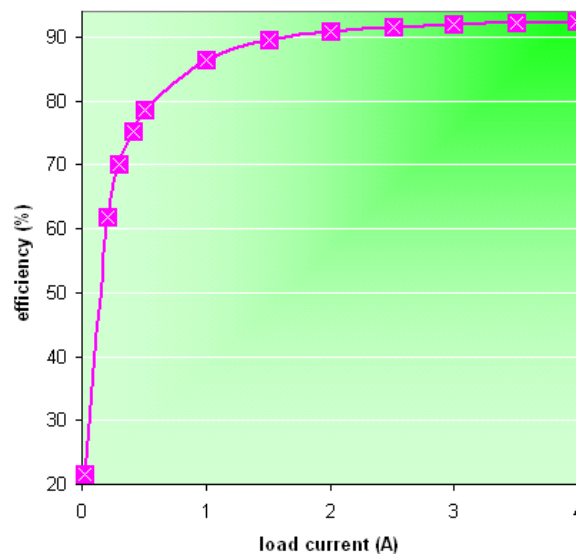


Figure 2 Circuit efficiency versus output current

The Half-Bridge LLC converter is regulated by modulating the switching frequency of the complementary primary switches. Since the PFC output voltage is a regulated 400V with a narrow variation in its normal operation, the LLC resonant converter is optimized to operate close to the load independent frequency at the nominal input voltage as shown in Figure 3. The load independent point which falls on the series resonant frequency is

$$f_r = \frac{1}{2\pi\sqrt{L_{lk}C_s}} = \frac{1}{2\pi\sqrt{180\mu\text{H} \times 22\text{nF}}} = 80\text{kHz}$$

Therefore, the output voltage can be regulated against a wide load variation with relatively narrow switching frequency change. Consequently, the switching frequency of the converter varies from 80kHz at full load up to 95kHz at 5% of peak loading. At zero load, the resonant converter works at its maximum frequency and power consumption of the converter is around 1.8W. Having a low consumption in sleep mode is now a key requirement in display unit. In practice, the resonant circuit could be turned off during standby mode and an auxiliary power supply supplies microcontroller that must remain alive.

The full load efficiency of the resonant LLC converter efficiency is 92.4%. Nevertheless, there is an emerging necessity for low voltage high current output such as those directly supplying microprocessor

or for systems that provide multiple outputs in 80PLUS® power supplies to reduce conduction loss within these rectifiers. In theory, the average currents flowing through each diode are,

$$I_{avg} = 0.5 \times I_{out} = 2A$$

For a typical 20A, 100V Schottky diode, the forward voltage drop at 2A and elevated temperature is about 0.425V. The conduction loss for each of the output diodes is around 850mW. That heat dissipation will raise the junction temperature of a diode in TO-263 on a 1in² to a tolerable 107°C at 80°C ambient. In fact in a 10A output converter for LCD TV with display screen size above 32 inches, a total loss of 2.13W will need to be dissipated from the diode and that cannot be removed easily without bulky heat sink. Thereby, in order to achieve the ultimate efficiency and high power density, MOSFETs with low on-state resistance should be considered to replace these diodes.

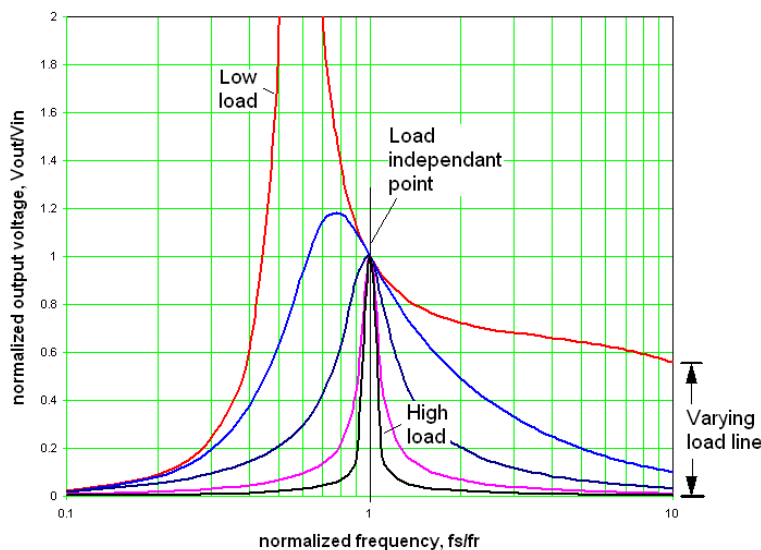


Figure 3 Voltage conversion curve of LLC resonant converter

Drain voltage sensing synchronous controller

The ZXGD3101 synchronous controller provides a solution that avoids the limitations mentioned above, by a scheme utilizing MOSFET voltage sensing, along with an analogue gate drive that is determined by the MOSFET on-state voltage drop.

The configuration in Figure 4 replaces normal diodes on the positive power path with MOSFETs driven by the synchronous controllers. The controller supply voltage is derived through auxiliary windings on the power transformer. Nevertheless, the auxiliary windings only needs to carry a few ten's of mA current. An alternative configuration is to have the synchronous MOSFET on the ground return path. It allows the controller to be powered directly from a low voltage output rail, recommended below 12V, via a drop down transistor at the expense of increasing the risk of ground noise and EMI pollution.

Figure 4 shows the controller monitors the differential voltage across the Drain-Source pin in relation to current flow through the MOSFET and then turns on the MOSFET upon the body diode conduction. The gate drive voltage is then proportional to the Drain-Source reverse voltage, ensuring rapid turn-off as the current decays. Since no timing information needs to be transferred from the primary side and no timing components are needed on the secondary side, the solution is very simple to implement.

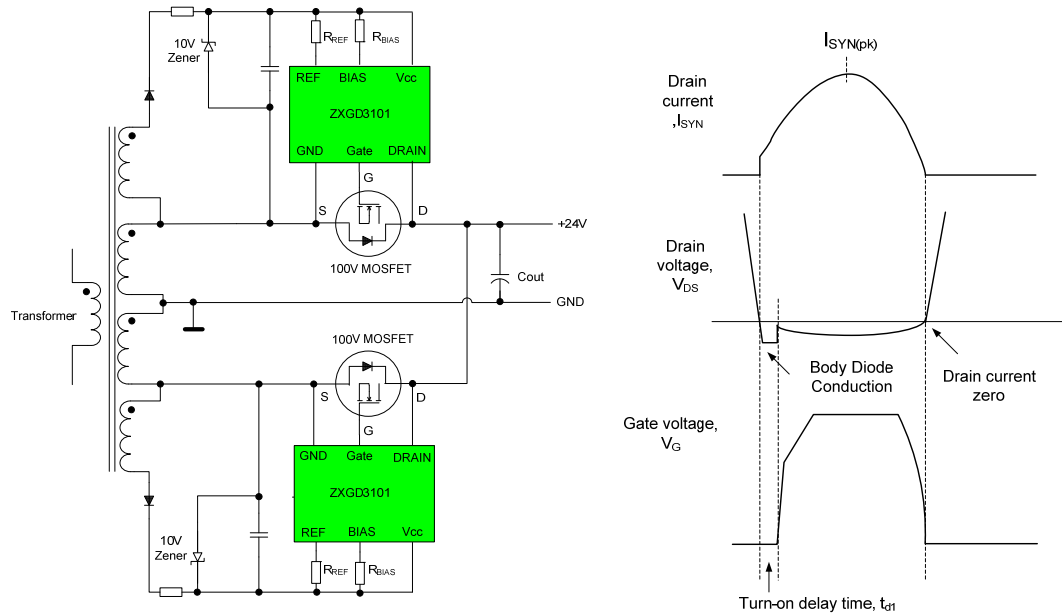


Figure 4 Synchronous rectifications on LLC resonant converter and operating waveforms

It is recommended that the MOSFET on state voltage drop at the peak of the secondary Drain current is equal or less than 100mV. This is to ensure sufficient MOSFET enhancement and to achieve maximum efficiency. Assuming that the LLC resonant tank adequately filters the higher harmonics of the input voltage at full load, the RMS current through the rectifier can be calculated from

$$I_{\text{rms(rect)}} = \frac{\pi}{2\sqrt{2}} \times I_{\text{out}} = 4.44\text{A}$$

From that the I_{rms} through each MOSFET is 2.22A. As the turn on propagation delay t_{d1} of the ZXGD3101 forms a conduction dead band which prevents simultaneous MOSFET conduction, the subsequent body diode conduction loss has been included for loss estimation. The conduction loss in a 100V, $r_{\text{DS(on)}}@T_j=25^\circ\text{C}=16\text{m}\Omega$, $Q_g=82\text{nC}$ MOSFET at 100°C junction temperature is

$$\begin{aligned} P_{\text{cond}} &= I_{\text{rms}}^2 \times r_{\text{DS(on)}}@T_j=100^\circ\text{C} + I_{\text{SYN(min)}} \times V_{\text{SD(body_diode)}} \times t_{d1} \times f_s \\ &= 2.22^2 \times 28.8\text{m}\Omega + 1\text{A} \times 1.2\text{V} \times 525\text{ns} \times 80\text{kHz} = 192\text{mW} \end{aligned}$$

where $I_{\text{SYN(min)}}$ is the MOSFET's current magnitude at the start of the output rectifier conduction cycle. In the example, $I_{\text{SYN(min)}}$ is around 1A at full load. Since the body diode turns on prior to the MOSFET conduction and the synchronous MOSFET switches off at zero current, the switching loss can be ignored in the loss estimation. In other words, the MOSFET drastically reduces the power loss in the semiconductor device from 850mW per diode to 192mW per MOSFET. The resulting junction temperature is 95.4°C at 80°C ambient in a SO-8 footprint. Taking similar extrapolation, 880mW will need to be dissipated from the synchronous MOSFET in a 10A output converter. The MOSFET if in surface mounted TO-263 footprint could still operate reliably with 37.8°C junction temperature rise. This reduces the production cost because manufacturing process reduces two-stage to a one-stage assembly as through hole heat sink is not required.

However, the low resistance MOSFET is high on gate charge Q_g such that the driving losses could become a critical factor for both light load and full load efficiency at high frequency. The summation of controller operating loss and gate driving loss can be estimated through the equation

$$P_{drv} = I_{op} \times V_{gs} + f_s \times V_{gs} \times Q_g$$

$$= 5.5mA \times 10V + 80kHz \times 10V \times 82nC = 120mW$$

Where I_{op} is the current consumed by the REF and BIAS pin when the controller drives synchronous MOSFET at 50% duty cycle. This loss also reduces the efficiency saving made by the MOSFET low resistance.

Figure 5 compares the efficiency of Schottky diode solution with one that uses 100V 16mΩ MOSFET. The curves show that synchronous rectification improves the conversion efficiency above 25% of the peak loading and the MOSFET solution is more than 1% more efficient at full load. At no load condition, the resonant LLC converter is 4% more efficiency with Schottky rectification.

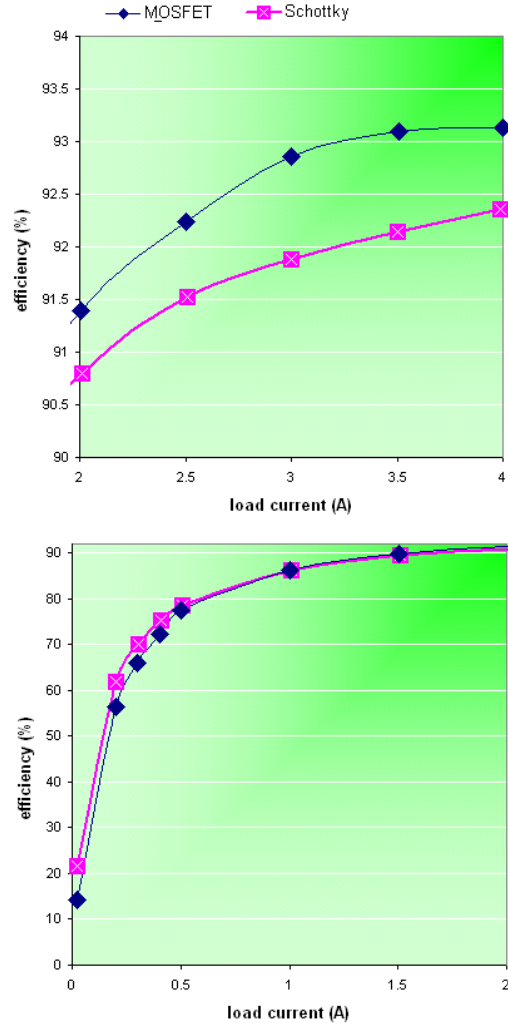
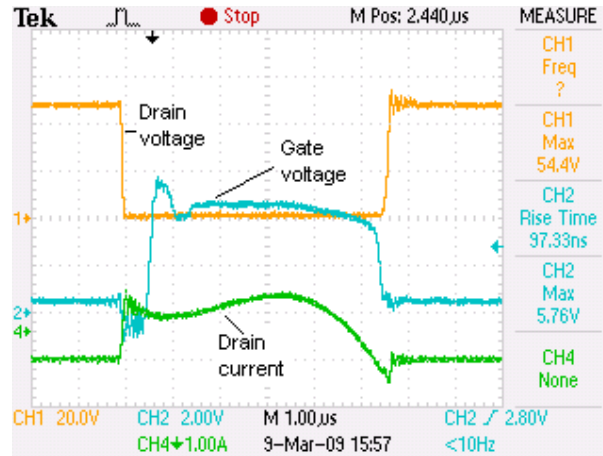


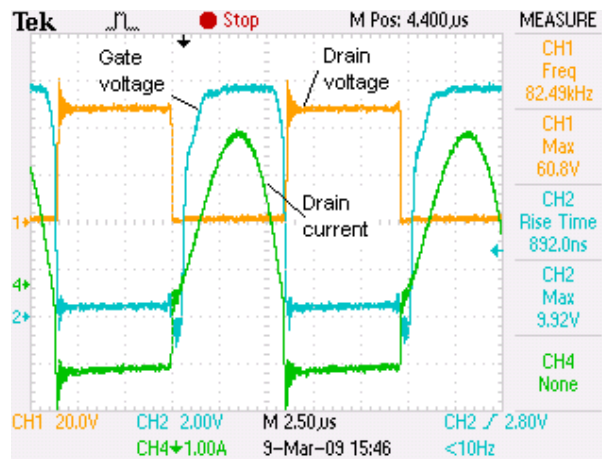
Figure 5 Efficiency comparison between Schottky and MOSFET solution

This is caused by the accumulation of losses associated with the synchronous MOSFET gate charge loss, quiescent power consumption of the ZXGD3101 itself. Although the intrinsic body diode of the MOSFET has to conduct the full rectifier current during the turn on delay, its detrimental effect on the efficiency is low because the rectifier current is normally sinusoidal in shape. The effect will be more prominent at high switching frequency above 200kHz.

Figure 6(a) and (b) shows the actual operating waveforms of the synchronous MOSFET. The Gate voltage was approximately 10V for a sustained period when the MOSFET current was high to achieve low resistance. When the Drain current is low, the Gate voltage then backed off to reduce the effective gate charge so the MOSFET can be turned off quickly at the current zero crossing point.



(a)



(b)

Figure 6 Operating waveforms at (a) 25% load and (b) full load condition

Conclusion

Synchronous MOSFETs will become an essential building block on the secondary side of the high power resonant converter for designing efficient power supplies as motivated by emerging environmental legislation as well as the need for slimmer form factor end product. When used in conjunction with the ZXGD3101 controller, the system offers a higher efficiency than Schottky or standard diodes. This design document describes a built and tested, resonant LLC converter with synchronous rectifier suitable for use in power supply of LCD TV with display screen size below 32 inches. A significant power saving can be achieved with the elaborate scheme especially for high current output converter, MOSFET will generate less heat and surface mounted MOSFET can be used instead of through hole component. This increases power density and reduces assembly cost.

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