AN54

Energy Star® V2.0 compliant flyback converter using the ZXGD3101 synchronous MOSFET controller

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Introduction

Several regulatory bodies around the world address efficiency issues in External Power Supply (EPS) and drive to reduce energy consumption in the compliant adaptors. One example of these is the Energy Star® V2.0 which comes into force in November 2008. The standard targets both the issues of active mode efficiency as well as no load power consumption as shown in Tables 1 and 2. This application note addresses the challenge of complying with the voluntary standard in a flyback converter typically employed as EPS below 100W output power. In particular, the paper discusses the efficiency improvement with the aid of the ZXGD3101 synchronous MOSFET controller and studies its practical limit against normal rectification method. Finally, experimental verification is presented to demonstrate efficiency improvement in a universal input 60W (19V 3.2A) flyback adapter.

Table 1 - active mode efficiency requirement for Energy Star® V2.0

Nameplate Output Power (P_{no})	Minimum Average Efficiency in Active Mode
0 to ≤ 1 watt	$\geq 0.495 * P_{no} + 0.143$
> 1 to ≤ 49 watts	$\geq [0.06 * \text{Ln}(P_{no})] + 0.638$
> 49 watts	≥ 0.870

Table 2 - no-load energy consumption criteria (from November 2008)

Nameplate Output Power (P_{no})	Maximum Power in No-Load	
	AC-AC EPS	AC-DC EPS
0 to < 50 watts	≤ 0.5 watts	≤ 0.3 watts
≥ 50 to ≤ 250 watts	≤ 0.5 watts	≤ 0.5 watts

Synchronous MOSFET controller improves flyback adapter's active mode efficiency

In general, flyback converters working as either the direct universal AC/DC conversion or the DC/DC conversion following the front end PFC stage are economical and practical in a wide range of typical offline applications with output power below 150W. This is because the power component count is minimal and the PWM control scheme is the simplest among all other topologies. Moreover, their critical parts including the power transformer, the primary switch, the input bulk capacitor, the output rectifier, the output capacitor and the heat sinks are optimal in terms of both size and cost.

For an output power up to about 100W for high voltage and low to medium current output operations, Discontinuous Conduction Mode (DCM) and Critical Conduction Mode (CrCM) is the preferred method, due to the absence of primary switch turn-on loss. Furthermore, the DCM transformer size can be reduced owing to the lower average energy storage while its smaller magnetizing inductance yields a better transient line/load response. Alternatively, the continuous conduction mode (CCM) operation offers a higher efficiency due to the lower primary and secondary peak/RMS currents at the expense of a bigger transformer. Critically, much of a flyback adapter's inefficiency is caused by the Schottky or ultra-fast recovery diode used on the secondary side.

Replacing the output diode in Figure 1 with a more efficient MOSFET is recognized as a clear means of drastically improving efficiency to meet the voluntary energy standard and removing the need for bulky heat sinks and reducing the size and weight of power adapters.

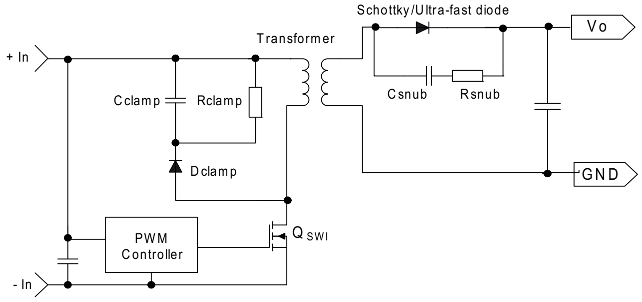

Figure 1 - Flyback converter with diode rectification

The ZXGD3101 synchronous MOSFET controller was introduced to drive MOSFET in such a way that it can emulate performance of an ideal diode. It integrates a high voltage differential amplifier stage and a high current driver into the compact SM8 chip package.

Figure 2 shows the new gate driving circuit on a single DC output flyback adapter in low-side rectification for the ease of deriving V_{cc} supply from the converter's output. The ZXGD3101 monitors the reverse Drain-Source voltage of the Q_{SYN} and when conduction occurs in the body-diode, it applies a positive voltage to its gate control pin, turning the MOSFET on. The gate drive voltage is then proportional to the Drain-Source reverse voltage, ensuring rapid turn-off as MOSFET 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 ZXGD3101 is very simple to implement.

The primary side power stage uses fixed frequency current mode controller U2 to drive primary switch Q_{SWI} in CrCM and reduces turn-on switching loss through ZVS of Q_{SWI} at high line condition. For efficient flyback design, the primary switch works in CCM at low line condition to take advantage of the lower primary and secondary peak/RMS currents. A RCD clamp network is added across the transformer primary to dampen high frequency resonance ringing and to ensure integrity of differential voltage across the output of synchronous MOSFET.

The R_{snub}, C_{snub} network across the synchronous switch provides filtering to clean high frequency oscillations during MOSFET turn-off transition. If the amplitude of oscillations is high then the drain voltage could ring below the controller's turn-on threshold voltage, inducing the controller to false-triggers. The snubber network has the added benefits of reducing conducted EMI generation and Q_{syn} voltage stress. In Figure 2, a 50Ω resistor is suggested alongside a 1nF capacitor for sufficient damping .

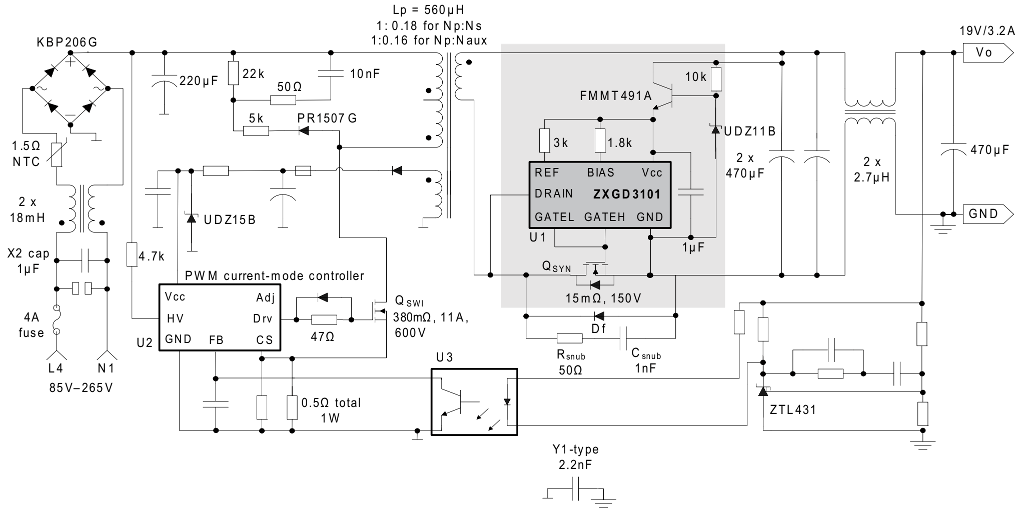

Figure 2 - Typical configuration of ZXGD3101 in a 60W flyback schematic

Design considerations

In order to drive the synchronous MOSFET properly and improve the efficiency of the flyback adapters, some important aspects must be considered such as power MOSFET selection, turn off threshold and delay as well as the power consumption.

1. Power MOSFET selection

A selection guide for the synchronous MOSFET in Figure 2, in particular a 19V 3.2A output adapter operating in CrCM at high line is hereby presented. Specifications of the converter are given in Table 3. Although the MOSFET current calculation in different operating mode can be slightly different, the example below can be easily extended to cater for all operating modes. The values in the equation are conservative.

Table 3 - example flyback converter specification

DC link (min), V_{DCmin}	**DC link (max), V_{DCmax}**	**Duty ratio (max), D_{max}**	**Transformer turn-ratio, N**	**Primary inductance, L_m**	**Frequency f_s**
110V	375V	0.5	1:0.18	560?H	60kHz

The first step is to determine the MOSFET maximum reverse voltage,

$$V_{DS} = V_{out} + \frac{V_{DCmax} \times (V_{out} + V_f)}{V_{RO}} = 19V + \frac{375V \times (19V + 0.8V)}{110V} = 86.5V$$

where V_{RO} is the transformer's secondary voltage reflected to the primary side

$$V_{RO} = V_{DCmin} \times \frac{D_{max}}{1 - D_{max}} = 110V \times \frac{0.5}{1 - 0.5} = 110V$$

Allowing typical voltage margin for the MOSFET the maximum reverse voltage is as follows,

$V_{DSS} = 1.3 \times V_{DS} = 112.5V$ which implies that at least 120V or a common 150V MOSFET should be chosen.

From the power dissipation point of view the most stringent operating condition for the synchronous MOSFET is encountered at low line. Since the body diode conducts prior to the Q_{SYN} turning on and it is being driven off at the zero current point, the switching loss is minimal and the overall power dissipated is dominated by on state conduction loss.

The maximum rectifier current can be calculated from,

$$I_{SYN(pk)} = \frac{2 \times I_{out}}{1 - D_{max}} = 2 \times \frac{3.2}{1 - 0.5} = 12.8A$$

Noting that the turn on propagation delay td1 of the ZXGD3101 forms the MOSFET dead time which prevents simultaneous conduction, the subsequent MOSFET body diode conduction loss has been included for efficiency estimation. Accounting for the inefficiency of body diode forward voltage drop, total conduction loss in Q_{SYN} at 100°C junction temperature can be estimated from,

$$\text{Ploss} = \underbrace{\left(I_{SYN(pk)} - \frac{N \times V_{RO} \times t_{d1}}{L_m}\right)^2 \times \left(\frac{1 - D_{max} - t_{d1} \times f_s}{3}\right) \times r_{DS(on)@T_j=100^oC}}_{\Downarrow \atop \text{MOSFET loss}} + \underbrace{I_{SYN(pk)} \times V_{SD(body-diode)} \times t_{d1} \times f_s}_{\Downarrow \atop \text{Body diode loss}}$$

$$= \left(12.8A - \frac{5.6 \times 110V \times 525ns}{560\,\mu H}\right)^2 \times \left(\frac{1 - 0.5 - 0.0315}{3}\right) \times r_{DS(on)@T_j=100^oC} + 12.8A \times 1.25V \times 0.0315$$

$$= 23.33 \times r_{DS(on)@T_j=120^oC} + 0.504W$$

The typical forward voltage drop of a 150V ultra fast diode at elevated temperature is around 800mV. The power dissipated in normal diode rectification equates to,

$$P_{diode} = I_{out} \times V_f = 3.2A \times 800mV = 2.56W$$

In order to achieve at least 50% power loss reduction in the secondary side switch through synchronous rectification, the required on state resistance has to be,

$$r_{DS(on)@T_j=100^oC} \leq \frac{50\% \times P_{diode} - 0.504W}{23.33} = \frac{50\% \times 2.56W - 0.504W}{23.33} \leq 33.26m\Omega$$

As on resistance at 25°C is approximately 1.8 to 2 times lower than that at 100°C, use a MOSFET with $r_{DS(on)@Tj=25^\circ C} = 15m\Omega$ to achieve the desired power loss reduction against normal rectification method. For adapter with high continuous output current, selecting a MOSFET or paralleled MOSFETs with lower combined resistance yields better efficiency enhancement at the expense of increased cost or component count.

Power supply designers interested in squeezing the last percentage of efficiency out of their system could place an optional Schottky or ultra-fast recovery diode Df across synchronous MOSET (see Figure 1) to alleviate the effect of body diode conduction. As shown in Figure 3(b), Df conducts during the MOSFET dead time where the secondary circulating is at the highest, so the PCB trace inductance between the diode and MOSFET should be kept small to create an efficient circulating energy flow path. Df should be selected to have the same breakdown voltage as the MOSFET but the average diode current is only 400mA, hence the ES3C can be used in the 19V 3.2A output converter.

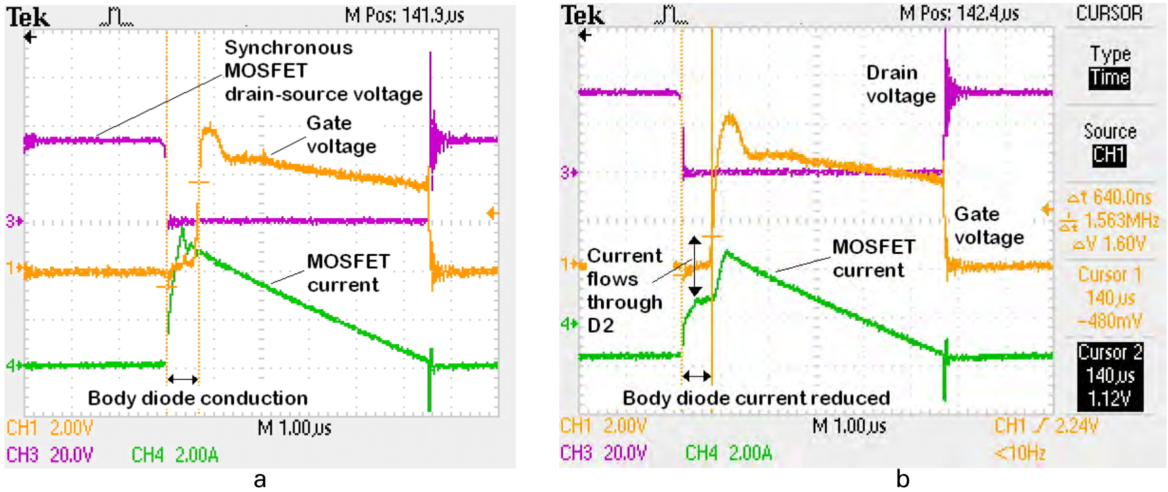

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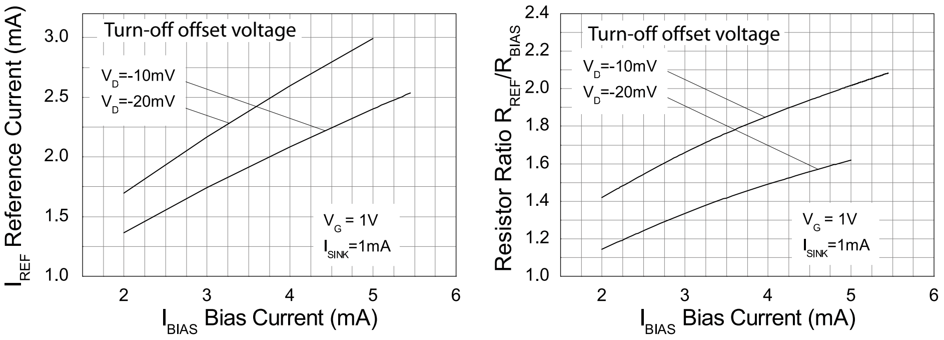
Figure 3 Operating waveforms of synchronous rectification (a) ZXGD3101 with turn on propagation delay (b) ultra-fast diode Df to reduce body diode conduction loss

2. Synchronous MOSFET controller turn-off phase and threshold

The ZXGD3101 can work in both continuous and discontinuous operation. The turn-off phase of the synchronous MOSFET controller is different depending on the mode of operation. In DCM and CrCM, the MOSFET current decays linearly and the ZXGD3101 backs off its gate drive output proportionately when the MOSFET voltage drop is less than -50mV, gradually reducing the capacitive charge that need to be extracted from the gate at turn-off. Upon the conduction voltage drop crossing the controller turn-off threshold, the gate voltage is removed rapidly to inhibit reverse current flow through the MOSFET.

There are two recommended turn-off threshold settings, which are '-10mV' and '-20mV'. The '-10mV' threshold is recommended for DCM to ensure sustained enhancement of a low resistance MOSFET, whilst the '-20mV' threshold is appropriate for high average current, low ripple current level converter in CCM. These thresholds depend on I_{BIAS} and I_{REF} level as shown in Fig. 4 and therefore are set by the value of R_{BIAS} and R_{REF}.

Datasheet and component selection for ZXGD3101 are available from the Zetex website.



Bias Current vs Reference Current **Bias Resistor vs Reference Resistor**

Figure 4 - Turn off threshold voltage

The transformer secondary circulating current in a CCM flyback converter (see Figure 5) doesn't decay to zero before the primary MOSFET is switched back on at the beginning of the switching period. As the primary MOSFET is gated on, the primary switch current starts to rise when the voltage reached the gate turn-on threshold and the synchronous MOSFET current is pulled down rapidly. This forces the drain-source voltage to drop beyond the synchronous MOSFET controller's turn-off threshold and the MOSFET is then turned off.

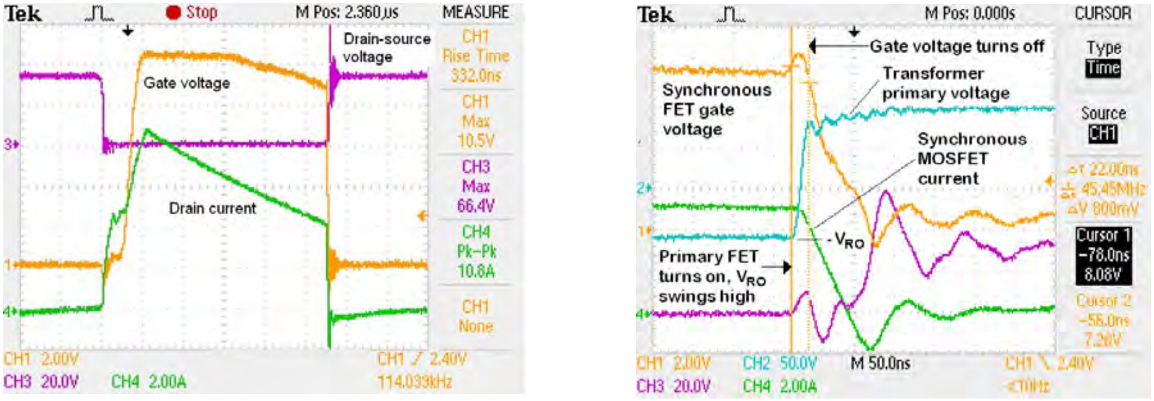


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Figure 5 - CCM operation (a) MOSFET current and voltage waveforms (b) Fast turn-off

The turn-off phase propagation delay and fall time on the ZXGD3101 have typical values of 15ns and 20ns respectively and excessive dissipation due to simultaneous conduction of MOSFETs can be avoided. This is critical because cross conduction will degrade efficiency or can lead to device failure due to the nature of the fast transition. To further minimize the possibility of cross conduction, the turn off threshold can be configured to be '-20mV' so that the MOSFET can be gated off sooner at the expense of less effective MOSFET enhancement at low load condition.

3. Synchronous MOSFET controller power consumption

In practice, the synchronous rectification scheme involves active devices which consume power. The synchronous MOSFET controller's operating current will vary over the entire load current range as shown in Figure 6. At high load, ZXGD3101 current consumption is at the highest because it has to provide a high source current into the MOSFET gate for fast turn on and to support low 'on-state' voltage drop. A lower operating current is needed as the load decreases corresponding to the reduction in the synchronous MOSFET current as well as conduction period. The primary side controller enters skip-mode operation at no load for reduced power dissipation, the synchronous MOSFET controller operating current drops to around 8mA.

As shown in Figure 2, power into the ZXGD3101 configured in the low side synchronous rectification can be derived directly from the output of power supply. An emitter follower transistor as the voltage source should be used to derive the Vcc supply from the regulated output voltage. Through this, the no-load energy consumption criteria in Energy Star® V2.0 can be fulfilled with the recommended implementation. Nevertheless, this minor power loss is offset by the significant active mode conduction loss savings offered by the synchronous rectification.

Alternatively, a dedicated supply could be drawn through an auxiliary flyback transformer winding or through a voltage tap on the main transformer winding. However, a simple Zener diode with a series current limiting resistor is not recommended as this incurs undesirable power dissipation within the Zener diode which will compromise the no-load efficiency.

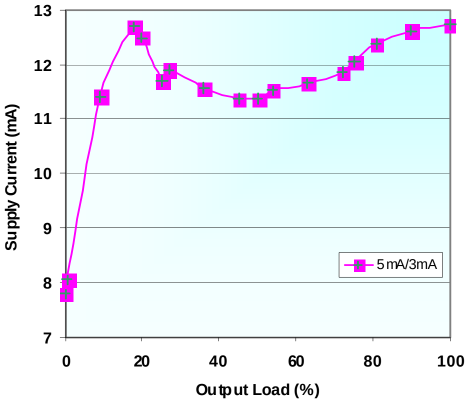

Figure 6 - ZXGD3101 operating current

System efficiency test

Figure 7 shows the efficiency of synchronous rectification using the ZXGD3101 in the 60W flyback adapter. A small 150V diode was mounted in parallel to a 15mΩ MOSFET to keep low the voltage drop during dead time. The operation condition is in CCM at low line and high load. The curve shows that synchronous rectification with the ZXGD3101 can achieve substantial efficiency improvement compared with standard (ultra-fast diode) rectification at output currents above 1A. The diode test is performed using STPR1020CT.

At output current below 1A, the accumulation of losses associated with body diode conduction, synchronous MOSFET gate charge loss alongside with increased capacitive turn-on loss in the primary switch offset the conduction loss saving provided by synchronous rectification. For completeness, performance curves at high line are presented in Fig. 8.

The efficiency data with output loading at 25%, 50%, 75% and 100% for 115Vac and 230Vac are shown in Table 4. Note that the average efficiency for both ranges meets the Energy Star® V2.0 program minimum requirement of 87% at this particular power level. With ultra-fast diode rectification, the average active mode efficiency of the adaptor is actually 85.85% and 84.939% at 115Vac and 230Vac respectively. In the 230Vac input case the efficiency degradation occurs at light loading due to increased circuit quiescent power, mainly due to higher MOSFET switching losses at this input level. For completeness, Table 5 presents the no-load supply power. The input power at zero load is always below 500mW.

Another major benefit of switching to a synchronous MOSFET is the reduction in device temperature which has a big impact on the power supply reliability. This can be clearly seen from the thermal images taken using Infra-Red camera during the power supply evaluation shown in Figure 9 where a 28.5°C reduction in adapter temperature is recorded. Both results are taken at 115Vac under full load condition

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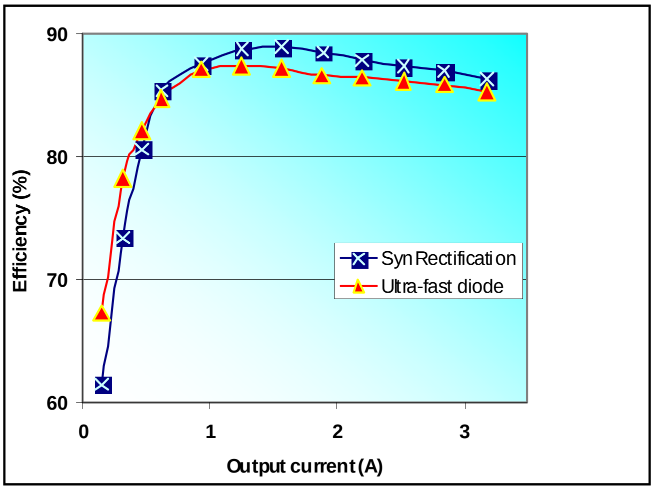

Figure 7 - Efficiency comparison at 115Vac

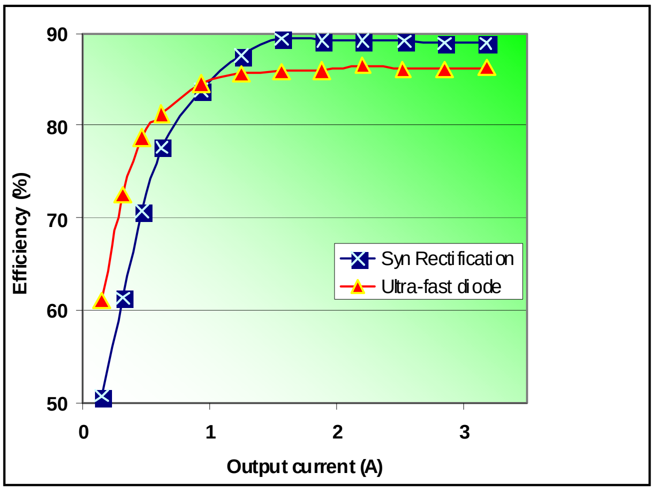

Figure 8 - Efficiency comparison at 230Vac

Table 4 - Active mode efficiency of low flyback adapter with Synchronous Rectification

Vin (Vac)	Pin (W)	Vout (Vdc)	Iout (Adc)	Pout (W)	Pout (%)	Eff (%)
115	17.32	19.24	0.779	15	25	86.39
115	33.77	19.13	1.568	30	50	88.82
115	51.42	19.08	2.363	45	75	87.68
115	69.52	19.04	3.151	60	100	86.31
Average Eff (%)						87.30
Vin (Vac)	Pin (W)	Vout (Vdc)	Iout (Adc)	Pout (W)	Pout (%)	Eff (%)
230	18.47	19.24	0.779	15	25	81.21
230	33.58	19.14	1.567	30	50	89.34
230	50.45	19.10	2.356	45	75	89.20
230	67.49	19.02	3.155	60	100	88.90
Average Eff (%)						87.16

Table 5 - No-load energy consumption

Vin (Vac)	Pin (W)
115	0.35
230	0.45

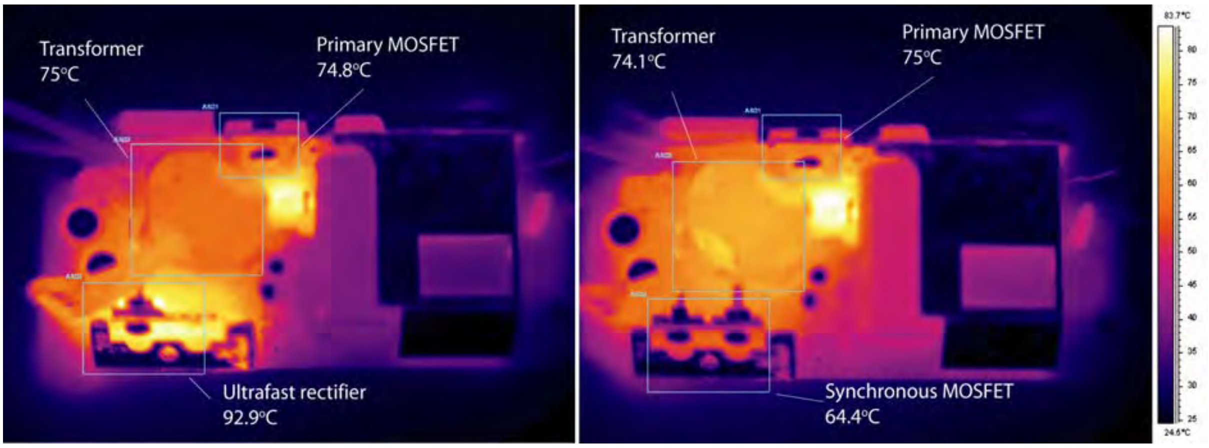

Figure 9 - Thermal comparison: ultra-fast diode vs. synchronous MOSFET

Conclusion

When a normal, ultrafast diode rectifier is substituted with a low resistance synchronous MOSFET it is possible to achieve the standards set out by Energy Star® V2.0. Using the ZXGD3101 to control and drive the synchronous MOSFET provides efficient conduction path with optimized delay in sensing the sharp drop of current during the turn-off phase ensuring no reverse conduction. The gate driving scheme combined with properly designed magnetic and power stage minimizes circuit losses while the power supply is in active mode and ensures the no-load conditions are satisfied.

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