AN-9725

Robust Body Diode Characteristics of the Latest Power MOSFETs, UniFET™ II for Resonant Converters

Introduction

Resonant converters are one of the most exciting power supply topologies. These converters are popular for many applications because the performance increases power efficiency, minimizes components count, and reduces Electromagnetic Interference (EMI) over older power supply topologies. Soft switching is the representative feature of resonant converters.[1][2] However, use of the body diode in resonant converters sometimes leads to system failures. The stored charge in the body diode should be completely removed to avoid high current and voltage spikes, including high dv/dt and di/dt, in these topologies. Therefore, critical parameters of power MOSFETs; such as $C_{oss(er)}$, Q_{rr}, and reverse-recovery dv/dt; directly affect dynamic performance of resonant converters A new power MOSFET, called UniFET™ II, is optimized for resonant converters. It provides better reliability and higher efficiency in resonant converters.

Resonant Converters Reliability

Several topologies of DC-DC converters for server and telecom power supplies have been introduced to reduce switching losses, device stresses on the power MOSFETs, and Radio Frequency Interference (RFI) while achieving high power density. Resonant converters that utilize the body diode of MOSFETs for Zero-Voltage Switching (ZVS) are very suitable for these applications. Specifically, the phase-shifted ZVS full-bridge converters have been widely accepted for high-end power supplies since they allow all switches to operate at ZVS by effective C_{OSS} of power MOSFETs and leakage inductance of transformer without an additional auxiliary switch. However, ZVS range is very narrow and the freewheeling current consumes high circulating energy. In the late 1990s, power MOSFET failures were reported in the phase-shifted ZVS full-bridge topology. One cause of failure is slow reverse recovery of the body diode by low reverse voltage. The other failure is due to the $C_{dv/dt}$ shoot-through at no-load or light-load conditions.[3][4] This kind of failure does not occur in LLC resonant converters because LLC resonant converters can guarantee ZVS operation, even at no load.

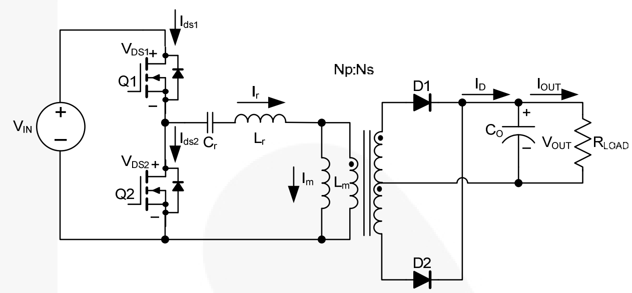

Figure 1. LLC Resonant Converter

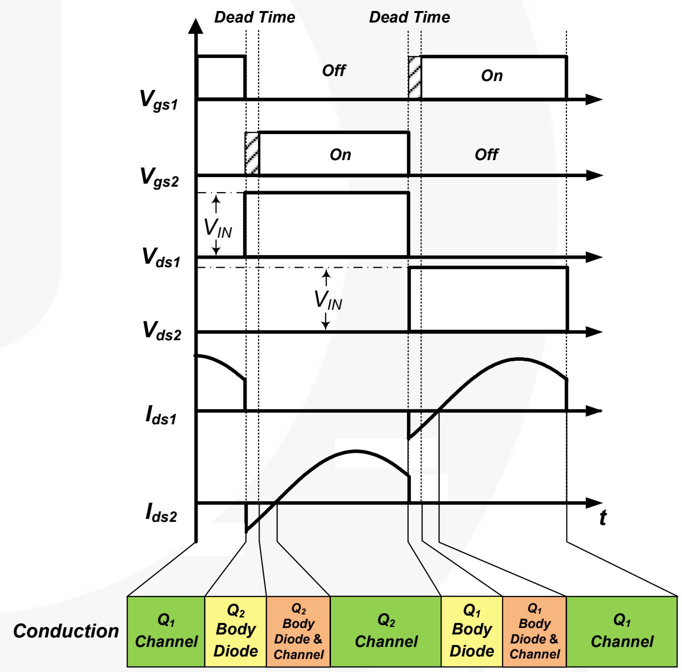

Figure 2. Zero Voltage Switching in Resonant Converter

LLC resonant converters can achieve high efficiency at high input voltage with low voltage stress on the secondary rectifier since there is no inductor on the secondary. Due to of these unique characteristics, LLC resonant converters are becoming a popular topology for many applications, especially server and telecom power supplies and low-profile flat-panel display TV power supplies. A block diagram of an LLC resonant converter is shown in Figure 1. Figure 2 shows typical waveforms of its zero voltage switching. Conduction periods of Q1 and Q2 should not overlap to guarantee proper operation of the converter. A dead time must be introduced to prevent simultaneous conduction of the MOSFETs. As shown in Figure 3, during this delay time, current flows through the body diode of the each MOSFET to guarantee ZVS operation. ZVS is achieved with magnetizing current, which is not related to load current, so ZVS can be realized even with zero load. The voltage across the MOSFET is the forward-voltage of the body diode, which can be negligible. When the other MOSFET turns on, the body diode naturally turns off, resulting in no reverse-recovery losses. Therefore, a fast-recovery MOSFET is not necessary in normal ZVS operation. However, MOSFET failures in LLC resonant converters are associated with shoot-through current due to the poor reverse-recovery characteristics of the body diode at startup. Figure 3 shows the first five switching waveforms of the power MOSFET at startup. Just before startup of the converter, resonant capacitance and output capacitance are completely discharged. These empty capacitances cause further conduction of the body diode of the low-side MOSFET during startup, compared to normal operation conditions. As a result, the reverse-recovery current that flows through body diode of the low-side MOSFET is much higher and is enough to create shoot-through problems when the high-side MOSFET is turned on.[5]

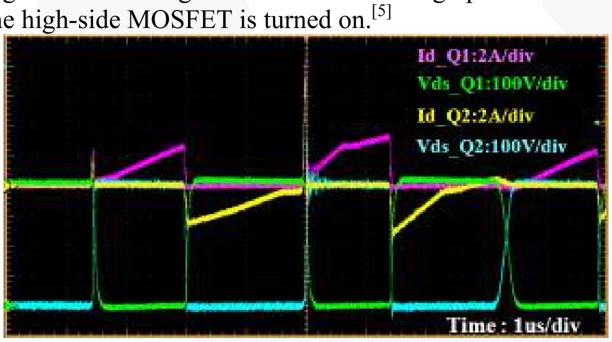

Figure 3. Waveforms of Power MOSFETs at Startup

Another field failure was revealed at specific conditions, such as overload or short-circuit condition in the LLC resonant converter.[6] Even though the voltage and current of power MOSFETs are within safe operating range, some unexpected failures associated with shoot-through current, reverse recovery dv/dt, and breakdown dv/dt occur in conditions such as overload and output-short circuit. Figure 4 shows how an operating point moves during overload and short-circuit condition. As shown in Figure 4, DC gain characteristics of an LLC resonant converter is classified into three regions according to different operating frequency and load condition. The right-side (blue box) of resonant frequency, Fr1, is the ZVS region. The left-side (red box) is minimum second resonant frequency, Fr2, at no load, which is ZCS region. The region between Fr1 and Fr2 can be either ZVS or ZCS region, according to load condition. The converter operates with ZVS in normal operation, but the operating point moves to the ZCS region under overload or short-circuit condition and the characteristics of a series resonant converter become dominant. During overload or short-circuit condition, the switch current is increased and ZVS is lost. L_m is fully shorted by a reflected load, R_{LOAD}, at overload condition. This condition usually results in ZCS operation. The most severe drawback of ZCS operation (below resonance) is that hard switching at turn-on leads to the diode reverse-recovery stress. Furthermore, switching loss increases at turn-on and noise or EMI is generated. The diode turns off at a very large dv/dt and, therefore; at a very large di/dt, generates a high reverse-recovery current spike. These spikes can be over ten times higher than the magnitude of the steady-state switch current. This high current causes considerable increase in losses and heats up the MOSFET. Then an increase in junction temperature degrades dv/dt capability of MOSFET. In extreme cases, it may destroy the MOSFET and cause system failure. In specific applications, load conditions are suddenly changed from no load to overload and more rugged operating is required for system reliability.[7][8]

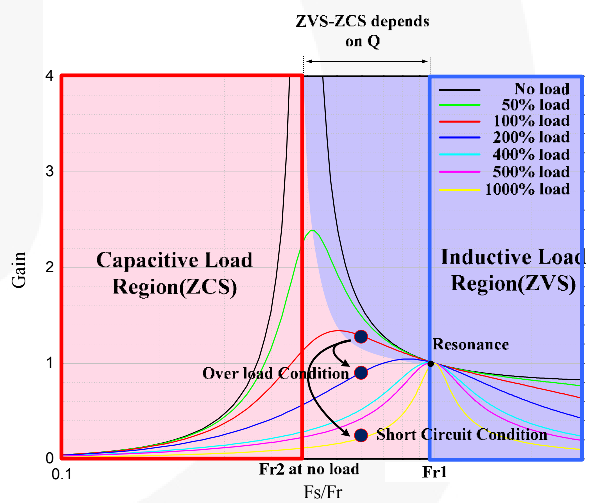

Figure 4. Operating Points of LLC Resonant Converter According to Load Condition

The worst case is a short-circuit condition. During short circuit, the MOSFET conducts extremely high (theoretically unlimited) current and frequency is reduced. When short circuit occurs, L_m is shunted in resonance. The LLC resonant converter can be simplified as a series resonant tank by C_r and L_r because C_r resonates with only L_r. Operation mode during short circuit is almost the same as in overload condition, but short-circuit condition is worse because reverse-recovery current, which flows through the body diode of the switch, is much higher. Figure 5 shows the switching waveforms of the power MOSFETs at short-circuit condition. Waveforms during short-circuit are similar to those during overload condition, but the higher current level during short-circuit condition can lead to increased junction temperature of MOSFET and increased likelihood of failure.

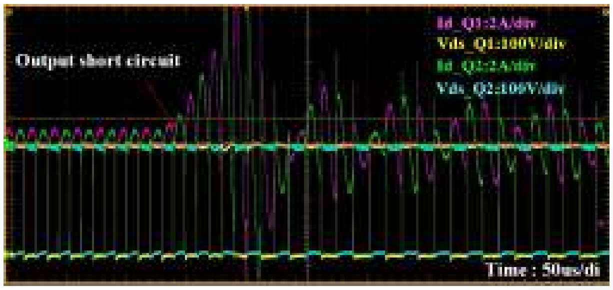

Figure 5. Waveforms of Power MOSFETs at Short-Circuit Condition

MOSFET Failure Mechanism

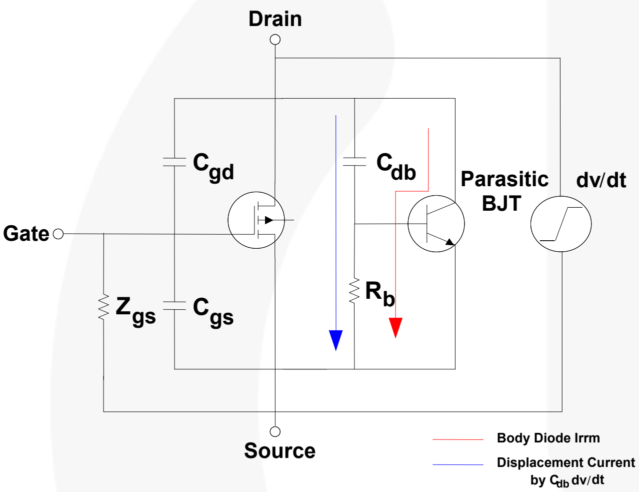

Figure 6. MOSFET Equivalent Circuit

As shown in Figure 6, there is a small resistance described as R_b. Basically, base and emitter of parasitic Bipolar Junction Transistor (BJT) are shorted together by source metal. Therefore, the parasitic BJT should not be activated. In practice, however, the small resistance works as base resistance. When large current flows through R_b, a voltage across R_b that acts as base-emitter forward bias becomes high enough to trigger the parasitic BJT. Once the parasitic BJT turns on, a hot spot is formed and more current crowds into it due to negative temperature coefficient of the BJT. Finally, the device fails.

Another failure mode is breakdown dv/dt. It is a combination of breakdown and static dv/dt: the device undergoes avalanche current and displacement current at same time. In the case of extremely fast transition, drain-source voltage may exceed maximum rating of a device during the body diode reverse-recovery process. If the MOSFET enters breakdown mode due to high-voltage spikes, commutating current flows through P-N junction. It is exactly the same mechanism as avalanche breakdown. In addition to this process, high dv/dt affects the failure point of the device. More displacement current is built up with greater dv/dt. The displacement current is added to avalanche current and the device becomes more vulnerable to failure. Basically, the root cause of failure is parasitic BJT turn-on due to high current and temperature. However, the primary cause is body diode reverse recovery or breakdown. In practice, these two failure modes occur randomly and sometimes in combination.

UniFET™ II MOSFET Technology

Figure 7. UniFET™ II MOSFET Technology Overview

The body diode of power MOSFETs has a very long reverse-recovery time and large reverse-recovery charge. In spite of its poor performance, the body diode has been utilized as a freewheeling diode because it simplifies the circuit without adding system cost in applications such as resonant converters. As more and more applications use an intrinsic body diode as the critical component in the system, body diode characteristics have been developed. Fast-recovery MOSFET is good choice for reliability on resonant converters, but there are drawbacks. More lifetime control results in further increase of MOSFET on resistance. This adds conduction loss and is critical to the resonant converter. Another negative effect is the increase of drain-source leakage current. Manufacturing cost increases due to additional process for life-time control. For better body diode performance, Fairchild designed a highly optimized power MOSFET, called UniFET™ II MOSFET, for resonant converters with deep analysis of MOSFET failure mechanisms. It has improved body diode ruggedness and output stored energy in C_{OSS}, while minimizing negative effects. Its peak reverse-recovery current has been reduced to the level that does not cause device failure without increasing on-resistance. It can withstand more than double the current stress during breakdown dv/dt mode. As shown in Figure 8, the reverse-recovery charge of UniFET™ II MOSFET is reduced by 50%; 88% when compared to competitor parts.

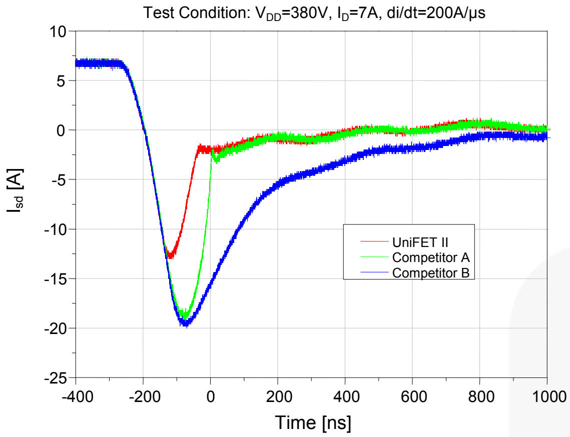

Figure 8. Measured Body Diode Reverse-Recovery Waveforms Showing UniFET™ II Low Q_{rr}, t_{rr}, and I_{rrm} Relative to Competitor Devices

Table 1. Critical Specification Comparison of DUTs

DUTs	$R_{DS(on)}$ Max.	BVD_{SS}	I_D	Q_g	T_{rr}	Q_{rr}
UniFET™ II	0.85	500V	8.0A	18nC	160ns	1.2μC
Competitor A	0.85	500V	7.2A	32nC	238ns	2.5μC
Competitor B	0.80	500V	8.0A	45nC	1200ns	10.0μC

MOSFET capacitance is nonlinear and depends on the drain-source voltage since its capacitance is essentially a junction capacitance. In soft-switching applications, MOSFET output capacitance can be used as a resonant component. When the MOSFET is turned on, the current extracted from the magnetizing energy stored in the transformer flows to discharge the MOSFET output capacitance to allow ZVS condition. Therefore, if the stored energy in output capacitance of MOSFET is small, less resonant energy required to achieve soft switching without increasing the circulating energy. The UniFET™ II MOSFET has approximately 35% less stored energy in output capacitance than the same on-resistance of competitor devices for typical switching power supply bulk capacitor voltage. The benchmark of stored energy in output capacitance is shown in Figure 9.

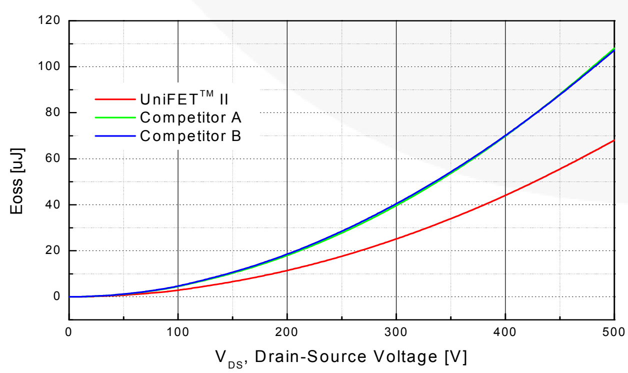

Figure 9. Stored Energy in Output Capacitance

The switching process of the diode from on state to reverse blocking state is called reverse recovery. First, the body diode is forward-conducted for a while. During this period, charges are stored in the P-N junction of the diode. When reverse-voltage is applied across the diode, stored charge should be removed to go back to blocking state. The removal of the stored charge occurs via two phenomena: the flow of a large reverse current and recombination. A large reverse-recovery current occurs in the diode during the process. This reverse-recovery current flows through the body diode of MOSFET because the channel is already closed. Some of reverse-recovery current flows right underneath the N+ source. Figure 10 shows MOSFET failing waveforms during body diode reverse recovery. With competitor A, failure occurs right after the current level reaches I_{rrm}, peak reverse recovery current at 6.87V/ns. This indicates the peak current triggered parasitic BJT. As shown in Figure 11, the UniFET™ II did not fail at even higher dv/dt (14.32V/ns) and di/dt(2,850A/us) conditions.

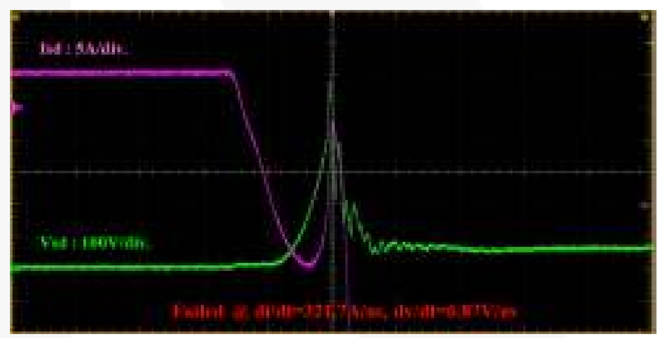

Figure 10. Competitor A MOSFET Failing Waveforms During Body Diode Reverse Recovery

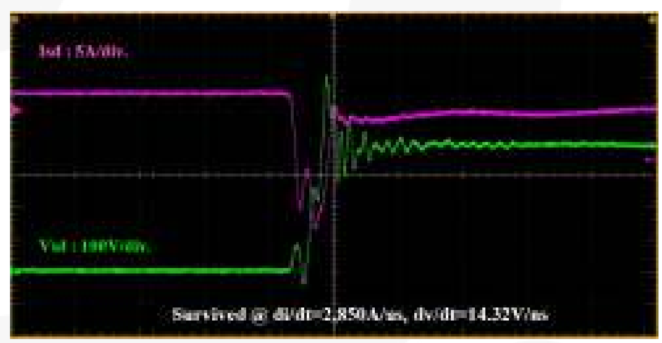

Figure 11. UniFET™ II MOSFET Withstanding Waveforms During Body Diode Reverse Recovery

Application Benefits

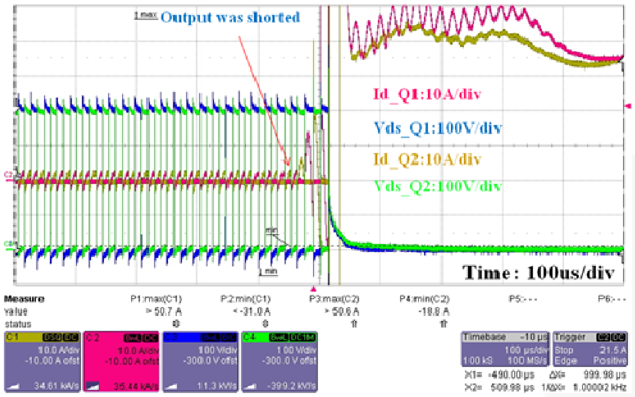

Figure 12. Waveforms of Competitor A Under Short-Circuit Condition

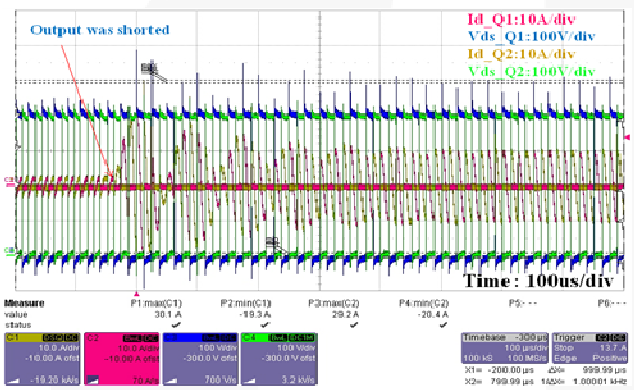

Figure 13. Waveforms of UniFET™ II Under Short-Circuit Condition

Figure 12 and Figure 13 present waveforms comparing reverse-recovery characteristics at short circuit between the competitive device and the UniFET™ II MOSFET. Operation mode is changed from ZVS to ZCS after the output short. A peak drain-source voltage of the competitor exceeded rated voltage (500V) and the current spike is several tens of ampere current due to large Q_{rr}. The MOSFET to be switched on carries reverse-recovery current of the other MOSFET. The current spike of UniFET™ II MOSFET is relatively lower due to much smaller Q_{rr} on ZCS operation during output short and the device did not fail.

The other failure case occurs during startup. Figure 14 and Figure 15 present key waveforms comparing reverse-recovery characteristics at startup between the competitor MOSFET and UniFET™ II MOSFET. With the competitor MOSFET, a high level of shoot-through current, exceeding 27.6A, is induced due to higher I_{rm} of body diode. It triggered a protection function of control IC. A low peak current spike occurred in the UniFET™ II MOSFET. These negative behaviors of the MOSFET may result in device failure as mentioned; reverse recovery dv/dt and breakdown dv/dt. The UniFET™ II MOSFET can effectively minimize shoot-through current, peak drain-source voltage, and reverse recovery dv/dt; which are potential causes of failure at startup, overload, and short-circuit conditions.

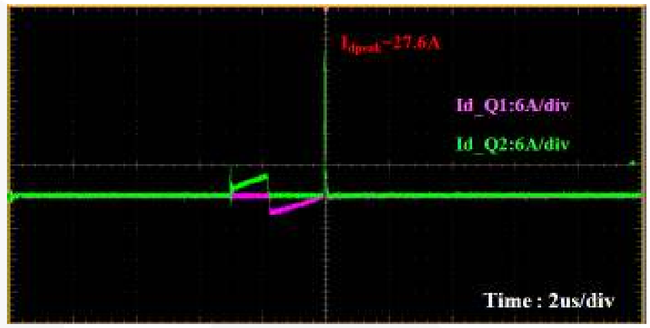

Figure 14. Waveform of Competitor A During Startup

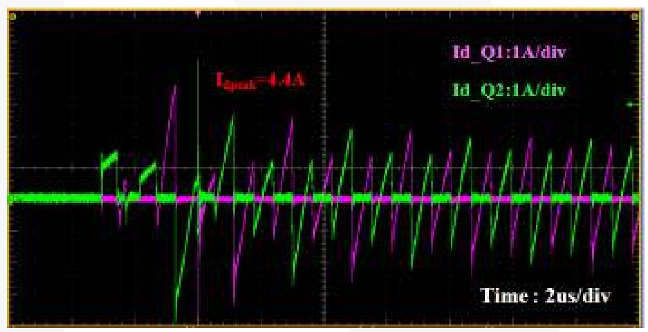

Figure 15. Waveform of UniFET™ II During Startup

To compare the efficiency of a UniFET™ II MOSFET and competitors, a 240W LLC resonant half-bridge converter was designed with input voltage of 110-220V_{AC} and output voltage and current set to 12V and 20A, respectively. Synchronous rectification was used for the secondary side. The summary of the efficiency measurements is shown in Figure 16. Efficiency increases about 0.5% compared to competitor MOSFETs at heavy load condition. The major reason for higher efficiency is the reduced switch-off loss and output capacitive loss because of lower Q_g and E_{oss}. UniFET™ II MOSFETs have a robust Electrostatic Discharge (ESD) capability of 2kV Human Body Model (HBM). This strong ESD capability is instrumental in protecting the application from adverse electrostatic events.

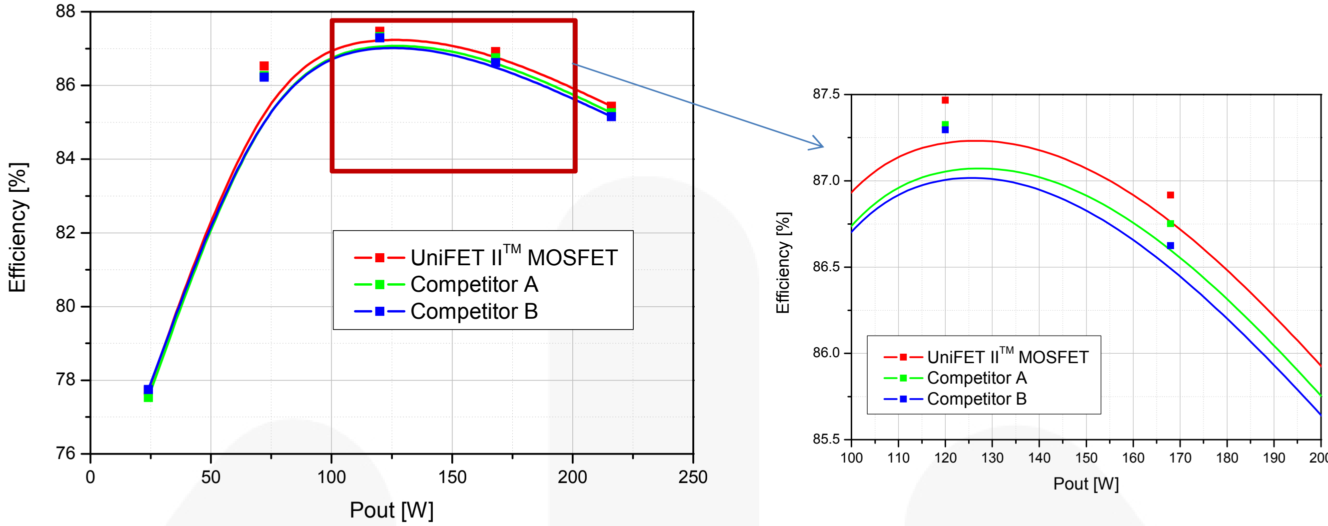

Figure 16. Efficiency Comparisons on LLC Resonant Converter

Conclusion

Fairchild's new power MOSFETs family, UniFET™ II, combines a faster and more rugged intrinsic body diode performance with fast switching, aimed at achieving better reliability and efficiency in applications including resonant converters. With reduced gate charge and stored energy in output capacitance, switching efficiency is increased and driving and output capacitive losses are decreased. Performance of UniFET™ II MOSFET allows designers to significantly increase system reliability, particularly for resonant converters.

Table 2. 500V, 600V UniFET™ II Lineup

Part Number[(1)]	BV_{DSS}	$R_{DS(ON).max}$ [Ω] at V_{GS} = 10V	$Q_{g.typ}$ [nC] at V_{GS} = 10V	I_D [A]	Package
FDPF3N50NZ	500	2.50	8	3.0	TO-220F
FDD3N50NZ	500	2.50	8	2.5	TO-252 (DPAK)
FDP5N50NZ	500	1.50	9	4.5	TO-220
FDPF5N50NZ	500	1.50	9	4.5	TO-220F
FDD5N50NZ	500	1.50	9	4.0	TO-252 (DPAK)
FDPF5N50NZF	500	1.75	9	4.2	TO-220F
FDD5N50NZF	500	1.75	9	3.7	TO-252 (DPAK)
FDPF5N50NZU	500	2.00	9	4.0	TO-220F
FDP8N50NZ	500	0.85	14	8.0	TO-220
FDPF8N50NZ	500	0.85	14	8.0	TO-220F
FDD8N50NZ	500	0.85	14	6.5	TO-252 (DPAK)
FDPF8N50NZF	500	1.00	14	7.0	TO-220F
FDPF8N50NZU	500	1.20	14	6.5	TO-220F
FDP12N50NZ	500	0.52	25	11.5	TO-220
FDPF12N50NZ	500	0.52	25	11.5	TO-220F
FDP22N50N	500	0.21	49	22.0	TO-220
FDPF5N60NZ	600	2.00	11	4.5	TO-220F
FDD5N60NZ	600	2.00	11	4.0	TO-252 (DPAK)
FDP7N60NZ	600	1.25	13	6.5	TO-220
FDPF7N60NZ	600	1.25	13	6.5	TO-220F
FDD7N60NZ	600	1.25	13	5.5	TO-252 (DPAK)
FDU7N60NZ	600	1.25	13	5.5	TO-251 (IPAK)
FDD7N60NZU	600	1.70	13	4.6	TO-252 (DPAK)
FDP10N60NZ	600	0.75	27	10.0	TO-220
FDPF10N60NZ	600	0.75	27	10.0	TO-220F
FDP12N60NZ	600	0.65	30	12.0	TO-220
FDPF12N60NZ	600	0.65	30	12.0	TO-220F
FDPF17N60N	600	0.34	48	17.0	TO-220F

Note:
1. Part suffix: N = UniFET™ II, Z = internal ESD diode.

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