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# AN-5235

## 650V Fast Recovery SuperFET® II MOSFET for High System Efficiency and Reliability in Resonant Topologies


## Abstract

Telecom and sever power systems are required to deliver more power within smaller volume due to limited space and increased power consumption. Under rapidly changing circumstances that encourage energy saving, most industry experts agree that new power technologies can play a critical role in the power conversion applications. The super-junction MOSFET enables a dramatically reduced on-resistance compared to conventional MOSFETs thanks to its charge balance structure. Since conduction losses are directly proportional to on-resistance of MOSFET, super-junction MOSFETs can greatly reduce conduction loss in system. Therefore, super-junction MOSFETs have been used in resonant converters to increase system efficiency, but generally, its body diode performance is not attractive for these topologies. Newly developed 650V fast recovery super-junction MOSFETs, called SuperFET® II FRFET® MOSFET have fast body diode, higher threshold voltage (Vth=4 V), ultra low on-resistance, low stored energy in output capacitance and extremely fast switching speed. It can provide improved reliability and efficiency in server and telecom power applications.


## Introduction

Distributed power systems are under pressure continuously to achieve high efficiency and reduce energy consumption in server and telecom power supplies. The increasing efficiency and power density is enabled by the continuous development of novel resonant topologies and outstanding power devices which allow a system reliability and a higher switching frequency at relatively low switching losses, which leads to a reduced converter dimensions. Several soft switching topologies for server and telecom power supplies have been introduced to reduce switching losses and device stress while achieving high power density and improved reliability. However, power MOSFET failures have been issued in the phase-shifted ZVS full-bridge topology and LLC resonant topology. As shown in Figure 1, reverse recovery of planar MOSFET is relatively softer than that of super-junction MOSFET. When all situations are same, snappy body diodes always cause higher voltage spikes and dv/dt which cause device failure. Soft body diode of Planar MOSFET is suitable for resonant topologies. However, low $R_{DS(ON)}$ and stored energy in output capacitance, $E_{OSS}$ of the MOSFET is critical factor for resonant converters to maximize system efficiency. Furthermore, low $Q_{RR}$ and robust body diode characteristics are related to the reliability issues. Therefore, lower $R_{DS(ON)}$ and $E_{OSS}$ with robust body diode of fast recovery super-junction MOSFETs can effectively minimize resonant energy required to achieve soft switching without increasing the circulating energy and improve the system reliability.

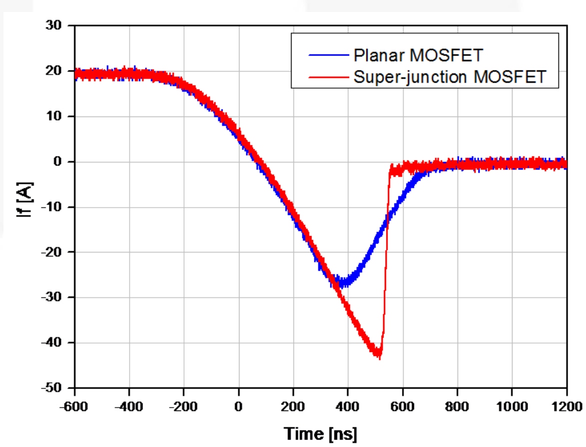



**Figure 1. Reverse recovery behavior comparison between Planar MOSFET and Super-junction MOSFET (test condition: Vdd=400 V, di/dt=100 A/µs, Isd=20 A)**

## 650V Fast Recovery SuperFET® II MOSFET Technology

SuperFET II MOSFET combines faster switching and Qrr of body diode performance with $R_{DS(ON)}$ reduced by 40% compared to previous generation super-junction MOSFETs called SuperFET I MOSFETs as shown in Figure 2 [1]. As shown in Table 1, the gate charge, Qg of 650 V/190 mΩ SuperFET II FRFET MOSFET is dramatically reduced by 27% compared to previous generation 600 V/190 mΩ SuperFET I FRFET MOSFET.

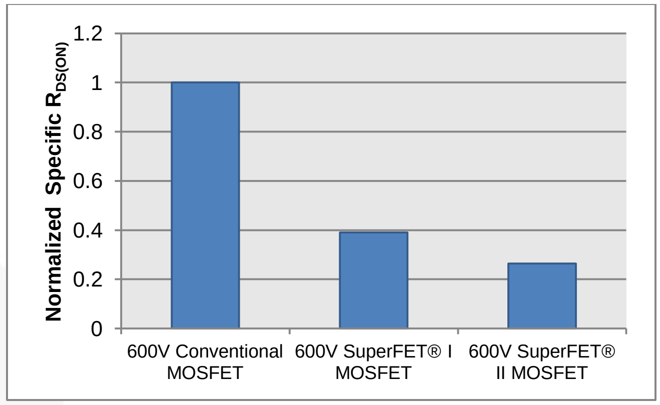



**Figure 2. Normalized on-resistance per specific area comparisons**

**Table 1. Critical Specification Comparison**

| DUTs | BVDSS | $R_{DS(ON)}$ Max. | Qg Max. | Trr Typ. | Qrr Typ. | $E_{OSS}$ @ 400VDS |
|---|---|---|---|---|---|---|
| SuperFET® II FRFET® MOSFET, FCP190N65F | 650 V | 190 mΩ | 78 nC | 105 ns | 515 nC | 6.55 µJ |
| SuperFET® I FRFET® MOSFET, FCA20N60F | 600 V | 190 mΩ | 98 nC | 160 ns | 1,100 nC | 8.08 µJ |

## Low $E_{OSS}$ in Resonant Topologies

Zero voltage switching (ZVS) topologies can achieve lossless turn-on while drain-source voltage is zero by flowing current through the body diode during dead time as shown in Figure 3.

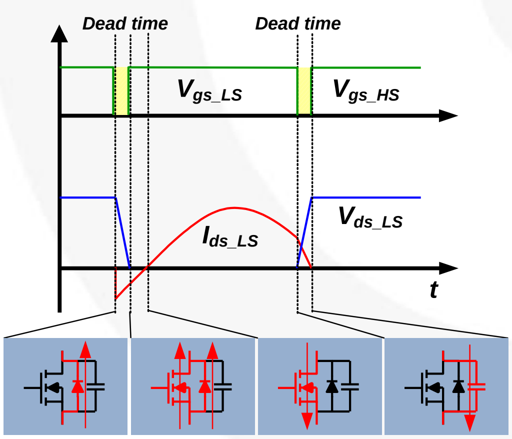



**Figure 3. ZVS Operation Modes of Power MOSFET in LLC Resonant Converter**

MOSFET output capacitance is another crucial parasitic parameter to understand for zero voltage switching (ZVS) topologies. It determines how much inductance is required to provide ZVS conditions because MOSFET output capacitance can be used as a resonant component in soft switching topologies. In the soft switching topologies, zero voltage turn-on is achieved by using the energy stored in inductor, the leakage and series inductance or magnetizing inductance of the transformer, to discharge the output capacitance of the switches through resonant action.

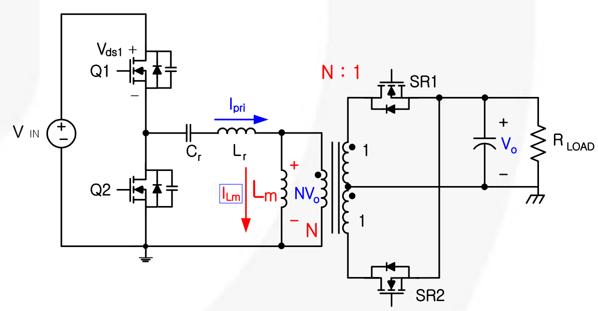



**Figure 4. LLC Resonant Converter**

The inductance should be precisely designed to prevent hard switching that causes additional power losses. LLC resonant half-bridge converter topology is shown in Figure 4. The following equation (1) and (2) shows ZVS requirements for LLC resonant converter in Figure 5.

$$\frac{1}{2}\cdot L_{eq}\cdot I_p^2 \geq \frac{1}{2}\cdot 2\cdot C_{OSS(er)}\cdot V_{IN}^2 \quad (1)$$

$$\frac{1}{2}\cdot L_{eq}\cdot I_p^2 \geq 2\cdot E_{OSS} \quad (2)$$

Where, $C_{oss(er)}$ is energy related output capacitance of $Q_1$ or $Q_2$ at $V_{IN}$, $L_{eq}$ is equivalent inductance.

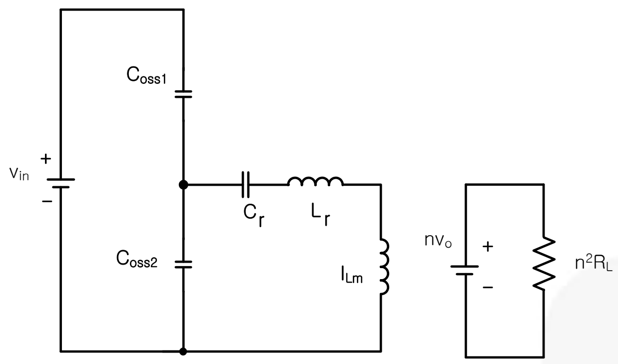



**Figure 5. Resonant components for ZVS mode in LLC Resonant Converter**

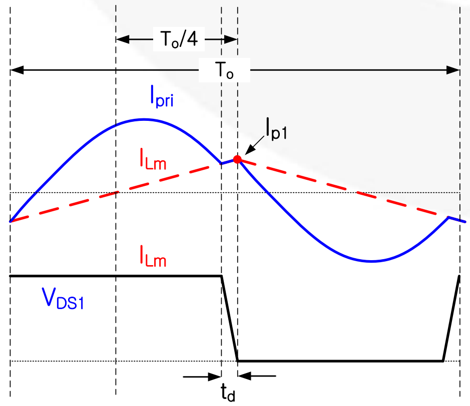
The output capacitance plays an important role in soft switching topologies. Magnetizing current must be large enough to discharge the $C_{OSS}$ of MOSFET during dead time to ensure the ZVS turn-on as shown in equation (3). Low output capacitance of MOSET can reduce the need of magnetizing current, less circulating energy, less turn-off loss and less dead time

$$L_m \le \frac{t_d \cdot T_O}{16 \cdot C_{oss}} \tag{3}$$

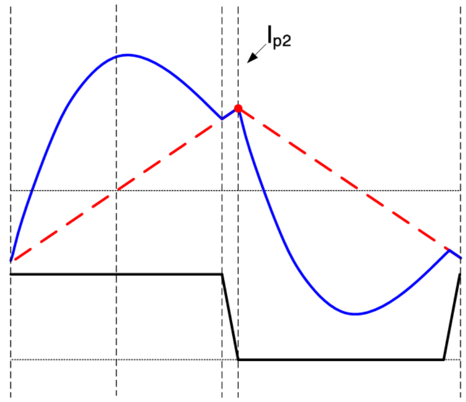
Figure 6 shows operation waveforms in LLC resonant converter according to $L_m$ with $f_s < f_r$. The peak magnetizing current ($I_P$) shows in equation (4) [2]

$$I_p \approx \frac{NV_o}{L_m} \cdot \frac{T_O}{4} \tag{4}$$

Where N is the transformer turns-ratio, $V_O$ is the output voltage, Lm is the magnetizing inductance, $t_d$ is dead time, and $T_O$ is the switching period.




**(a) Waveforms with Large $L_m$ ($f_s < f_r$)**




**(b) Waveforms with Small $L_m$ ($f_s < f_r$)**

**Figure 6. Waveforms in LLC Resonant Converter according to Lm**

As shown in Figure 6, the turn-off current of the MOSFETs is determined by magnetizing inductance. With Small Lm, high peak magnetizing current will increase turn-off current of the primary side MOSFETs and circulating current. The increased current results in higher turn-off switching loss and conduction loss respectively. To achieve minimum conduction loss and turn-off loss, a large Lm is preferred. As shown in Figure 7, a SuperFET II FRFET MOSFET has approximately 23.3% less stored energy in output capacitance than SuperFET I FRFET MOSFET at 400 V across the MOSFET. Figure 8 shows the switching losses comparison. A SuperFET II FRFET MOSFET has much better switching performance, that is 22~42% less switching losses according to load current, compared to previous generation SuperFET I FRFET MOSFET in clamped inductive switching test under the following test condition : Vdd=400 V, Rg=4.7 ohm and Id=2~20 A

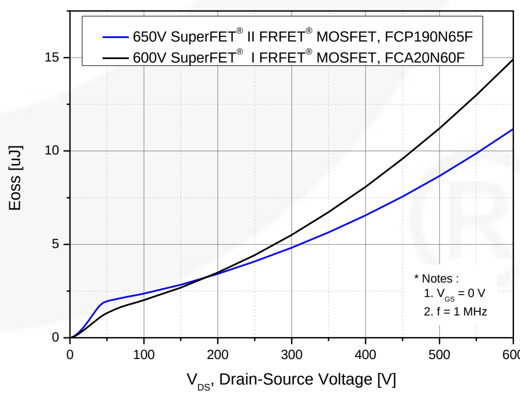



**Figure 7. Comparisons of stored energy in output capacitance, EOSS**

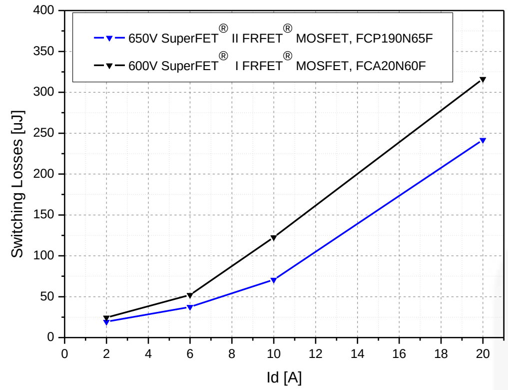



**Figure 8. Comparisons of switching losses (Eon + Eoff) under Vdd=400 V, Rg=4.7 ohm and Id=2~20 A**

## Robust Body Diode in Resonant Topologies

One of the MOSFET failure modes in LLC resonant converter is losing ZVS in abnormal conditions. Figure 9 shows waveforms of the power MOSFETs in LLC resonant converter at startup. The LLC resonant converter requires a device with body diode ruggedness characteristic because there is high current stress in over load, output short circuit condition and inrush current during start-up. In start-up condition, Peak inrush currents can be several orders of magnitude greater than the normal current in steady state condition. These inrush currents flow through the body diode of low-side MOSFET during start up. It makes shoot-through problem when high-side MOSFET is turned-on due to reverse recovery current, which flows through body diode of low-side MOSFET. As a result, the potential failure of power MOSFET may happen during body diode reverse recovery at start-up state. And another field failure can be occurred at over-load or short-circuit condition in the LLC resonant converter. Even though voltage and current of power MOSFETs are within safe operating area, some unexpected failures associated with shoot through current, reverse recovery dv/dt, and breakdown dv/dt happen in various conditions, such as over load and output short circuit. The worst case is a short-circuit condition. During short circuit, the MOSFET conducts extremely high (theoretically unlimited) current. When short circuit occurs, operation mode during short circuit is almost same as overload condition, but short-circuit condition is worse because reverse-recovery current, which flows through the body diode of the switch, is much higher [3][4].

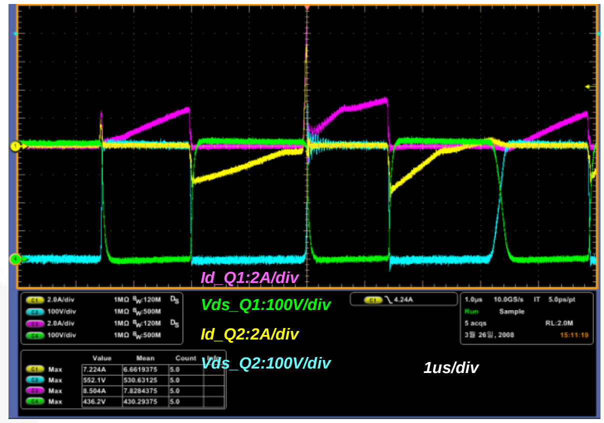



**Figure 9. Waveforms of Power MOSFETs at Start-up**

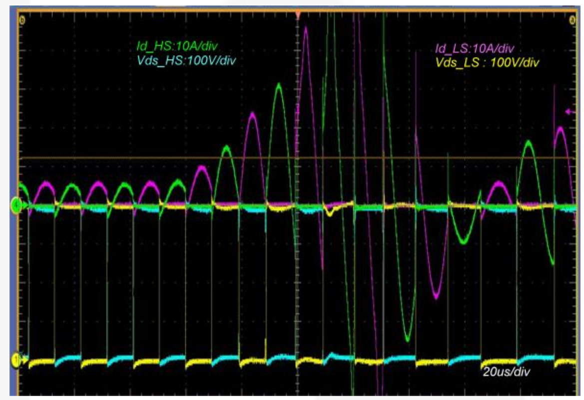
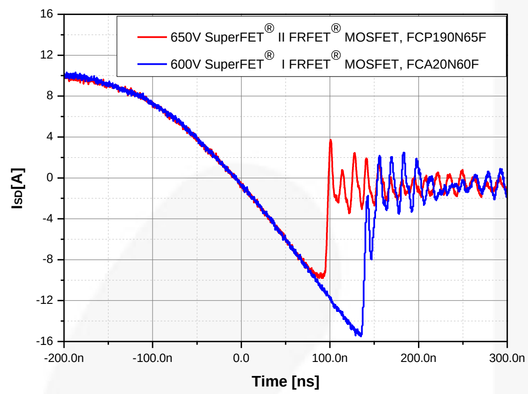


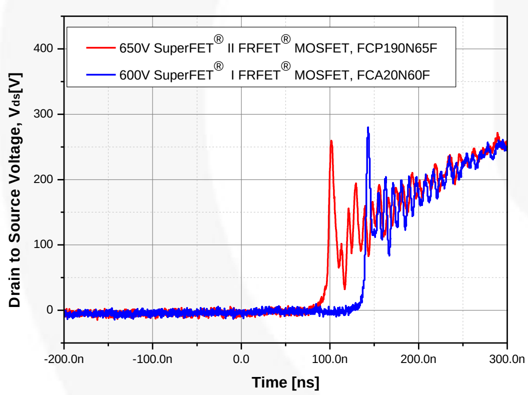

**Figure 10. Waveforms of Power MOSFET at Output Short Condition**

Figure 10 shows the waveforms of the power MOSFETs in LLC resonant converter at short circuit condition. The current level during short-circuit condition is much higher and can lead to increased junction temperature of MOSFET, which makes it easier to fail. Body diode reverse recovery is switching process of the body diode from on state to reverse blocking state. First, the body diode was 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 N+ source. Basically, base and emitter of parasitic 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. More current flows through it due to negative temperature coefficient of the

BJT. Finally, the device fails. Body diode conduction should be minimized to lower peak reverse-recovery current. As the di/dt becomes bigger, peak reverse-recovery current goes up as well. In the LLC resonant converter, the di/dt of one power MOSFET body diode is related to turn-on speed of the other complementary power switch. So, slowing down the turn-on also lowers the di/dt. Fast recovery MOSFET can prevent this failure thanks to its robust body diode performance




**(a) Measured $I_{SD}$ during Reverse Recovery Behavior of Body Diode**




**(b) Measured $V_{DS}$ during Reverse Recovery Behavior of Body Diode**

**Figure 11. Comparisons of reverse recovery behavior under ISD=10 A, di/dt=100 A/µs, VDS=400 V, Tj=25ºC**

Figure 11 shows the reverse recovery behavior comparison at $I_{SD}$=10 A, di/dt=100 A/µs, $V_{DS}$=400 V and $T_j$=25ºC. It can be clearly seen that the reverse recovery charge, $Q_{rr}$ of SuperFET II FRFET MOSFET, FCP190N65F reduced by 47% compared to SuperFET I FRFET MOSFET, FCA20N60F. Furthermore, peak voltage spikes of a SuperFET II FRFET MOSFET during reverse recovery behavior is lower than previous generation due to its soft reverse recovery characteristics and small $Q_{rr}$.

Figure 12 shows competitor's fast recovery MOSFET failing waveforms during body diode reverse recovery. With competitor, failure occurs after the current level reaches $I_{rrm}$, peak reverse recovery current at 800 A/µs. As shown in Figure 13, SuperFET II FRFET MOSFET did not fail at even higher di/dt (1,200 A/µs) conditions. SuperFET II FRFET MOSFET provides soft and rugged body diode during hard commutation of body diode.

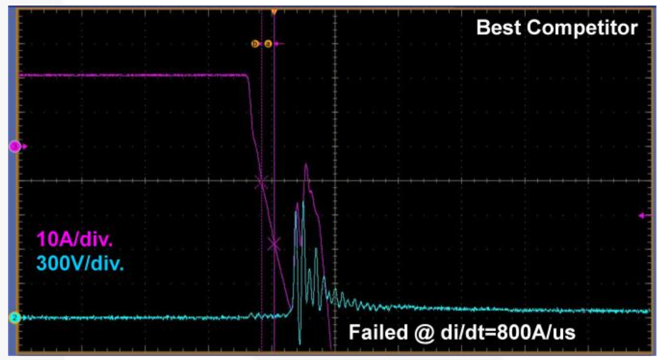



**Figure 12. Competitor's Fast recovery MOSFET Failing Waveforms During Body Diode Reverse Recovery**

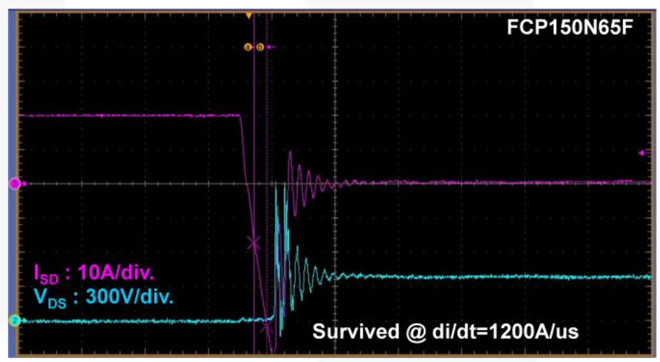



**Figure 13. SuperFET® II FRFET® MOSFET Withstanding Waveforms During Body Diode Reverse Recovery**

## Application Evaluation Results

Efficiency of a SuperFET II FRFET MOSFET, FCH077N65F, a 650 V/77 mΩ is compared to 650 V / 80 mΩ competitor's fast recovery SJ MOSFET in 2 kW telecom AC/DC rectifier. As shown in Figure 14, Turn-off loss of FCH077N65F is 25% less compared to competitor MOSFETs at 10A drain current due to its low $Q_g$. The summary of the efficiency measurements is shown Figure 15. Efficiency increases about 0.58% and 0.31% compared to competitor MOSFETs at light load and heavy load condition respectively. The major reason for higher efficiency of FCH077N65F is the reduced turn-off loss and output capacitive loss because of its lower $Q_g$ and $E_{oss}$.

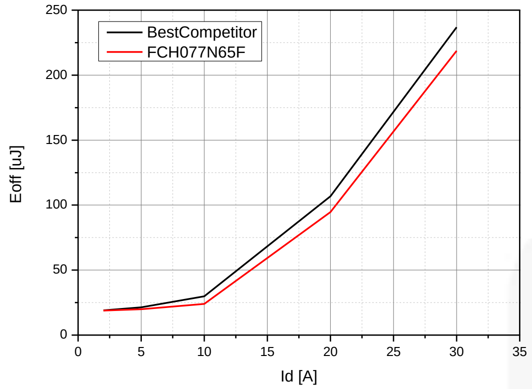



**Figure 14. Turn-off Loss Comparison between SuperFET® II FRFET® MOSFET, FCH077N65F and 650 V, 80 mΩ competitor's fast recovery MOSFET**

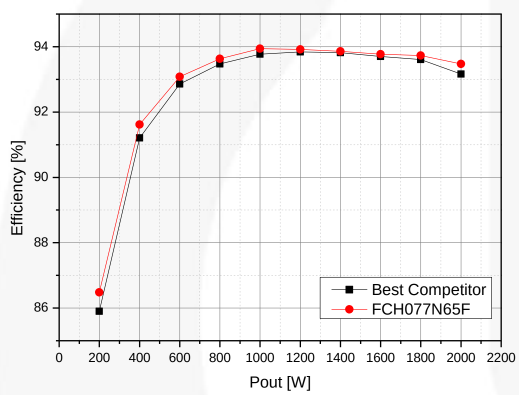



**Figure 15. Efficiency versus output power in 2 kW telecom power supply between SuperFET® II FRFET® MOSFET, FCH077N65F and 650 V, 80 mΩ competitor's fast recovery MOSFET**

# Conclusion

The new 650 V fast recovery SuperFET II MOSFET combines a faster and more rugged body diode performance with fast switching performance, aimed at achieving better reliability and efficiency in power system 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 fast recovery SuperFET II MOSFET allows designers to significantly increase system efficiency and reliability, particularly for in phase shifted full-bridge converters or half-bridge LLC resonant converters under abnormal conditions.

## References


[1] *Wonsuk Choi and Dongkook Son "New Generation Super-Junction MOSFETs, SuperFET® II and SuperFET® II Easy Drive MOSFETs for High Efficiency and Lower Switching Noise", Fairchild Application note, AN-5232, Sept., 2013.*

[2] *Hangseok Choi, "Analysis and Design of LLC Resonant Converter with Integrated Transformer," APEC 2007, Feb. 2007.*

[3] *Wonsuk Choi and Sungmo Young, "Improving System Reliability Using FRFET® in LLC Resonant Converters," PESC 2008, June 2008.*

[4] *Wonsuk Choi and Sungmo Young "MOSFET Failure Modes Analysis in LLC Resonant converter", Fairchild Application note, AN9067, Nov., 2009*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