Driving eGaN® FETs in High Performance Power Conversion Systems

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As enhancement mode gallium-nitride-on-silicon (eGaN®) FETs gain wider acceptance as the successor to the venerable - but aged - power MOSFET, designers have been able to improve power conversion system efficiency, size, and cost. eGaN FETs, however, are based on a relatively immature technology and only recently have eGaN FET-based products begun to hit the market in applications such as power over Ethernet (PoE) and isolated, as well as non-isolated DC-DC converters for telecom and computing applications. Four topologies are explored, and comparisons made between the performance of existing state-of-the-art power MOSFETs and eGaN FETs: (1) Flyback converters where costs are sensitive and power levels low, (2) forward converters that are best suited in applications requiring high power density and low power, (3) buck converters for applications requiring high power densities, and (4) full bridge isolated converters for applications requiring high power density, high power, and input-to-output isolation. These four topologies cover the majority of applications in computing and telecommunications where eGaN FETs are making the earliest inroads and offer greatest value to the user.

13W Flyback Converter

One of the most common topologies used for isolated DC-DC conversion is the flyback converter. The flyback converter is a buck-boost converter with the inductor split to form a transformer so the voltage ratios are multiplied with an additional advantage of isolation. To understand the advantages of eGaN FETs compared with their silicon counterparts in a flyback converter, we used an IEEE 802.3 compliant power over Ethernet (PoE) converter.

Equipment powered by its Ethernet connection has two basic challenges, (1) the power source is limited and well-defined, and (2) the products are highly cost-competitive. A 13W, IEEE 802.3 compliant PoE converter utilizing eGaN® power FETs is compared to a MOSFET counterpart showing that eGaN FETs offer advantages in efficiency, reduced heat sinking, yet with smaller PCB area. A conventional PoE IC controller is used to demonstrate feasibility and ease of use with eGaN FETs.

Figure 1 shows the schematic of the flyback converter using the LM5020 [1] from National Semiconductor. This circuit is virtually identical to the application given in the LM5020 datasheet. The converter efficiency was measured at 300 kHz and 500 kHz. The results are shown in Figure 2 on the following page. It can be seen that the 300kHz MOSFET based and eGaN based efficiency results are almost identical despite a 50% higher in $R_{DS(ON)}$ of the eGaN FET compared to the MOSFET. This can be accounted for by the eGaN having lower switching loss, measurement accuracy, and part-to-part variation in both the devices and magnetic components. The key point to note here is how much less the drop in efficiency for the eGaN solution is when the switching frequency is increased to 500 kHz – about 0.5% for the eGaN solution - vs. about 2% for the MOSFET solution.

Increasing the switching frequency in a power converter will allow a decrease in both magnetic core size and losses [2]. For similar losses, the core volume reduction will be roughly equal to the square root of the ratio of the lower frequency

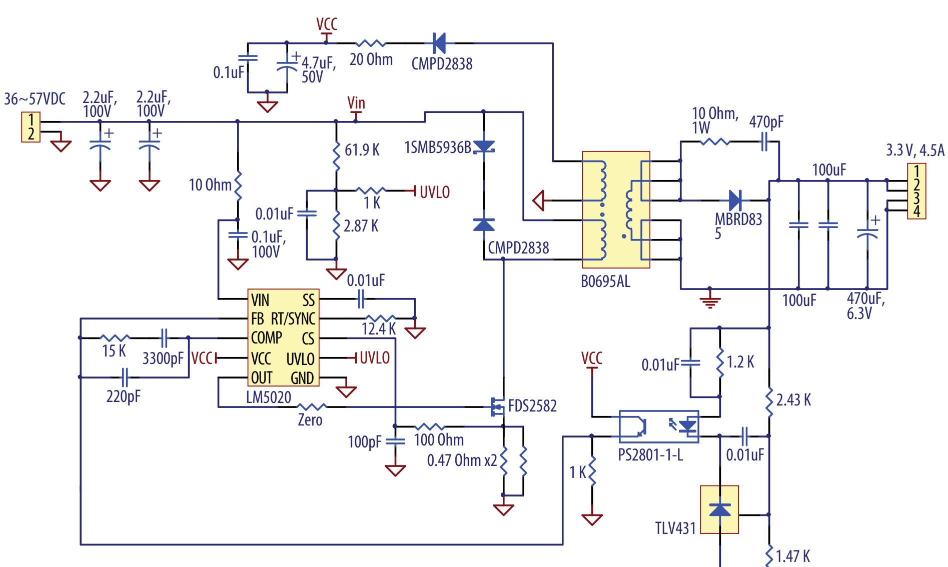

Figure 1 - LM5020 based 48 V to 3.3 V, 13 W PoE converter schematic.

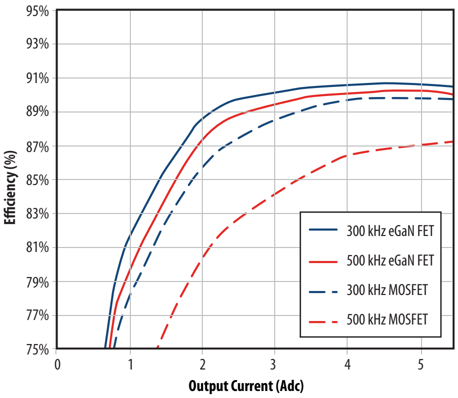

Figure 2 - Efficienty comparison of eGaN FET vs MOSFET for 48 V to 3.3 V, 13 W flyback PoE.

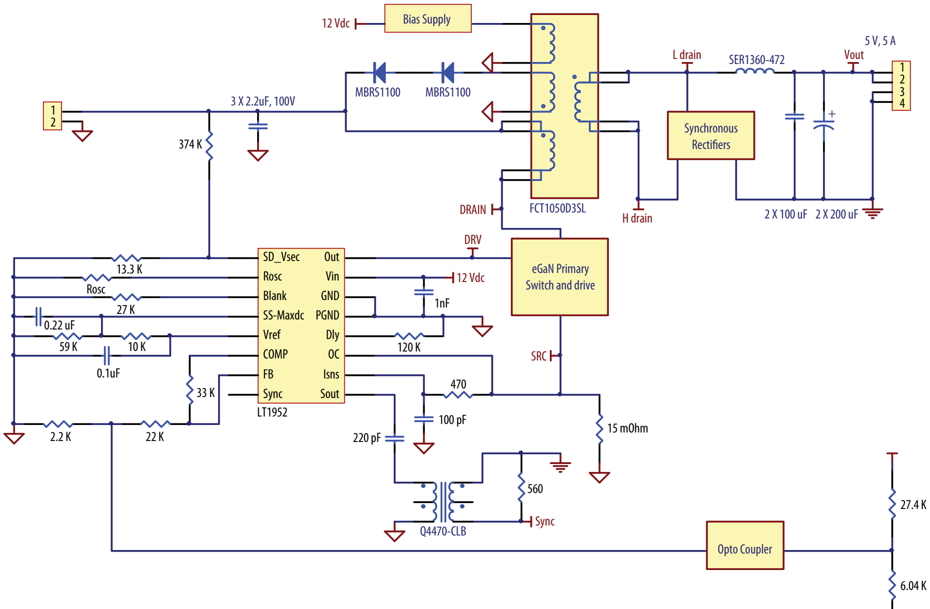

Figure 3 - Simplified schematic of the eGaN FET 26 W PoE forward converter.

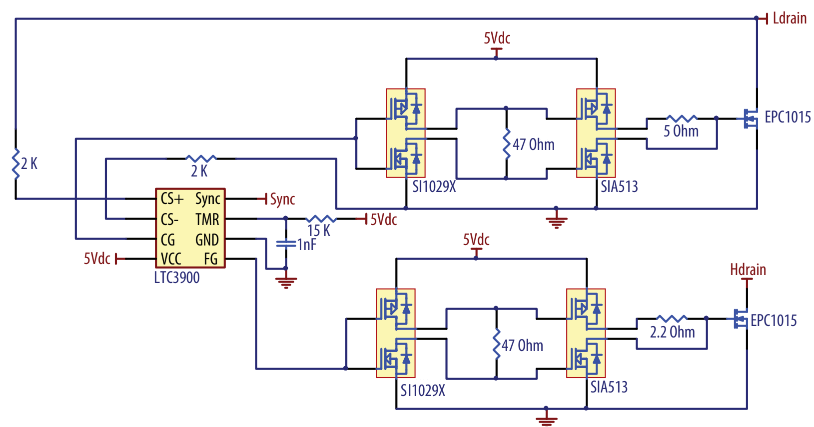

Figure 4 - eGaN FET based secondary side synchronous rectifier schematic for Figure 8.

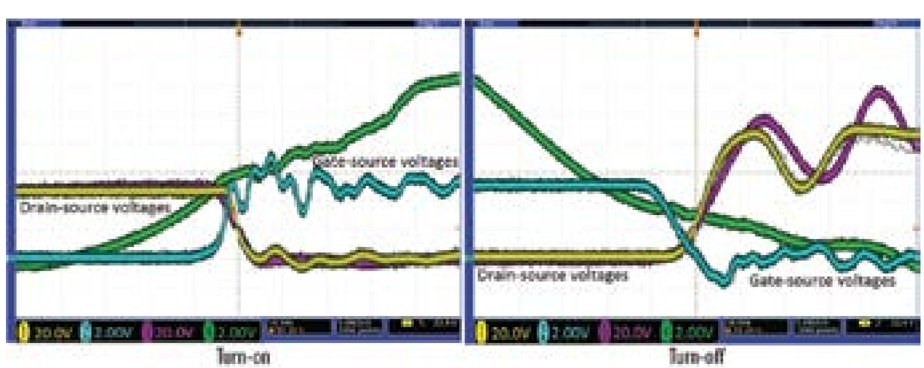

Figure 5 - LT1952 primary side gate and drain turn-on and turn-off waveforms (f = 500 kHz, V_{IN} = 48 V, V_{OUT} = 5 V, I_{OUT} = 5 A). CH1: eGaN FET drain-source voltage, CH2: eGaN FET gate-source voltage, CH3: MOSFET drain-source voltage, CH4: MOSFET gate-source voltage.

divided by the higher frequency. In high enough production volumes where material cost dominates the transformer cost, it would thus be fair to assume that the cost of the magnetic component would decrease accordingly.

High efficiency forward converter

The forward converter is a DC/DC converter that uses transformer windings to buck or boost the voltage (depending on the transformer ratio) and provide galvanic isolation for the load. It performs the same operation as the flyback converter but is generally more energy efficient.

Once again we look at PoE power supplies using a forward converter topology as a vehicle for comparing eGaN FET vs silicon power MOSFET performance.

A simplified forward converter schematic is shown in Figure 3 based on Linear Technology's LT1952 [3] in conjunction with the manufacturer's LTC3900 [4] synchronous rectifier controller on the secondary side. The eGaN synchronous rectifier circuitry is shown in Figure 4. The LTC3900 receives synchronization pulses from the primary side through an isolation /pulse transformer. Minimizing delay and on-off timings of the secondary side synchronous rectifiers is key to reducing body diode losses and improving overall efficiency. A MOSFET and an eGaN FET based converter were operated at 300 kHz and 500 kHz respectively to demonstrate the advantages offered by the eGaN FET solution.

The turn-on and turn-off waveforms for both the eGaN FET and MOSFET are compared in Figure 5. The significant difference between their respective gate rise times is due to a 10:1 ratio in respective input capacitance (C_{ISS}). The improved turn-on time of the eGaN is due to the five times lower miller

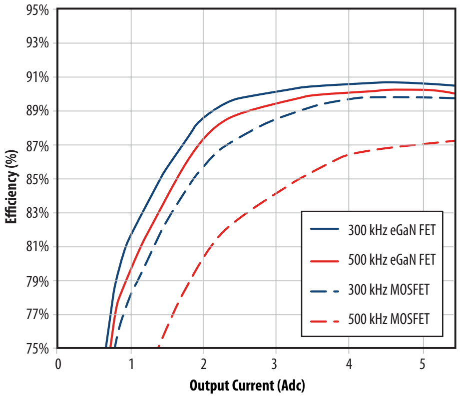

Figure 6 - Efficiency comparison of eGaN FET vs MOSFET for 48 V to 5 V, 26 W forward PoE.

charge (Q_{GD}), while the reduced drain rise time is due to the eGaN FET having about half the output capacitance (C_{OSS}) as compared to the MOSFET.

Figure 6 shows the efficiency of both MOSFET and eGaN FET converters operating at 300 kHz and 500 kHz respectively. There are a few important points that can be made from evaluation of the efficiency results:

- At 300 kHz, eGaN FETs offer a small improvement in efficiency at all loads and have comparable efficiencies at full load despite the 50% greater on-resistance of the eGaN FET in the primary socket when compare to the MOSFET $R_{DS(ON)}$.
- As in the previous cases, the eGaN FET converter efficiency performance relative to the MOSFET design significantly improves as frequency increases and is about 4% more efficient at 500kHz.
- The eGaN efficiency actually increases with increase in frequency. This is, however, almost entirely due to the use of two different output inductors for 300 kHz and 500 kHz versions chosen to maintain similar output current ripple between the two respective operating frequencies. This resulted in an approximately 5 mΩ reduction in inductor DC resistance (DCR) and halving the inductor volume. Subtracting this inductor improvement, the efficiency between 300 kHz and 500 kHz versions remain largely unchanged.

It should be noted that due to the higher forward drop of the eGaN FET body diode, the gate driver timing was adjusted to reduce diode conduction using a single adjustment over the entire load range.

Table 1: Characteristics of the Silicon and eGaN FETs

	Part Number	V_{DS} (V)	I_{DS} (A)	$R_{DS(ON)}$ (mΩ)	Q_G (nC)	Figure of Merit (mΩ.nC)	Package Type	PCB Area (mm²)
Silicon Control FET	Si7850	60	6.2	25	18	450	PowerSO-8	31.7
Silicon Sync FET	RJK0652	60	35	6.5	29	189	LFPAK	29.8
eGaN Control FET	EPC1007	100	6	24	2.7	65	Flip Chip	1.8
eGaN Sync FET	EPC1001	100	25	5.6	10.5	59	Flip Chip	6.7

High V_{IN}/V_{OUT} Buck Converters

A buck converter is a step-down DC to DC converter. The simplest way to reduce the voltage of a DC supply is to use a linear regulator, but linear regulators waste energy as they operate by bleeding off excess power as heat. Buck converters, on the other hand, can be extremely efficient, making them useful for tasks such as converting the 12–19 V typical battery voltage in a laptop down to the few volts needed by the processor.

Today, converting from a common 48 V power bus down to voltages around 1 V requires two stages due to the switching limitations of power MOSFETs. Direct conversion from 48 V to low voltage could eliminate the cost and space of a two stage solution if the overall efficiency of the system can be maintained. Efficient high input-to-output ratio buck capability could also lead the system architect to rethink the ubiquitous 12 V intermediate bus structure to gain efficiencies in the overall power distribution. A buck converter with an input voltage of 48 VDC and output voltage of 1.2 VDC is demonstrated over the range of a few hundred kHz for very high efficiency, to near MHz range for very small system size. Each operating condition is optimized for output currents in the 8 ADC to 10 ADC range (see Figure 7).

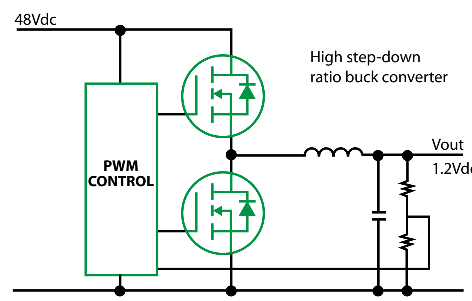

Figure 7 - Buck converter with an input voltage of 48 VDC and output voltage of 1.2 VDC.

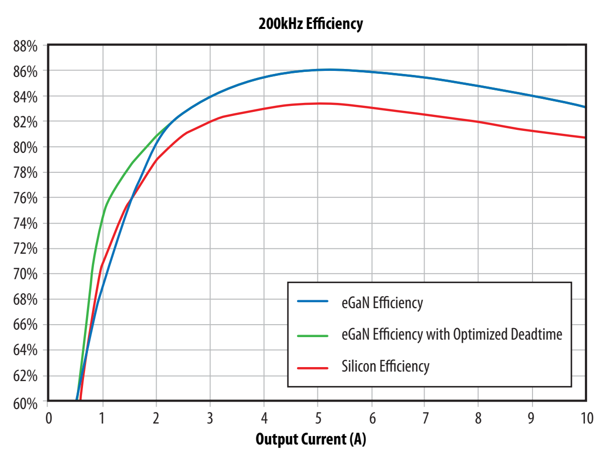

Figure 8 - 48 V to 1.2 V conversion efficiency at 200 kHz switching frequency.

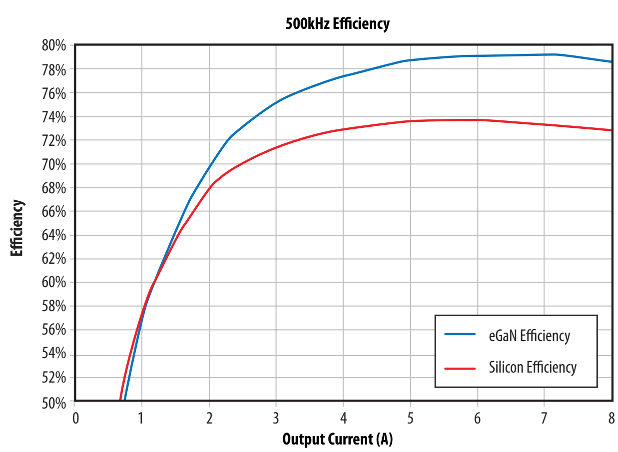

Figure 9 - 48 V to 1.2 V conversion efficiency at 500 kHz switching frequency.

Full Bridge Isolated Converter

Where a wide input voltage range and electrical isolation are necessary, the power designer is challenged to increase output power while reducing size. For standard 'brick' converters, the maximum output power achievable is directly limited by the maximum power loss that can be extracted at the given ambient with forced air cooling, making the thermal considerations every bit as important as the electrical losses. But a first pass comparison between using eGaN FETs and MOSFETs can be done by simply comparing power loss and efficiency. A high frequency, isolated, 1/8th brick DC-DC converter based on eGaN FET demonstrates the potential improvement in power density and efficiency that can be achieved by a fully optimized design.

The 36 V - 75 V to 12 V / 180 W converter is characterized and compared with a comparable power MOSFET circuit. This eGaN converter is a fully regulated, phase shifted full bridge topology, with full bridge synchronous rectification tested at both 333 kHz and 500 kHz respectively (schematic shown in Figure 10). The experimental prototype shown in Figure 11 utilizes the LM5113 half-bridge eGaN driver IC from National Semiconductor [6]. The efficiency of the eGaN FET design at 333 kHz and 500 kHz compared to equivalent MOSFET product is shown in Figures 12 and 13 respectively. The power loss for 333 kHz operation is shown in Figure 14 on the following page.

From these results it is clear that even a non-optimized design is capable of outperforming a leading MOSFET design by delivering up to 14A compared to 12A with the same total power loss. That's a 16% increase in power output. In fact,

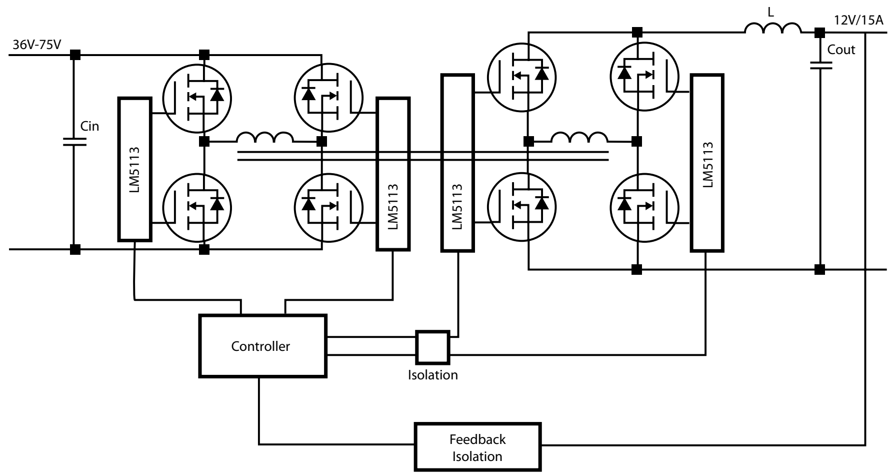

Figure 10 - 180W 1/8th brick fully regulated, phase shifted full bridge topology, with full bridge synchronous rectification using eGaN FETs.

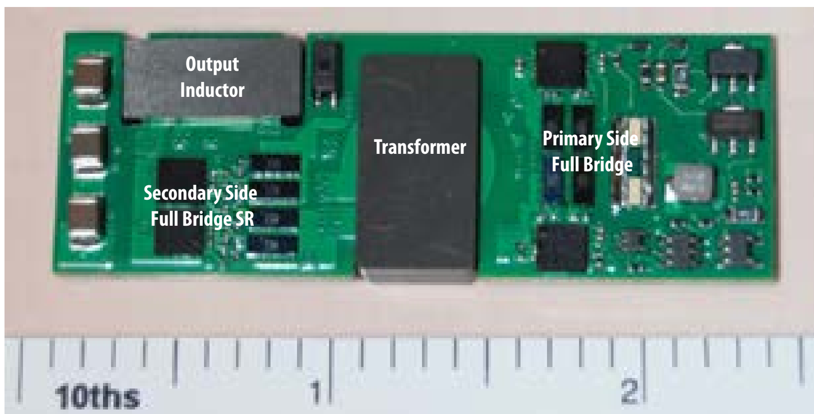

Figure 11 - Experimental 1/8th brick DC-DC converter using eGaN FETs.

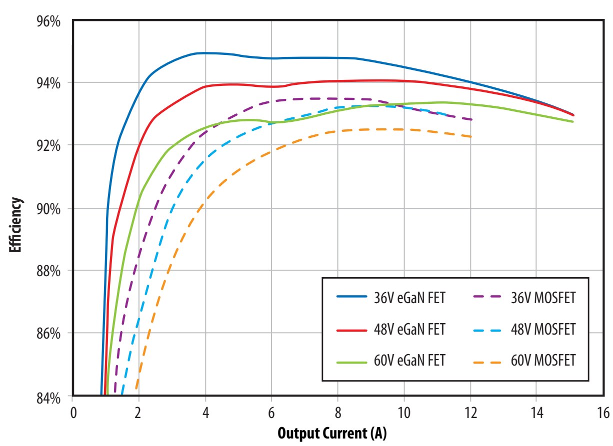

Figure 12 - Efficiency comparison between 1/8th bricks: eGaN FET at 333 kHz and MOSFET at 250 kHz [5].

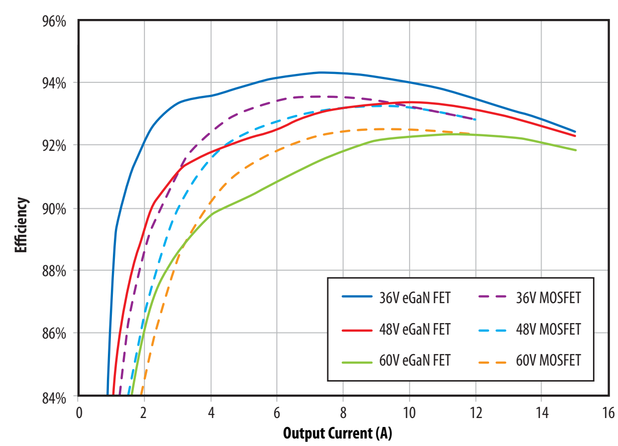

Figure 13 - Efficiency comparison between 1/8th bricks: eGaN FET at 500 kHz and MOSFET at 250 kHz.

doubling the operating frequency relative to the MOSFET design still results in a power supply with equivalent power loss.

It should be noted that since the converter was designed to be capable of 333 kHz operation, the transformer and output inductor were not optimized for 500 kHz operation. Thus a possible reduction in number of turns and winding resistance can yield further heavy load efficiency improvement.

Conclusions

Four basic power conversion topologies, flyback, forward, buck, and isolated full-bridge, have been characterized using state-of-the-art eGaN FETs and compared with the best available silicon devices. eGaN FETs offer significant advantage in each of these circuits. These advantages can be translated into lower system cost, reduced converter size, and higher conversion efficiency. The broad scale of the performance improvements available to designers due to the introduction of gallium nitride based products is further support for the contention that gallium nitride will be a displacement technology to silicon power MOSFETs over the next 4 to 6 years [7].

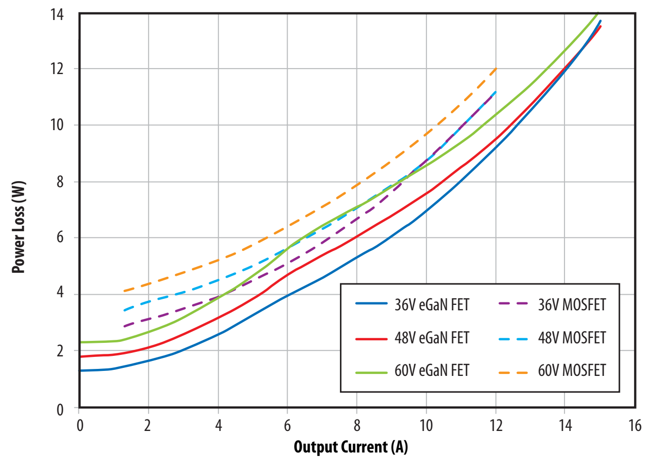

Figure 14 - Power loss comparison between 1/8th bricks: eGaN FET at 333 kHz and MOSFET at 250 kHz.

References:

[1] http://www.national.com/pf/LM/LM5020.html#Overview
[2] J. Strydom, M. de Rooij, "eGaNTM FET-Silicon PowerShoot-Out Part 3: Power over Ethernet", Power Electronics Technology Magazine, March 2011.
[3] http://www.linear.com/product/LT1952
[4] http://cds.linear.com/docs/Datasheet/3900fa.pdf
[5] http://www.ericsson.com/ourportfolio/products/pkb-c-series-eighth-brick
[6] http://www.national.com/pf/LM/LM5113.html#Overview
[7] http://epc-co.com/epc/documents/product-training/Appnote_Si_endofroad.pdf