AN4406
Application note

MDmesh™ M2:
the new ST super-junction technology ideal for resonant topologies

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Introduction

Today, power supply designers are facing a new and exciting challenge: the necessity to increase power density and efficient thermal management. A response to this challenge has been found in resonant topologies that typically employ the LLC resonant converter.

In this topology, the parasitic capacitances of the MOSFETs can impact system behavior by increasing switching losses and decreasing efficiency.

This application note provides the results of experimental performance analysis of the two latest and most advanced ST MOSFET super-junction technologies, MDmesh™ M2 and MDmesh™ M5, and compares them with well-known competitor devices in relation to MOSFET parasitic capacitance.

Contents

1 Description

To meet the ever-increasing demand for higher power density in consumer applications like notebooks, high-power adapters (over 150 W), desktop PCs, FPDTV, gaming SMPS, lighting, power supplies used for telecommunication equipment, mainframe computers and high-power systems in general (over 500 W), component counts, power loss, heat-sinks and reactive component sizes must be reduced.

The LLC resonant half bridge [*1*] represents a new alternative to the typical hard-switched half (full) bridge topology, whereby the load enables commutation of the bridge switches with near-zero voltage or current switch conditions, resulting in low switching losses and thus eliminating power loss due to overlapping switch current and voltage at each transition.

With this technique, the switching losses associated with the main power switching remain low even when the system operates at high frequencies, allowing for reduced component reactive sizes and simplified thermal management.

According to the resonance principle, each reactive component in the circuit contributes to the overall working frequency. As the frequency of the load range in the LLC topology is influenced by the magnetic transformer, two main working frequency values can be distinguished.

When the system operates under a light load, the effects of the intrinsic parasitic capacitances of the power MOSFET can impact both operation and switching power loss, resulting in decreased efficiency.

Resonant conversion has attracted concerted academic and industry research efforts over the last few decades because of the associated waveform, efficiency and power density improvements. However, the use of this technique in off-line powered equipment has long been confined to niche applications, such as high-voltage power supplies and audio systems.

Recent applications like flat panel TVs and the introduction of new voluntary and mandatory regulations concerning efficient energy use are pushing power designers to find increasingly efficient AC-DC conversion systems, promoting renewed interest in resonant conversion.

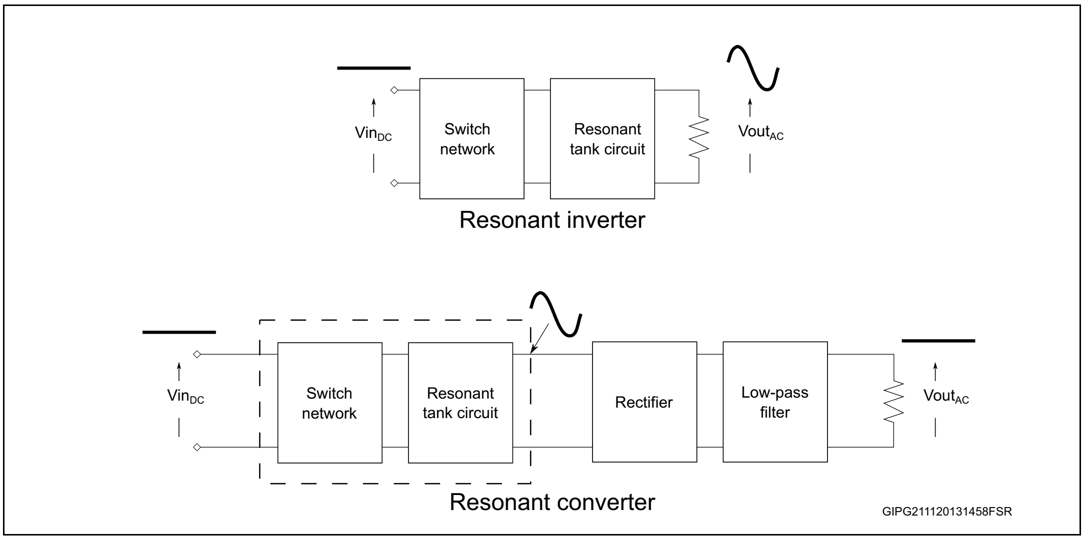
1.1 Resonant converters

Resonant converters form an extremely vast family of devices that are not easily gathered under one comprehensive definition. Generally speaking, they are switching converters with a tank circuit which influences the input-to-output power flow.

Most resonant converters are based on "resonant inverters", which are systems that convert DC into sinusoidal voltages (or AC voltages with low harmonic content) and provide AC power to a load [*2*]. To do so, a switch network typically produces a square-wave voltage applied to a resonant tank tuned to the fundamental component of the square wave. In this way, the tank responds primarily to this component and negligibly to the higher order harmonics, so that its voltage and/or current, as well as those of the load, are essentially sinusoidal or piecewise sinusoidal.

Figure 1 shows a resonant DC-DC converter providing DC power to a load by rectifying and filtering the AC output of a resonant inverter.

Figure 1. Simplified block diagram of a resonant inverter, the core of resonant converters

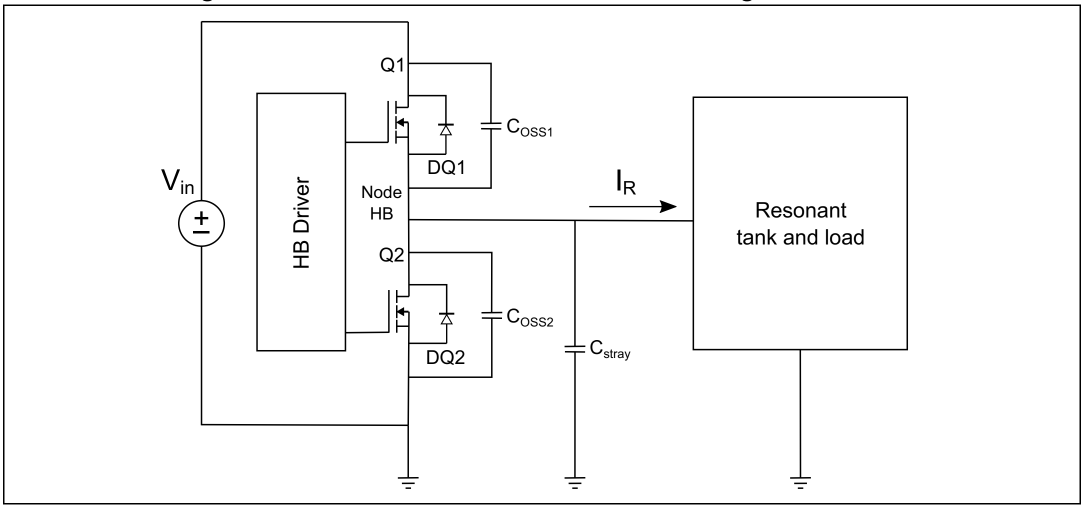


Various types of DC-AC inverters can be built with differing switch networks and resonant tank characteristics by altering the quantity and configuration of reactive elements.

1.2 Half-bridge and full-bridge switch networks

Switch networks that drive the resonant tank symmetrically with respect to both voltage and time, and act as a voltage source are known as half-bridge and full-bridge switch networks. Borrowing from power amplifier terminology, switching inverters driven by this kind of switch network are categorized "class D resonant inverters".

Figure 2. Resonant tank and load in half-bridge schematic



For resonant tanks with two reactive elements (one L and one C), there are a total of eight possible configurations, of which four are usable with a voltage source input. Two of these form part of the popular series-resonant and parallel-resonant converters for which an abundance of literature is available.

With three reactive elements, there are 36 possible tank circuit configurations, of which 15 are usable with a voltage source input and two popular resonant inverter topologies can be formed:

- an LCC (one L and two Cs) resonant inverter – the load is connected in parallel with one of the capacitors; commonly used in electronic, gas-discharge lamp ballasts;
- an LLC (two Ls and one C) resonant inverter – the load is connected in parallel with one inductor.

As previously stated, for any resonant inverter there is a corresponding DC-DC resonant converter obtained by rectification and filtering of the inverter output. The above mentioned inverters of course belong to the "class D resonant converters" category.

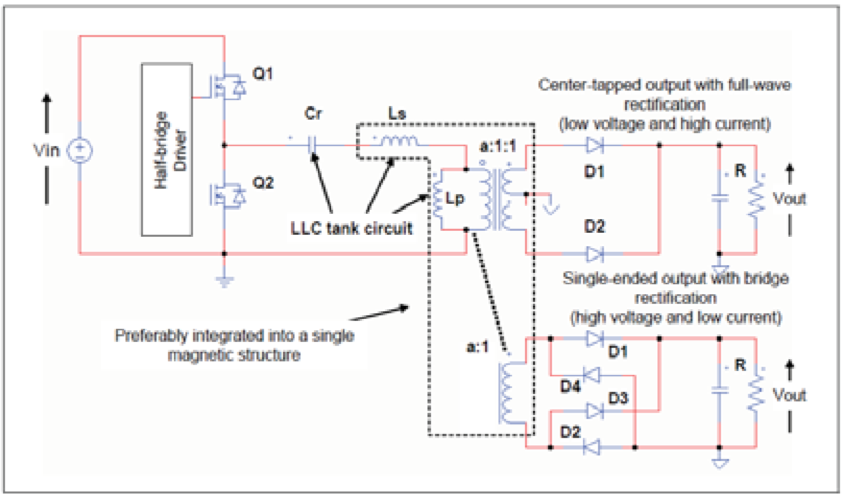
In off-line applications, the rectifier block is usually coupled to the resonant inverter through a transformer to provide the isolation required by safety regulations. To maximize the efficiency of the inverter, the rectifier block can be configured as:

- a full-wave rectifier (for low voltage / high current output) with a center tap arrangement of the transformer's secondary winding
- a bridge rectifier (for high voltage /low current output) without tapping.

The low-pass filter can be configured with capacitors only or with an L-C type smoothing filter, depending on the configuration of the tank circuit. The so-called "series-parallel" converter used in typical in high-voltage power supplies is derived from the LCC resonant inverter described above. Its mirror configuration, the LLC inverter, generates the converter with the same name.

We will consider the half-bridge implementation illustrated in *Figure 3*, but it can be easily extended to the full-bridge version.

Figure 3. LCC resonant half-bridge schematic



In resonant inverters and converters, power flow is controlled via the switch network by:

- changing the frequency of the square wave voltage, or its duty cycle, or both
- by special control schemes such as phase-shift control.

We shall control power flow through frequency modulation by adjusting the frequency of the square wave closer to or further from the tank circuit's resonant frequency, while keeping its duty cycle fixed.

2 MDmesh™ M2: the new ST super-junction technology ideal for resonant topologies

Table 1. ST super-junction technologies available on the market

Technology	Features
MDmesh™ M2 (500 V, 600 V, 650 V)	Extremely easy to use high performance device
	Ideal for resonant topologies such LLC converters, and also suitable for hard switching topologies
MDmesh™ M5 (550 V, 650 V)	Enhanced $R_{DS(on)}$ x area
	Best choice for higher power density and very low $R_{DS(on)}$

2.1 Key features and differences

MDmesh™ M2 is the latest ST step-up efficiency MOSFET technology featuring reduced gate charge that increases the efficiency of LLC topologies commonly used in power supplies and other electronics applications. It is a special, fast-acting variant of ST’s advanced super-junction Power MOSFET technologies already used in energy-efficient consumer products, computing and telecom systems, lighting controllers and solar energy equipment.

Super-junction technology has only been perfected by a small number of manufacturers and it allows power transistors to combine small dimensions, high voltage capacity and outstanding energy efficiency when activated.

ST is a world leader in this type of technology with its MDmesh Power MOSFETs, and now it delivers even better performance with its latest MDmesh™ M2 range. These devices feature reduced internal charge for high efficiency when switching as well as when conducting, saving even more energy in resonant-type power supplies commonly found in LCD TVs which occupy the mid-sized television market in the 200-500 W power range.

Their enhanced design results in a low gate charge (Qg) as well as low input and output capacitance, contributing to faster and more efficient switching, which further encourages designers wishing to implement super-junction transistors in resonant type power supplies for LCD TVs.

Until now, super junction transistors have been used most effectively in hard-switching topologies, where the device is forced to switch even under high current and voltage conditions. In a resonant power supply, two inductors and a capacitor (LLC converter) ensure the transistor is switched at zero voltage to smooth the flow of energy in the system and help increase efficiency.

The new MDmesh™ M2 family is also highly resistant to the effects of large and sudden changes in applied voltage (high dv/dt ruggedness), which can damage transistors and cause spurious switching. This allows the latest devices to perform reliably, even when exposed to large voltage transients such as noise and harmonics on AC power lines.

The first MDmesh™ M2 device produced by ST was the STP24N60M2 in the TO-220 package. ST is now expanding the family with devices up to 650 V across a range of more than 50 devices in a variety of packages, including TO-220FP, I^2PAK, I^2PAKFP, D^2PAK, TO-247 and PowerFLAT 8x8 HV and the new PowerFLAT 5x6 HV.

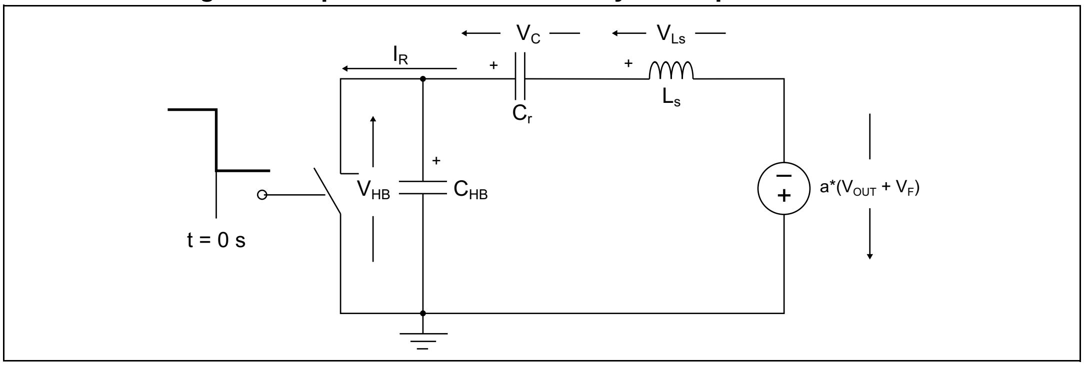
STP24N60M2 features:

- on-state resistance ($R_{DS(on)}$): 190 mΩ; Qg = 29 nC (typ.); -30% improvement
- breakdown voltage = 600 V; optimized capacitance profile
- maximum continuous drain current (I_D) = 18 A
- dv/dt ruggedness: 50 V/ns
- 100% avalanche tested

3 Impact of the MOSFET parasitic capacitances

The effects of the intrinsic capacitances of the MOSFET in the LLC topology under light load conditions can be analyzed through the midpoint transitions in the half-bridge topology [3]. In , the voltage value of the VHB point switches between 0 and V_{bus} via the two switches Q1 and Q2. As the effects of the parasitic capacitances are discernible under light loads, we shall refer to the equivalent circuit in *Figure 4* to simplify the analysis.

Figure 4. Equivalent circuit when system operates in CCM



When the system operates in CCM, the secondary side of the transformer is conducting and its effect on the primary side can be summarized as a constant voltage generator. C_{HB} represents the total parasitic capacitance of the V_{HB} node; during the transitions, it is in series with the C_r.

Taking into account the relationships between $V_c(0)$, I_{in}, C_r, T_s, when the system is in CCM:

Equation 1

$$V_C(0) = \frac{1}{2}\left(V_{in} \quad \frac{I_{in}}{C_r} T_S\right)$$

- $V_c(0)$ is the voltage across C_r
- I_{in} is the input current
- T_s the switching period
- I_R the current tank

while the equation for the Va node is:

Equation 2

$$\frac{d^2V_{HB}}{dt} + \frac{1}{C_{HB}L_S} V_{HB} = \frac{V_C(0) \quad a \quad (V_{out} + V_F)}{C_{HB}L_S}$$

Equation 3

$$I_R(t) = C_{HB}\frac{dV_{HB}(t)}{dt}$$

So, for the time T_T for voltage V_{HB} to reach V_{in}, T_T can be expressed as:

Equation 4

$$T_T = \frac{V_{in}(t)}{I_R(0)} C_{HB}$$

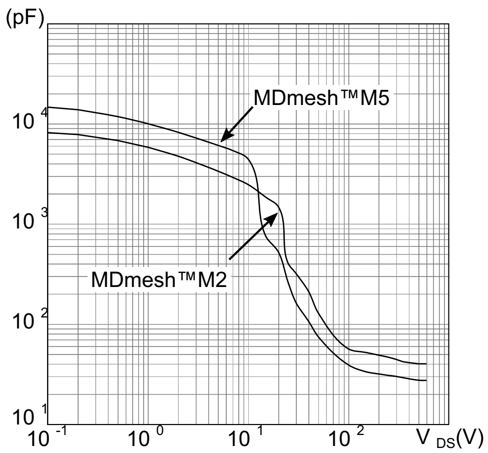
Note: In order to guarantee the ZVS transitions, the value of T_T must not exceed the dead time T_D to ensure that the switch is turned on with zero V_{DS} voltage.

From the previous equation, it is possible to note that converter operation may be influenced by the parasitic capacitances of the MOSFET, so MOSFET's switching behavior can be affected by the parasitic capacitances between the three terminals of the device: gate-to-source (C_{GS}), gate-to-drain (C_{GD}) and drain-to-source (C_{DS}) capacitances.

These capacitance values are non-linear and a function of device structure, geometry, and bias voltages V_{DS}. The magnitudes are largely determined by the size of the chip and cell topology used. Manufacturers do not generally specify C_{GD}, C_{GS} and C_{DS} directly, but the magnitudes and the profile of the parasitic capacitances are given in datasheets by the voltage V_{DS} and also by the technology of the MOSFET.

In *Figure 5*, the C_{oss} parasitic capacitances of two MOSFETs with the same die size but with different technologies are shown.

Figure 5. Output capacitances of two devices with same die size but different technologies

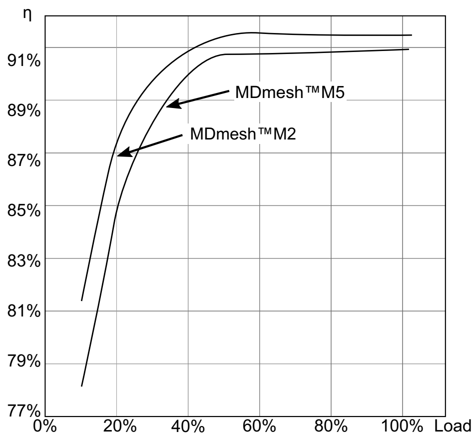


The technology with the larger density cell (MDmesh™ M5) clearly has a higher C_{OSS} parasitic capacitance value at low V_{DS} voltages. This aspect is not only due to the cellular density, but also the different doping process used to obtain the same V_{DSS}. In fact, the two analyzed devices have same die size, same B_{VDSS}, but different $R_{DS(on)}$ owing to the different technologies adopted.

The theory introduced earlier helps explain the impact of MOSFET parasitic capacitances when it used on resonant topologies.

The following graph shows the efficiency data of a 200 W LLC system

Figure 6. Efficiency of the system @ V_{in}= 230 V_{ac}



In *Figure 6* the MDmesh™ M2 performed better across the entire load range. The gain is noticeably larger at light load and decreases as the system approaches full load. To help explain this important phenomenon, the switching operations are shown below.

Figure 7 and *Figure 8* relate to the turn-off operations for the MDmesh™ M5 and MDmesh™ M2, respectively.

Figure 7. Turn-off operations for the MDmesh™ M5 at light load

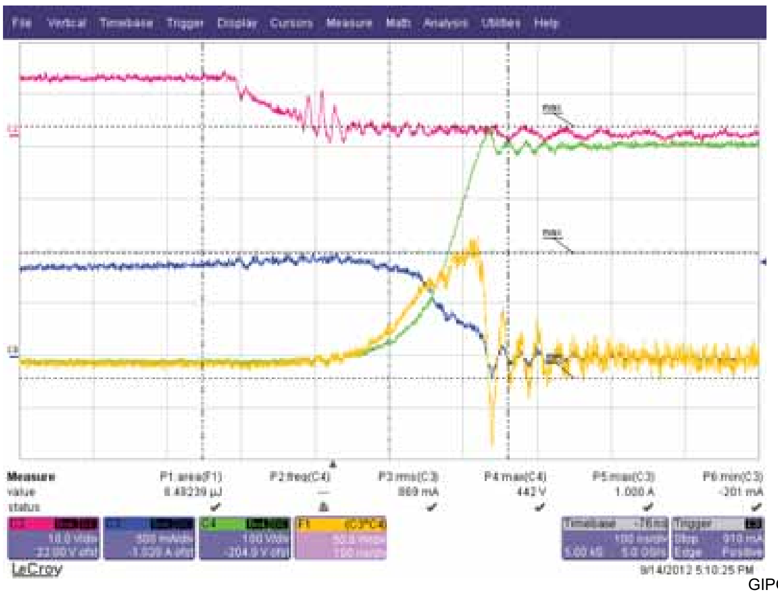


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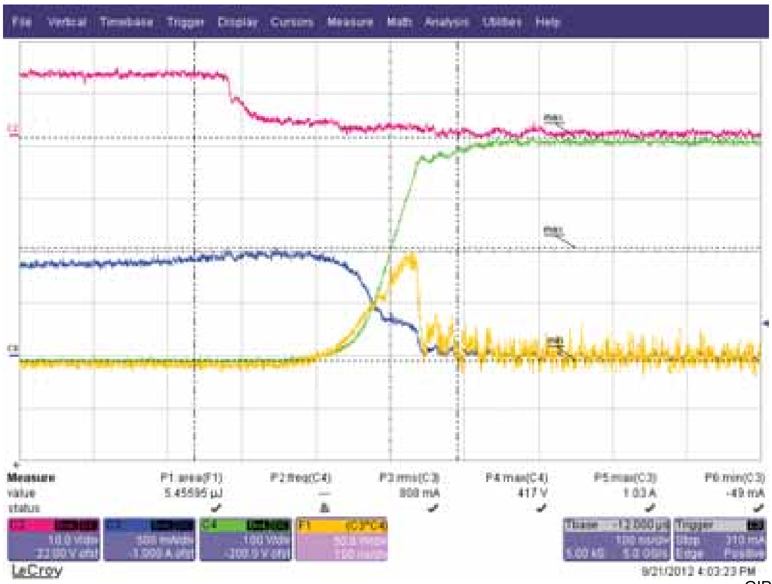
Figure 8. Turn-off operations for the MDmesh™ M2 at light load



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In the above images, it is also possible to note the higher power losses for the MDmesh™ M5 device with respect to the MDmesh™ M2.

Moreover, we can add that the energy stored in the resonant inductor Lm quickly charges the C_{oss} of the device. Since the energy is fixed by the current level, the energy stored inside Lm is the same in both cases. Therefore one of the most important factors influencing the different shapes is the C_{OSS} value and its evolution during the transition. The non-ideal state of the transistor in the storage process during turn-off is also influential.

4 Testing and comparing

Three demonstration boards (150 W, 200 W and 400 W) are used to test and compare the electrical performance of the ST MDmesh™ M2 and MDmesh™ M5 MOSFET super-junction technologies in resonant topologies.

4.1 150 W resonant LLC high power adapter based on L6599 and STP9N60M2

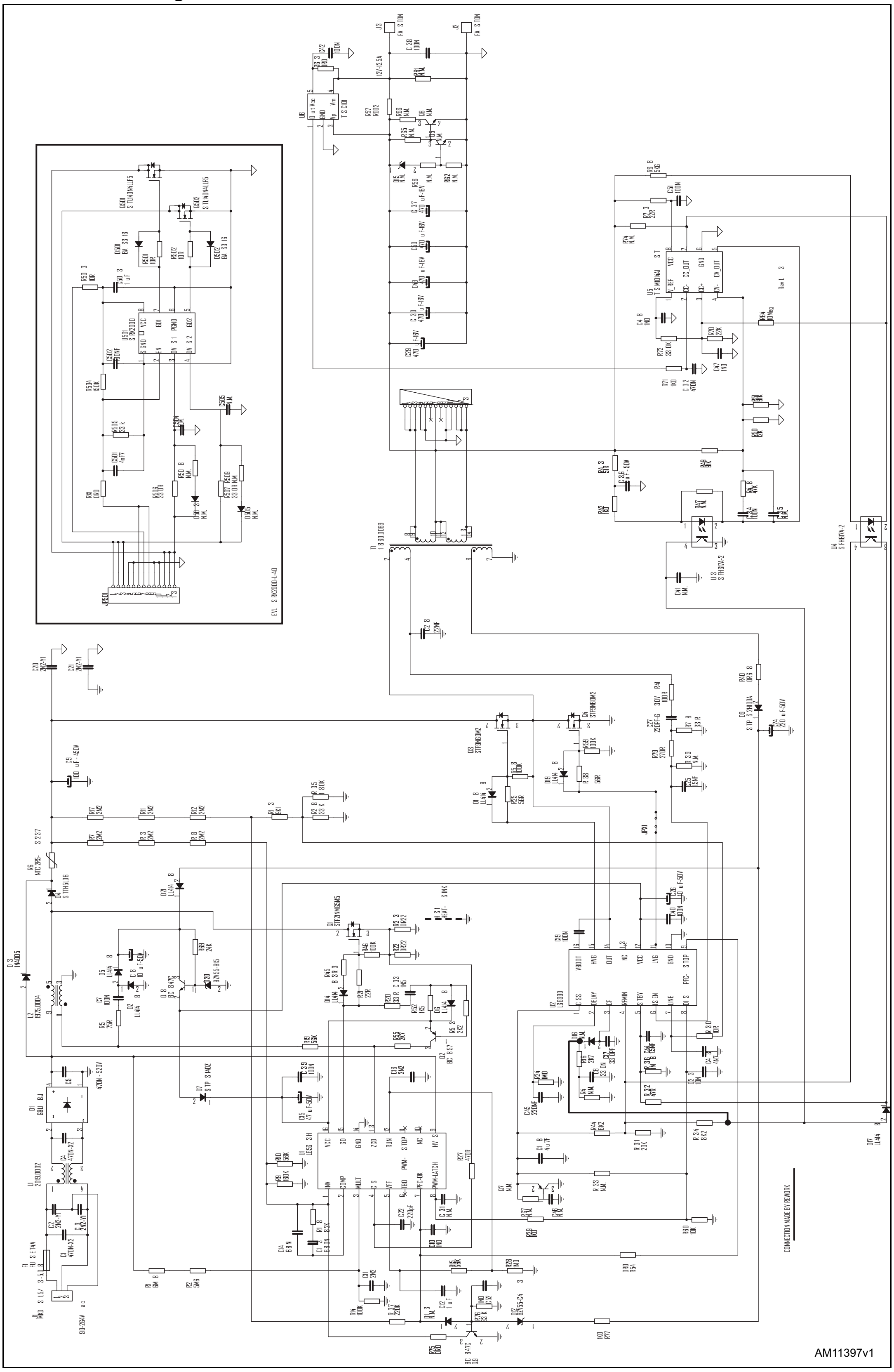
The first demonstration board used to test and compare the electrical performance of the MDmesh™ M2 and MDmesh™ M5 ST MOSFET technologies is the EVL6699-150W-SR, a 12 V – 150 W converter tailored to a typical all-in-one (AIO) computer power supply or a high power adapter specification [4].

The architecture is based on a two-stage approach:

1. a front-end PFC pre-regulator based on the L6563H TM PFC controller
2. a downstream LLC resonant half-bridge converter using the new L6699 resonant controller

Figure 9. EVL6699-150W-SR 150 W SMPS demonstration board

Figure 10. EVL6699-150W-SR 150 W electrical schematic



4.1.1 Purpose and description

This analysis tested and compared the electrical performance of the STF9N60M2 and STF8N65M5 MOSFET devices using the MDmesh™ M2 and MDmesh™ M5 technologies respectively, when mounted on a EVL6699-150W demo board (LLC topology).

To perform the test, the devices were removed from the original position and soldered on the back without a heat sink. All the measurements were performed at 25 °C ambient temperature.

In order to obtain the waveforms of the main electrical parameters of the devices, small wires loop were inserted on each pin.

Attention was focused on the electrical parameters of the MOSFETs, including voltage across drain and source (V_{DS}), current (I_D) and voltage across gate to source (V_{GS}).

The test sequence was with V_{in} = 230 V_{ac} and steady state at:

- 10% of the maximum load – $I_{OUT(tot)}$ fixed (1.2 A);
- 20% of the maximum load – $I_{OUT(tot)}$ fixed (2.4 A);
- 50% of the maximum load – $I_{OUT(tot)}$ fixed (6.0 A);
- 100% of the maximum load – $I_{OUT(tot)}$ fixed (12 A);

4.1.2 Main parameters

Device selection was based on electrical characteristics like $V_{(BR)DSS}$, $R_{DS(on)}$ and package.

Table 2. ST super-junction technologies available on the market

Parameter	Test conditions	STF9N60M2	STF8N65M5	Unit
(1)$V_{(BR)DSS}$	V_{GS} = 0 V, I_D = 1 mA	680	700	V
(1)$R_{DS(on)}$	V_{GS} = 10 V, I_D = 5.5 A	0.719	0.401	Ω
V_{th}	I_D = 250 µA	2.9	4.5	V
C_{iss}	50 V / 100 V	320	690	pF
C_{oss}	50 V / 100 V	18	18	pF
C_{rss}	50 V / 100 V	0.68	2	pF
Q_g	V_{DD} = 520 V, V_{GS} = 0 V	10	15	nC
R_g (typ.)	f = 1 MHz	6.5	4	Ω

1. Measured parameter

4.1.3 Results

From the electrical results, the performance of the devices under test are conditioned by the current level. Since this topology operates at low current levels during the switch-off operations, the main advantages of the MDmesh™ M5 technology are lost and the MDmesh™ M2 devices perform better, showing higher efficiency in resonant topologies, especially when the system is operating at low load.

Figure 11. Efficiency data vs load level in 150W resonant LLC

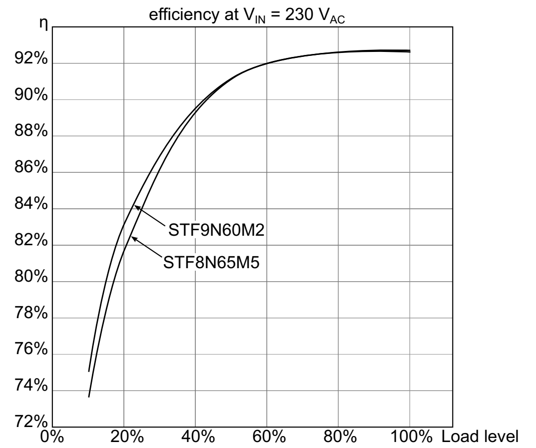


Figure 12. η (%) efficiency at V_{IN} = 230 V_{AC} for specific load %

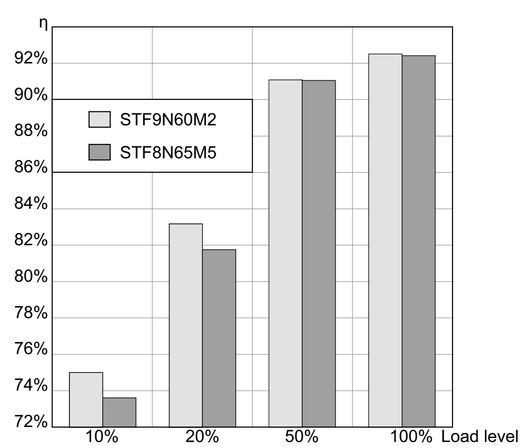
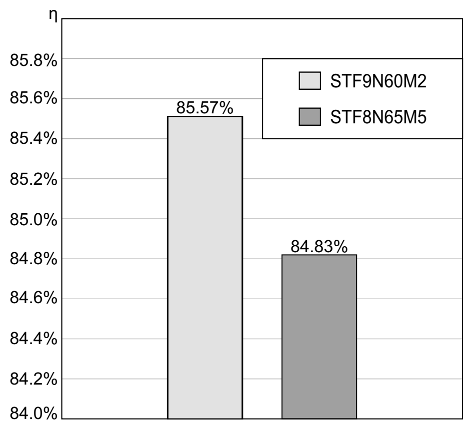


Figure 13. Average % efficiency at V_{IN} = 230 V_{AC}



4.2 200 W HB LLC resonant converter for LCD TV and flat panels based on L6599 and STF13N60M2

A 200 W reference board was used to test and compare the electrical performance of the ST MDmesh™ M2 and MDmesh™ M5 MOSFET technologies against the best competitor super-junction devices, with wide-range mains operation and power-factor-correction (PFC) []. Its electrical specification is tailored to typical high-end LCD TV or monitor applications.

The main features of this design are:

- very low no-load input consumption (<0.5 W)
- very high global efficiency; > 87% at full load and nominal mains voltage (115 – 230 V_{AC}).

The circuit consists of three main blocks:

1. a front-end PFC pre-regulator based on the L6563 PFC controller
2. a multi-resonant half-bridge converter which is controlled through the STMicroelectronics L6599 resonant controller.
3. an auxiliary flyback converter based on the VIPer12A-E off-line primary switcher completes the architecture, mainly intended for microprocessor supply and display power management operations.

Figure 14. L6599 and L6563 200 W evaluation board (EVAL6599-200W)

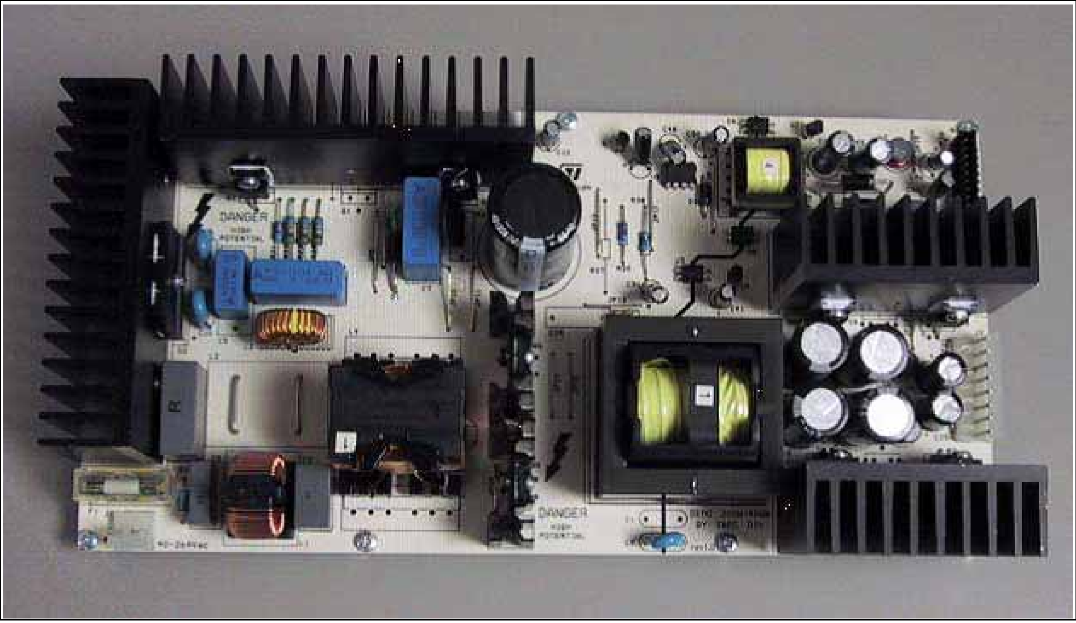
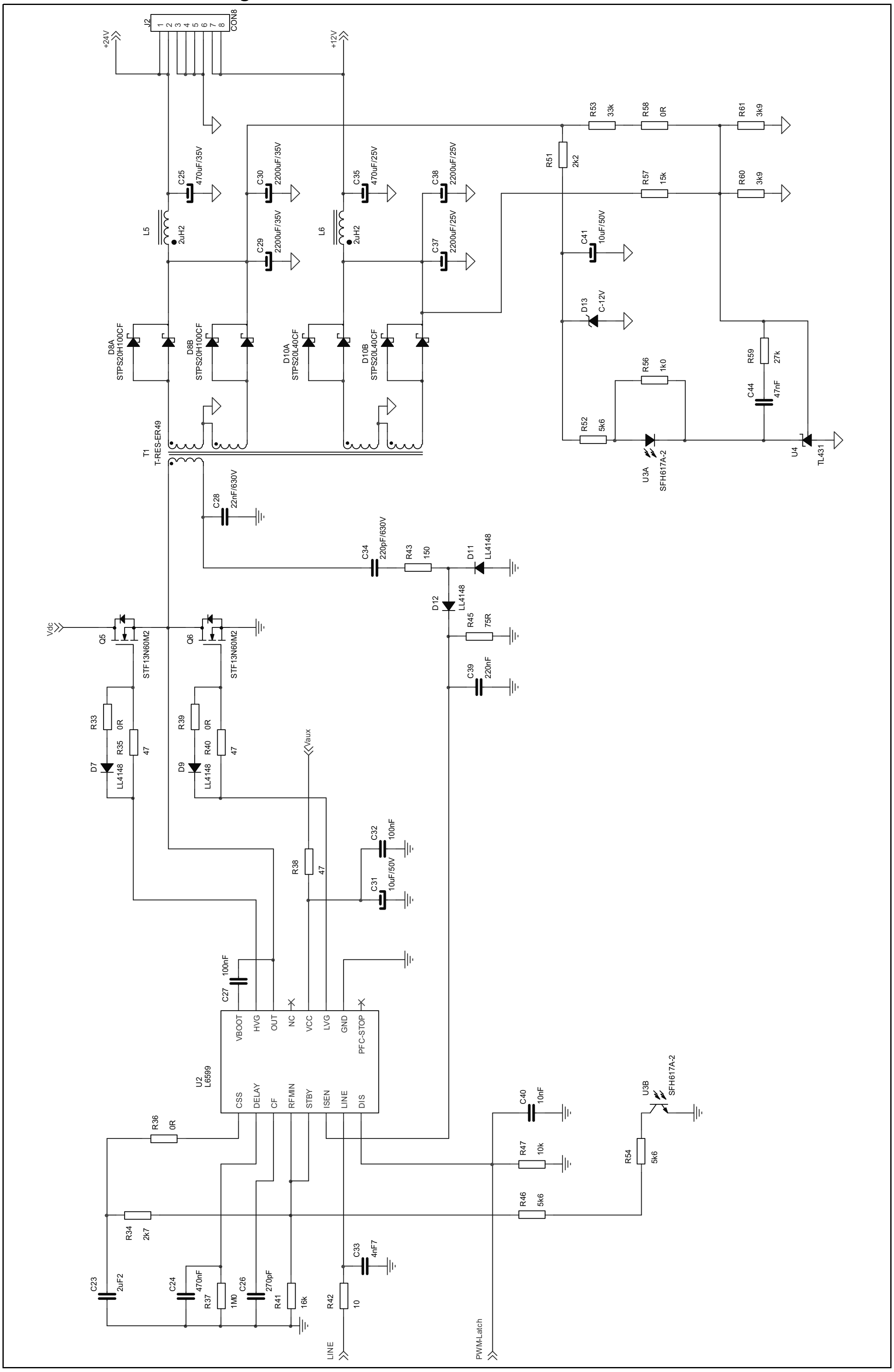


Figure 15. 200 W SMPS electrical schematic



4.2.1 Purpose and description

This analysis tested and compared the electrical performance of the STF9N60M2 and STF8N65M5 MOSFETs using the MDmesh™ M2 and MDmesh™ M5 technologies respectively against well-known super-junction competitor device A, when mounted on an EVAL-6599 demo board (200 W LLC topology).

To perform the test, the devices were removed from the original position and soldered on the back without a heat sink. All the measurements were performed at 25 °C ambient temperature.

In order to obtain the waveforms of the main electrical parameters of the devices, small wires loop were inserted on each pin.

Attention was focused on the electrical parameters of the MOSFETs, including voltage across drain and source (V_{DS}), current (I_D) and voltage across gate to source (V_{GS}).

The test sequence was with V_{in} = 230 V_{ac} and steady state at:

- 10% of the maximum load – $I_{OUT(tot)}$ fixed (0.262 A);
- 20% of the maximum load – $I_{OUT(tot)}$ fixed (0.525 A);
- 50% of the maximum load – $I_{OUT(tot)}$ fixed (1.312 A);
- 100% of the maximum load – $I_{OUT(tot)}$ fixed (2.625 A);

4.2.2 Main parameters

Device selection was based on electrical characteristics like $V_{(BR)DSS}$, $R_{DS(on)}$ and package.

Table 3. ST super-junction technologies available on the market

Parameter	Test conditions	STF13N60M2	STF15N65M5	Competitor	Unit
(1)$V_{(BR)DSS}$	V_{GS} = 0 V, I_D = 1 mA	680	680	730	V
(1)$R_{DS(on)}$	V_{GS} = 10 V, I_D = 5.5 A	0.334	0.25	0.34	Ω
C_{iss}	50 V / 100 V /50 V	580	983	710	pF
C_{oss}	50 V / 100 V /50 V	32	57	41	pF
C_{rss}	50 V / 100 V /50 V	1.1	4.5	—	pF
R_g	f = 1 MHz	6.6	4.6	7.5	Ω

1. Measured parameter

4.2.3 Results

From the electrical results, the performance of the devices under test are conditioned by the current level. In the resonant topology, at low load, the impact of the output capacitance of the MOSFETs determine the lost energy dissipated inside the devices.

Figure 16. Efficiency data vs load level in 200 W evaluation board

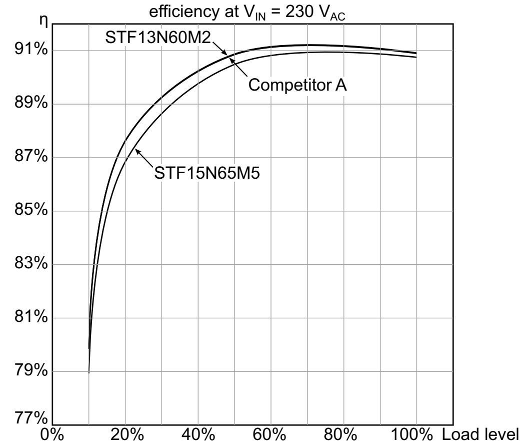


Figure 17. η (%) efficiency at V_{IN} = 230 V_{AC} for specific load %

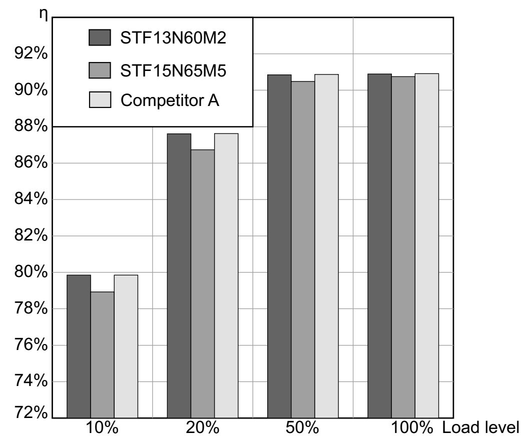
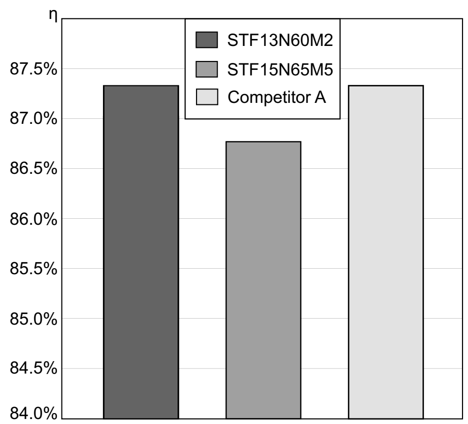


Figure 18. Average % efficiency at V_{IN} = 230 V_{AC}



4.3 400 W HB LLC resonant converter for PDP applications based on L6599 and STP24N60M2

This section describes the performances of a 400 W reference board, with wide-range mains operation and power-factor-correction (PFC) and presents the results of the bench evaluation [6]. The electrical specification refers to a power supply for a typical high-end PDP application.

The main features of this design are:

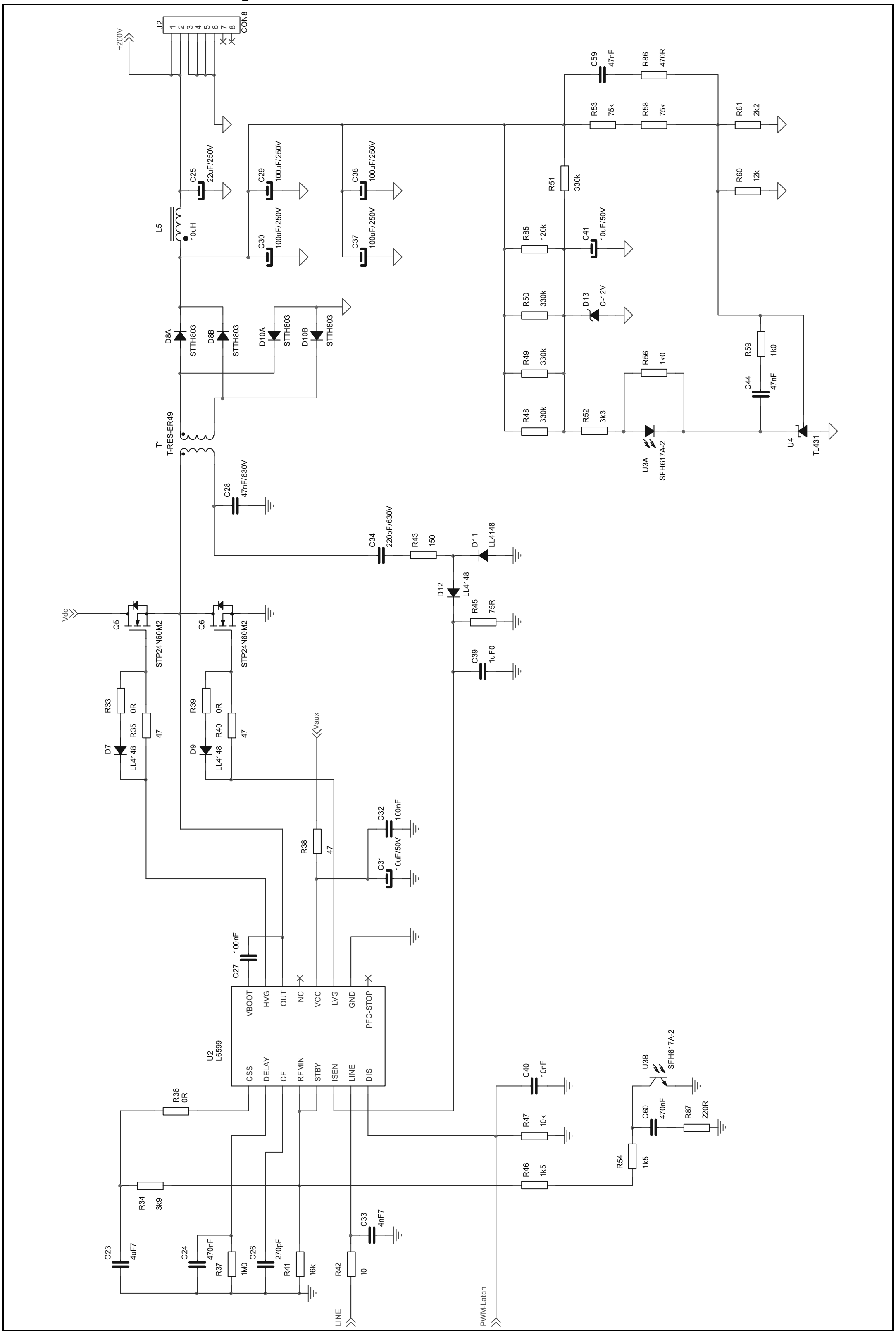
- very low no-load input consumption (< 0.5 W)
- very high global efficiency; > 90% at full load and nominal mains voltage (115 – 230 V_{AC}).

The circuit consists of three main blocks:

1. a front-end PFC pre-regulator based on the L6563 PFC controller
2. a multi-resonant half-bridge converter with an output voltage of +200 V / 400 W, controlled through the L6599 resonant controller
3. an auxiliary flyback converter based on the VIPer12A off-line primary switcher completes the architecture, delivering a total power of 7 W on two output voltages (+3.3 V and +5 V), mainly intended for microprocessor supply and display power management operations.

Figure 19. L6599 and L6563 400 W evaluation board (EVAL6599-400W-S)

Figure 20. 400 W SMPS electrical schematic



4.3.1 Purpose and description

This analysis tested and compared the electrical performance of the STP24N60M2 and STP20N65M5 MOSFETs using the MDmesh™ M2 and MDmesh™ M5 technologies respectively against well-known super-junction competitor devices A and B, when mounted on a demo board (400 W LLC topology).

To perform the test, the devices were removed from the original position and soldered on the back without a heat sink. All the measurements were performed at 25 °C ambient temperature.

In order to obtain the waveforms of the main electrical parameters of the devices, small wires loop were inserted on each pin.

Attention was focused on the electrical parameters of the MOSFETs, including voltage across drain and source (V_{DS}), current (I_D) and voltage across gate to source (V_{GS}).

The test sequence was with V_{in} = 230 V_{ac} and steady state at:

- 10% of the maximum load – $I_{OUT(tot)}$ fixed (0.371 A);
- 20% of the maximum load – $I_{OUT(tot)}$ fixed (0.742 A);
- 50% of the maximum load – $I_{OUT(tot)}$ fixed (1.855 A);
- 100% of the maximum load – $I_{OUT(tot)}$ fixed (3.71 A);

4.3.2 Main parameters

Device selection was based on electrical characteristics like $V_{(BR)DSS}$, $R_{DS(on)}$ and package.

Table 4. ST super-junction technologies available on the market

Parameter	Test conditions	STF13N60M2	STF15N65M5	Competitor A	Competitor B	Unit
(1)$V_{(BR)DSS}$	V_{GS} = 0 V, I_D = 1 mA	640	713	700	635	V
(1)$R_{DS(on)}$	V_{GS} = 10 V, I_D = 5.5 A	0.712	0.158	0.177	0.137	Ω
V_{th}	I_D = 250 µA	2.9	4.1	3.1	3.7	V
C_{iss}	100 V / 100 V / 100 V / 25 V	1060	1434	1400	1600	pF
C_{oss}	100 V / 100 V / 100 V / 25 V	55	38	85	61	pF
C_{rss}	100 V / 100 V / 100 V / 25 V	2.2	3.7	-	8.2	pF
Q_g	V_{DD} = 520 V, V_{GS} = 0 V	29	36	63	27	nC
R_g	f = 1 MHz	7	3.5	8.5	2.5	Ω

1. Measured parameter

4.3.3 Results

From the electrical results, the performance of the devices under test are conditioned by the current level. In the resonant topology, at low load, the impact of the output capacitances of the MOSFET's determine the energy losses dissipated inside the devices. Their variation with voltage V_{DS} and their symmetry play a fundamental role on the final performance.

Figure 21. Efficiency data vs load level in 400 W evaluation board

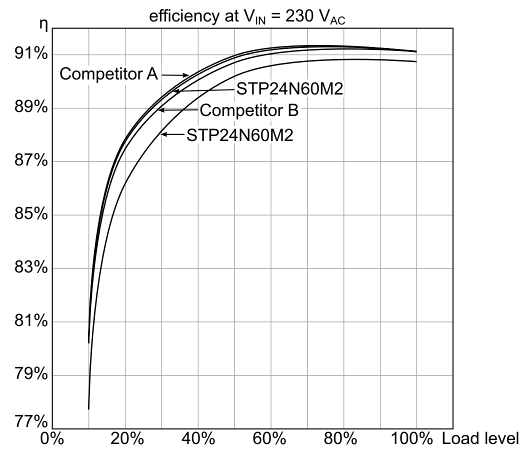


Figure 22. η (%) efficiency at V_{IN} = 230 V_{AC} for specific load %

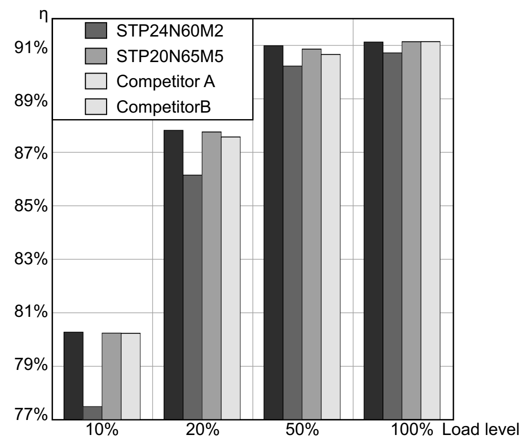
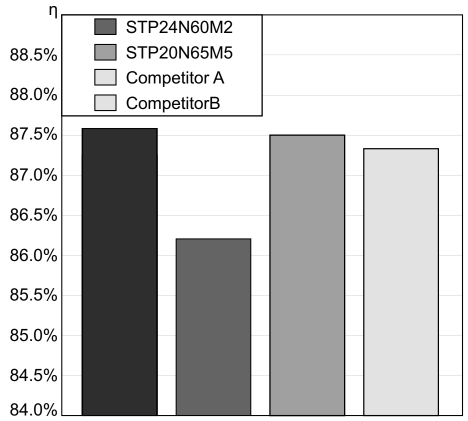


Figure 23. Average % efficiency at V_{IN} = 230 V_{AC}



5 Conclusion

In the present document, we analyzed the LLC resonant topologies, looking at the effects of the parasitic elements of the MOSFET used in the half bridge configuration. Tests were performed on 150 W, 200 W and 400 W LLC SMPS using ST and competitor technologies with differing intrinsic capacitance behavior.

The results have shown that the output capacitance profile influences the switching operation and determines the total performance of the system. Even though the technology MDmesh™ M5 has a better $R_{DS(on)}$ parameter than MDmesh™ M2 on the resonant topologies, the advantages obtained during the conduction phase may be countered by the performance during the transition phases, especially under light load conditions.

As these topologies operate at low current levels during switch-off operations, the main advantages of the MDmesh™ M5 technology are lost and the performance of the MDmesh™ M2 is superior.

The MDmesh™ M2 offers higher efficiency, especially when the system operates under low load.

6 References

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7 Revision history

Table 5. Document revision history

Date	Revision	Changes
30-Mar-2015	1	Initial release.