International IOR Rectifier

APPLICATION NOTE

Application Note AN-1070

Class D Audio Amplifier Performance Relationship to MOSFET Parameters

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This application note discusses key parameters to be considered in the selection of MOSFETs for class D amplifier and their relationship with amplifier performance such as efficiency, EMI, and THD. In addition, benefits and advantages of IR Digital Audio MOSFETs in class D audio amplifier are presented.

Abstract

This application note discusses key parameters to be considered in the selection of MOSFETs for class D audio amplifier and their relationship with amplifier's performance such as efficiency, EMI, and THD. In addition, benefits and advantages of IR Digital Audio MOSFETs in class D audio amplifier are presented.

Introduction

Class D audio amplifier is a switching amplifier that consists in a pulse width modulator (with switching frequency in order of several hundred kHz), a power bridge circuit and a low pass filter. This type of amplifier has demonstrated to have a very good performance. These include power efficiencies over 90%, THD under 0.01%, and low EMI noise levels that can be achieved with a good amplifier design. Details of class D audio amplifier theory are explained in Application Note "Class D Audio Amplifier Basics" [4].

Key factors to achieve high performance levels in the amplifier are the switches in power bridge circuit. Power losses, delay times, and voltage and current transient spikes should be minimized as much as possible in these switches in order to improve amplifier performance. Therefore, switches with low voltage drop, fast on and off switching times and low parasitic inductance are needed in this amplifier.

MOSFET have proved to be the best switch option for this amplifier because of its switching speed. It is a majority carrier device, its switching times are faster in comparison with other devices such as IGBT or BJT [1], resulting in better amplifier efficiency and linearity.

Key MOSFET Electrical Parameters in Class D Audio Amplifiers.

As in any other application, the MOSFET selection is done in base amplifier specifications. Thus, information such as amplifier output power and load impedance (i.e. 100W into 8Ω), power bridge circuit topology (i.e. Full-Bridge or Half-Bridge), and modulation factor (i. e. 80% - 90%) should be known before the selection process.

- Drain-Source Breakdown Voltage, BV_{DSS}.

Amplifier operating voltage determines the selection of MOSFET voltage rating. However, other circuit design related factors should be taken in consideration, such as stray resistance, MOSFET switching peak voltages because of stray inductance, and power supply fluctuations. Otherwise, the MOSFET can be in avalanche condition during operation degenerating amplifier performance.

Thus, the minimum BV_{DSS} is chosen by the desired amplifier output power and load impedance, power bridge circuit topology, modulation factor, and an additional factor related with circuit issues (frequently used 10% - 50%) as follows:

$$BV_{DSS\ min\ (full\text{-}bridge\ conf.)} = \frac{\sqrt{2 * P_{OUT} * R_{LOAD}}}{M} + \text{Additional factor due to circuit related issues}$$

$$BV_{DSS\ min\ (half\text{-}bridge\ conf.)} = 2 * \sqrt{\frac{2 * P_{OUT} * R_{LOAD}}{M}} + \text{Additional factor due to circuit related issues}$$

The following table is an example of minimum MOSFET voltage rating selection for different class D audio amplifier conditions:

Full-Bridge Configuration						
	BV_{DSS} Minimum (V)			Corresponding IR MOSFET BV_{DSS} (V)		
	Load (Ohms)			Load (Ohms)		
Output Power (W)	**4**	**6**	**8**	**4**	**6**	**8**
100	36.6	44.8	51.8	40	55	55
150	44.8	54.9	63.4	55	55	75
200	51.8	63.4	73.2	55	75	75
250	57.9	70.9	81.8	75	75	100

Half-Bridge Configuration						
	BV_{DSS} Minimum (V)			Corresponding IR MOSFET BV_{DSS} (V)		
	Load (Ohms)			Load (Ohms)		
Output Power (W)	**4**	**6**	**8**	**4**	**6**	**8**
100	73.2	89.7	103.5	75	100	150
150	89.7	109.8	126.8	100	150	150
200	103.5	126.8	146.4	150	150	150
250	115.7	141.8	163.7	150	150	200

Note 1. Modulation factor, M = 85%.
Note 2. Additional factor due to circuit related issues = 10%.

Table 1. Minimum MOSFET voltage rating for different class D audio amplifier conditions.

It is important to choose the lowest BV_{DSS} possible because this parameter is related to others such as $R_{DS(on)}$. Higher BV_{DSS} results in higher $R_{DS(on)}$ and higher MOSFET power losses. Therefore, this should be taken into consideration for "factor due to circuit related issues" selection.

In summary, the voltage rating of the MOSFET should be selected according to amplifier operating voltage. It should also be large enough to avoid avalanche condition during operation.

- Static Drain-to-Source On-Resistance, $R_{DS(on)}$.

Amplifier efficiency is related to MOSFET total power losses. These power losses are the result of MOSFET conduction, switching, and Gate charge losses. Furthermore, the MOSFET's junction temperature T_J and heatsink size depend on this power losses amount. High power losses increase T_J, and therefore, heatsink size.

MOSFET conduction losses are directly related to $R_{DS(on)}$ parameter. $R_{DS(on)}$ is the Drain-Source resistance, typically specified on datasheet at 25°C with V_{GS} = 10V for standard Gate MOSFETs [5]. $R_{DS(on)}$ along with Drain current define MOSFET conduction losses during amplifier operation, and can be calculated as follows:

$$P_{CONDUCTION} = (I_{D\ RMS})^2 * R_{DS(on)}$$

$R_{DS(on)}$ is temperature-dependent, increasing when T_J increases. Care must be taken during the thermal design, regarding this, to avoid thermal runaway. In addition, it is important that the maximum MOSFET junction temperature $T_{J\ max}$, should not be higher than specified in the datasheet during all amplifier operating conditions. Then, the maximum MOSFET conduction losses calculation should be done at maximum amplifier operating conditions, using $R_{DS(on)}$ at $T_{J\ max}$, typically specified in the datasheet, and maximum $I_{D\ RMS}$ current.

Therefore, lower $R_{DS(ON)}$ results in lower MOSFET conduction losses and consequently better amplifier efficiency. This is illustrated in Figure 1.

Lower $R_{DS(ON)} \Rightarrow$ Lower $P_{CONDUCTION} \Rightarrow$ Better efficiency

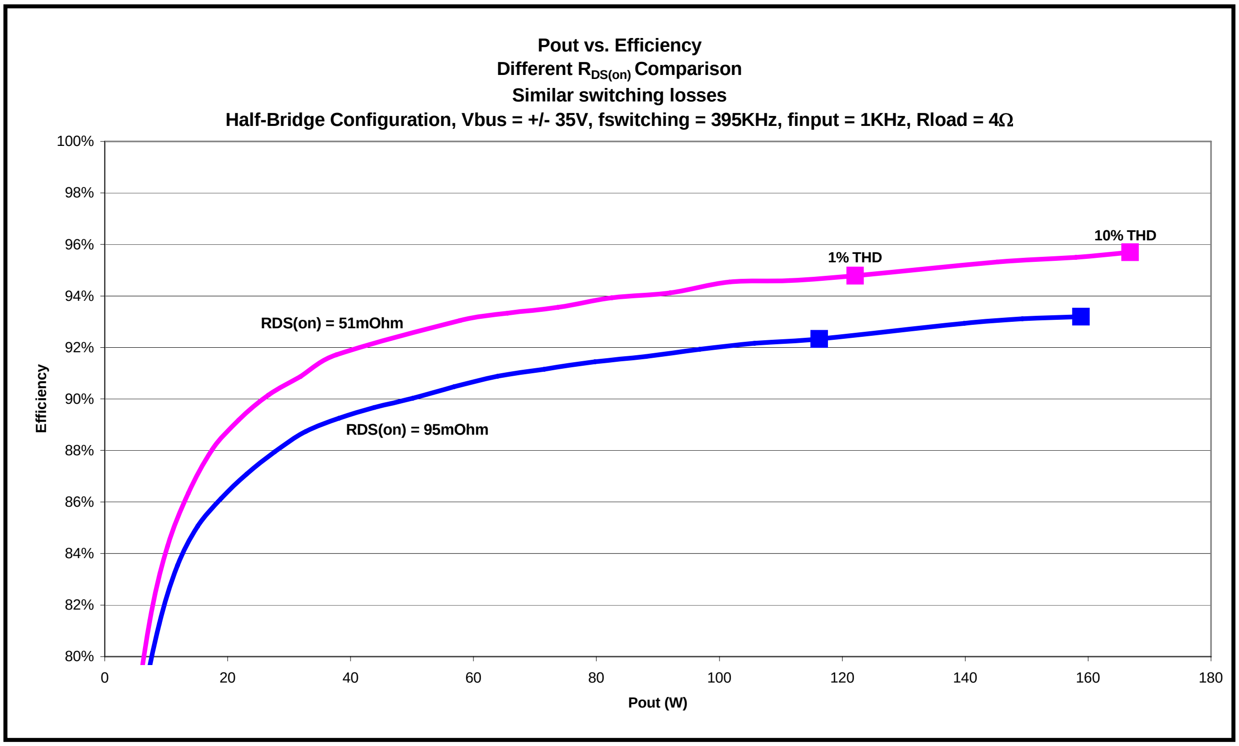


Figure 1. Amplifier efficiency using different MOSFET $R_{DS(on)}$ and similar switching losses.

- Gate Charge, Q_g.

The MOSFET Gate charge Q_g is the charge required by the Gate to fully turn-on the MOSFET. This parameter is temperature-independent and is directly related to the MOSFET's speed. Lower Q_g results in faster switching speeds and lower Gate losses; consequently, lower switching losses and better efficiency is achieved.

MOSFET switching losses are defined as:

$$P_{TOTAL\ SWITCHING} = P_{SWITCHING} + P_{GATE}$$

Switching losses are the result of MOSFET turn-on and turn-off switching times illustrated in Figure 2. Switching losses are calculated by multiplying switching energy E_{sw}, with the amplifier's PWM switching frequency f_{sw}.

$$P_{SWITCHING} = E_{sw} * f_{sw}$$

And, switching energy E_{sw} is obtained by:

$$E_{sw} = \int_0^t V_{DS}(t) * I_D(t)\, dt$$

Where, t is the length of switching pulse.

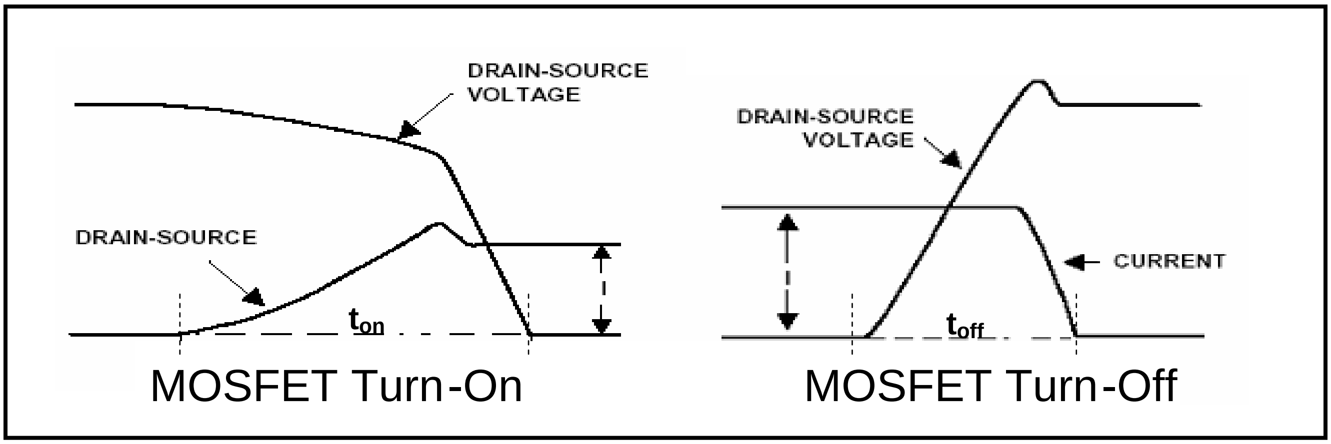


Figure 2. MOSFET turn-on and turn-off waveforms.

Acceptable switching losses estimations can be done by using the amplifier's specifications and the MOSFET's datasheet parameters as follow:

$$P_{SWITCHING} = [0.5 * I_D * V_{bus} * (t_r + t_f) * f_{sw}] + [0.5 * C_{oss} * V_{bus}^2 * f_{sw}] + [K * 0.5 * Q_{rr} * V_{bus} * f_{sw}]$$

Where V_{bus} is amplifier's bus voltage, t_r and t_f are MOSFET rise and fall times, C_{oss} is MOSFET output capacitance, Qrr is MOSFET body diode reverse recovery charge, and K is the factor due to MOSFET T_J and specific amplifier's conditions such as I_F and dI_F/dt.

Gate losses can be estimated:

$P_{GATE} = 2 * Q_g * V_{driver} * f_{sw}$

Where, V_{driver} is voltage of the Gate driver.

Also, amplifier linearity is affected by switching timing errors such as MOSFET turn-on and turn-off delay times. This implies that the amplifier linearity is also affected by higher Q_g. However, these timing errors caused by MOSFET switching are not as significant when compared to dead time and, can be significantly reduced by selecting the right dead time value [4]. This is illustrated in Figures 3 and 4.

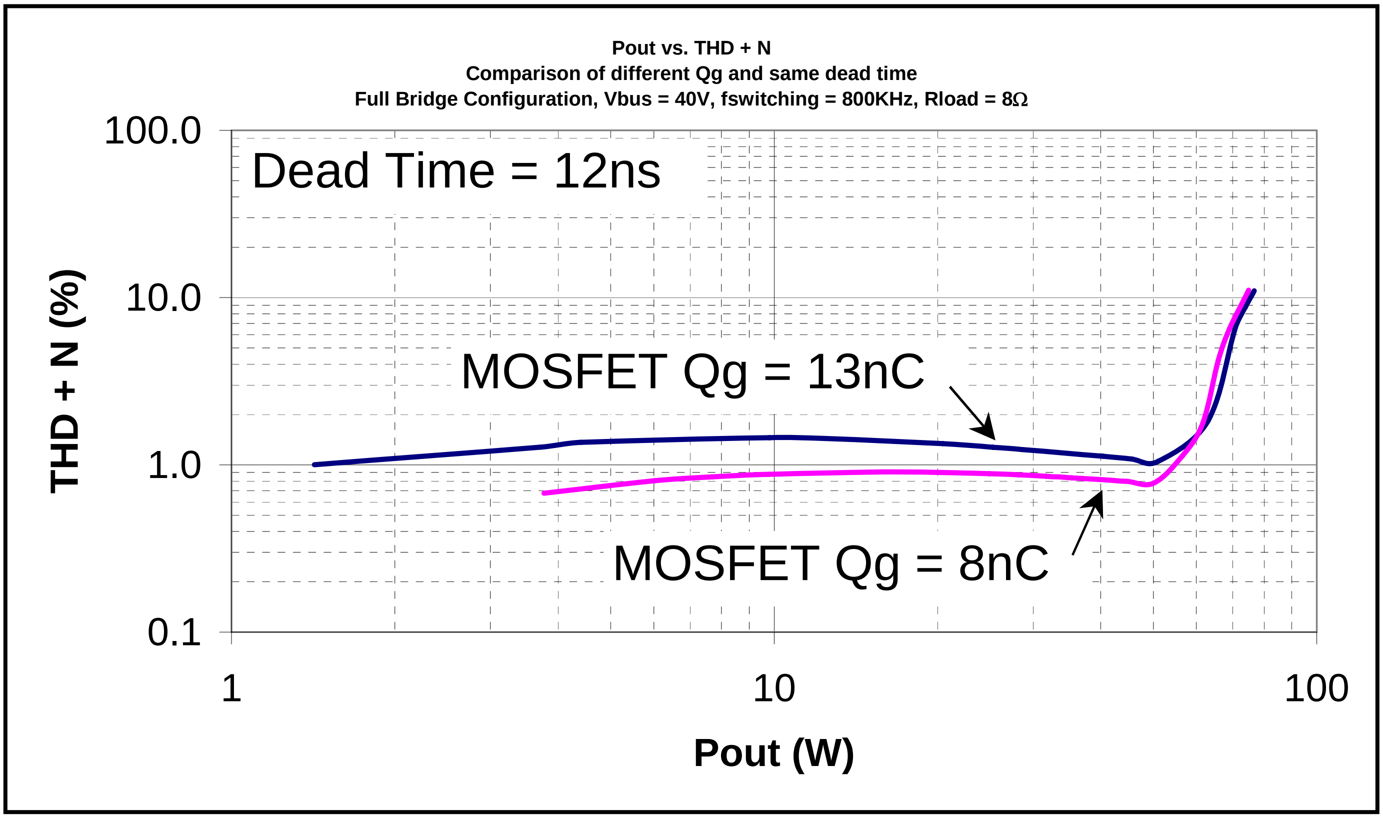


Figure 3. Amplifier THD+N at different MOSFET Q_g and same dead time.

Therefore, MOSFET Q_g is related to amplifier efficiency and linearity. However, it affects amplifier efficiency more significantly than linearity. Since linearity can be improved with dead time optimization, Q_g should be lower mainly to achieve lower MOSFET switching losses and increase amplifier efficiency. This is illustrated in Figure 5.

Lower $Q_g \Rightarrow$ Lower $P_{SWITCHING} \Rightarrow$ Better efficiency

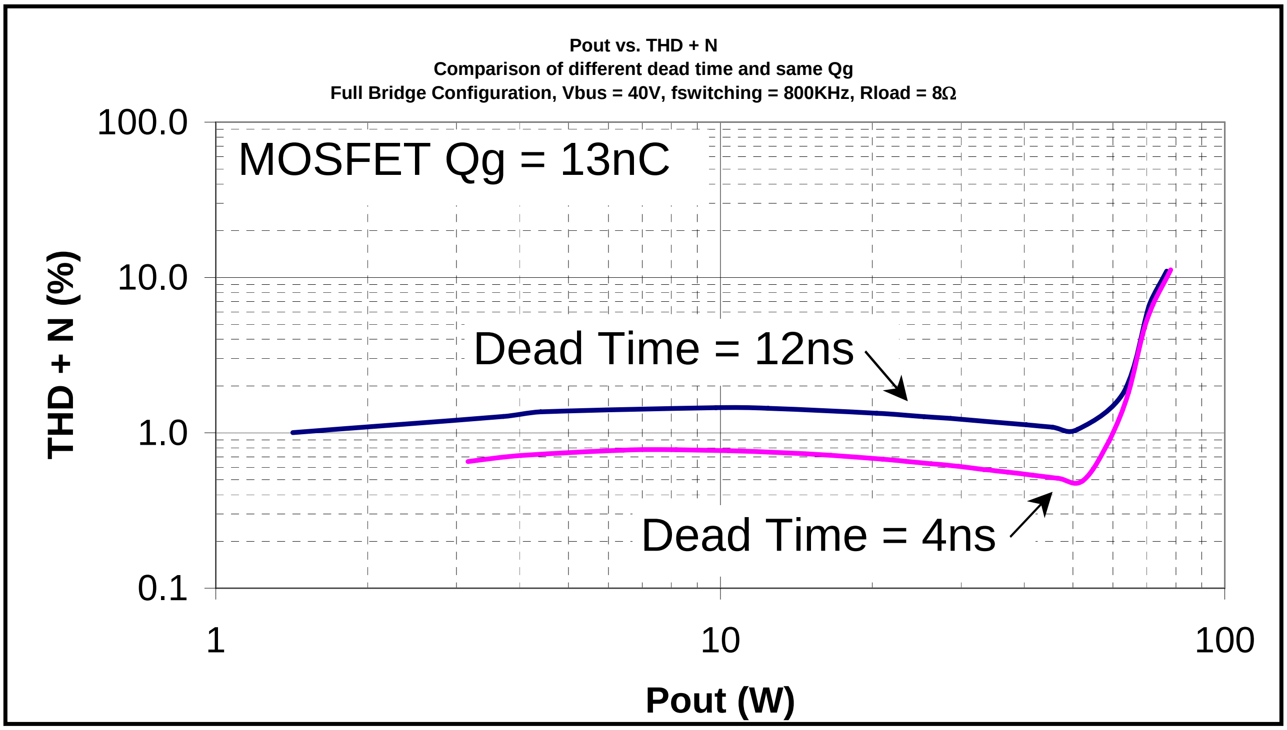


Figure 4. Amplifier THD+N at different dead time and same MOSFET Q_g.

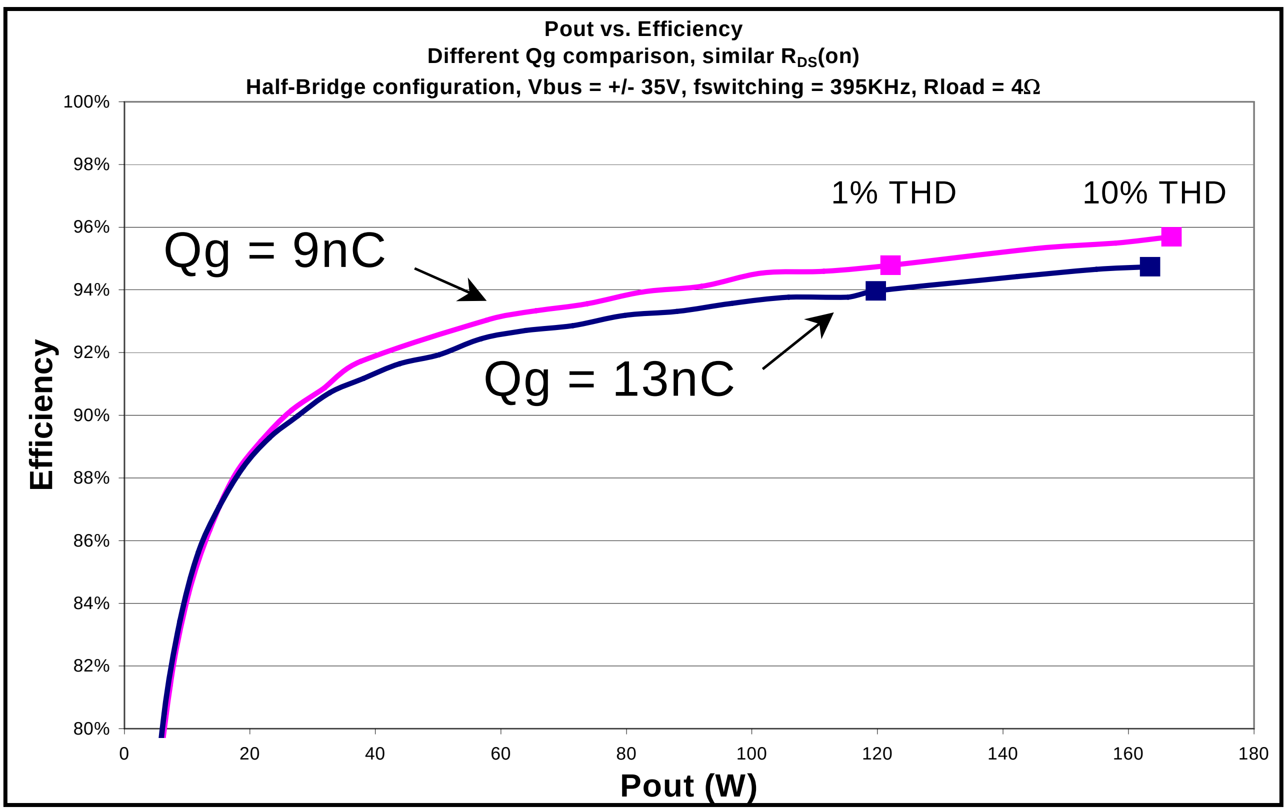


Figure 5. Amplifier efficiency at different MOSFET Q_g and similar $R_{DS(ON)}$.

- Body Diode Reverse Recovery Charge, Q_{rr}.

Intrinsically by design, the MOSFET structure has a built in reverse diode, and its reverse recovery characteristics are related to amplifier performance as well. Reverse recovery charge Q_{rr}, is defined as the area under I_{rr} during t_{rr}. This is illustrated in Figure 6. Q_{rr} is mainly determined by I_F and dI_F/dt. It is a temperature dependent parameter, increasing when T_J increases.

Q_{rr} affects amplifier efficiency and EMI performance. The relationship with efficiency is due to the power bridge circuit configuration. During operation, the reverse recovery current generated by the MOSFET's body diode after commutation current, flows also in the complementary MOSFET of bridge circuit, causing an increase in turn-on switching losses due to the current increment. This is illustrated in figure 7. Details of these switching events are explained in Application Note "Using HEXFET III in PWM Inverters for Motor Drives and UPS Systems" [2].

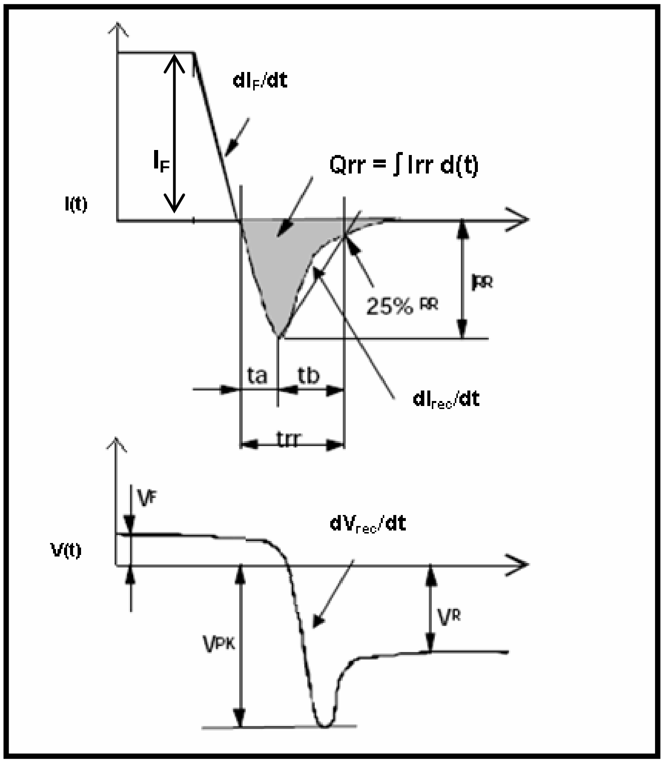


Figure 6. Typical MOSFET body diode reverse recovery waveforms.

However, similar to amplifier linearity, the selection of right dead time can improve efficiency due to Q_{rr} reduction. Reduction of dead time causes the commutation current to flow most of the time into the MOSFET channel, reducing MOSFET body diode current pulse width, and hence, minority carrier charge and Q_{rr}. Still, smaller dead time may cause shoot through current, as shown in Figure 8. This is a risky condition for power bridge MOSFETs and also it degenerates the amplifier performance [4]. Therefore, optimized dead time can help to reduce Q_{rr} and improve efficiency and linearity as well. This is illustrated in Figure 9.

Q_{rr} is also related with amplifier EMI performance. High recovery current dI_{rec}/dt (i. e. faster t_b) generates high dV_{rec}/dt, and this results in large high-frequency current and voltage ringing transients in the

MOSFET due to stray inductances and capacitances in the amplifier circuit, increasing radiated and conducted EMI noise. Therefore, a smaller and soft recovery is fundamental to avoid these transients to improve EMI performance. Details of this EMI and reverse recovery relationship are explained in White Paper “Ultra-fast Recovery Diodes Meet Today Requirements for High Frequency Operations and Power Ratings in SMPS Applications” [3].

Hence, smaller and soft reverse recovery improves amplifier efficiency and EMI performance, due to reduction in MOSFET switching losses and current-voltage transient ringing.

Smaller and soft Qrr $\Rightarrow$ Lower $P_{SWITCHING}$ $\Rightarrow$ Better efficiency and EMI performance

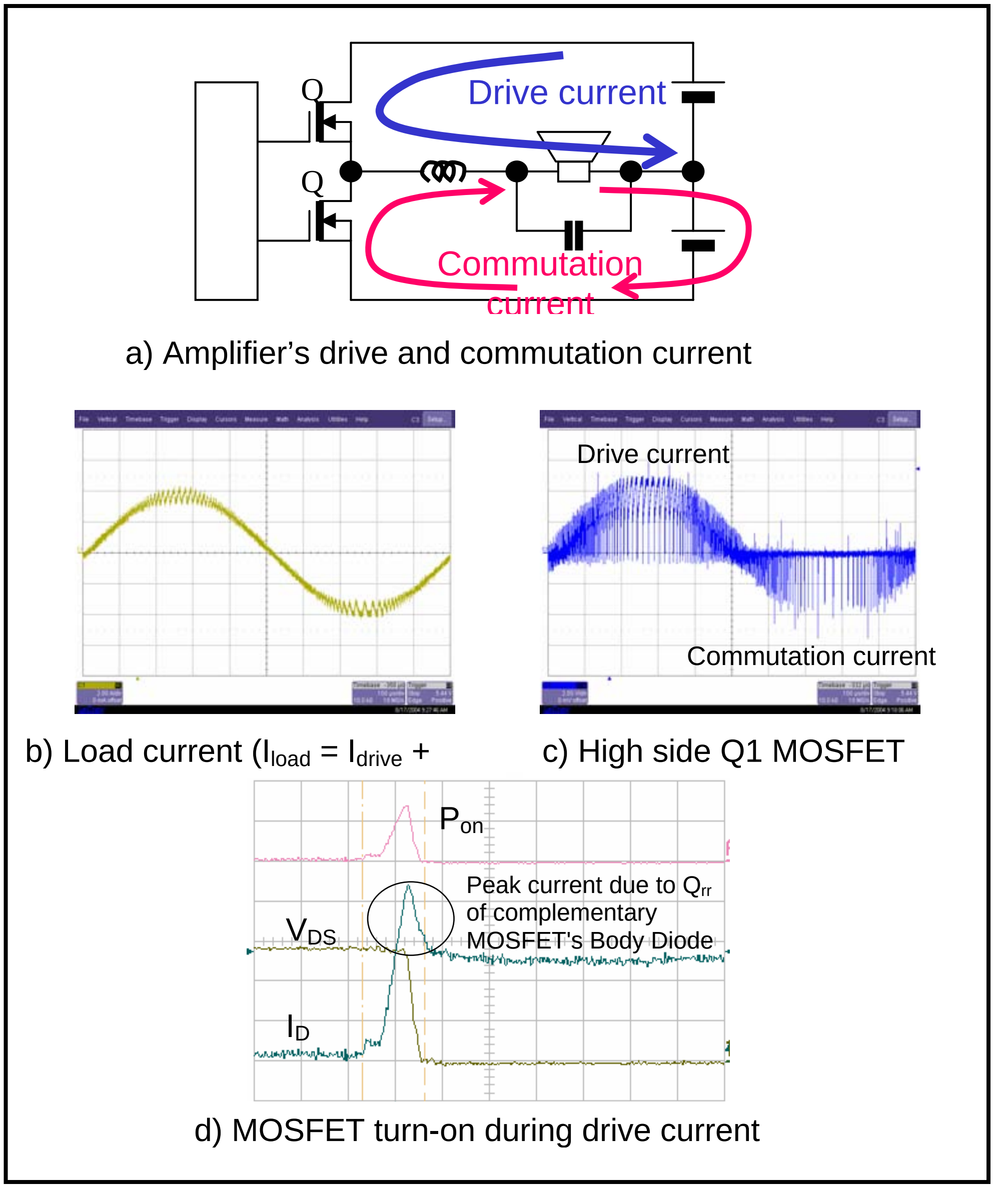


Figure 7. MOSFET turn-on waveforms during drive current.

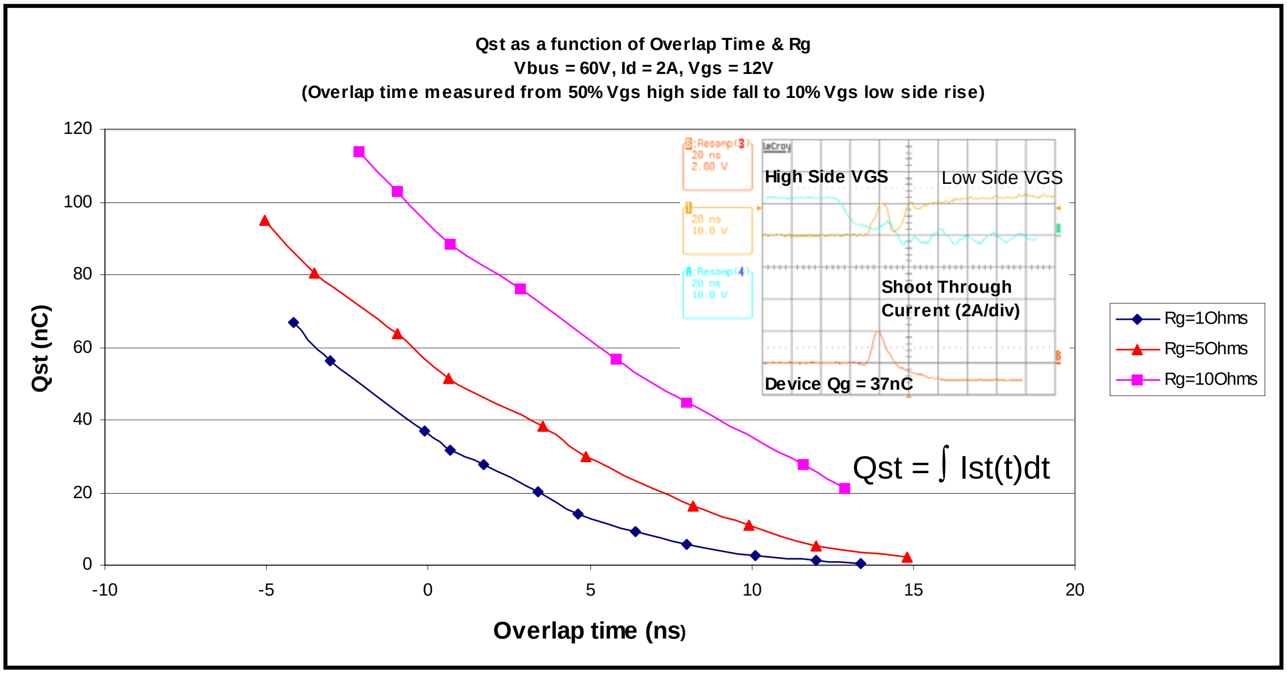


Figure 8. Example of shoot through charge [Qst = ∫ Ist(t)dt] as a function of dead time.

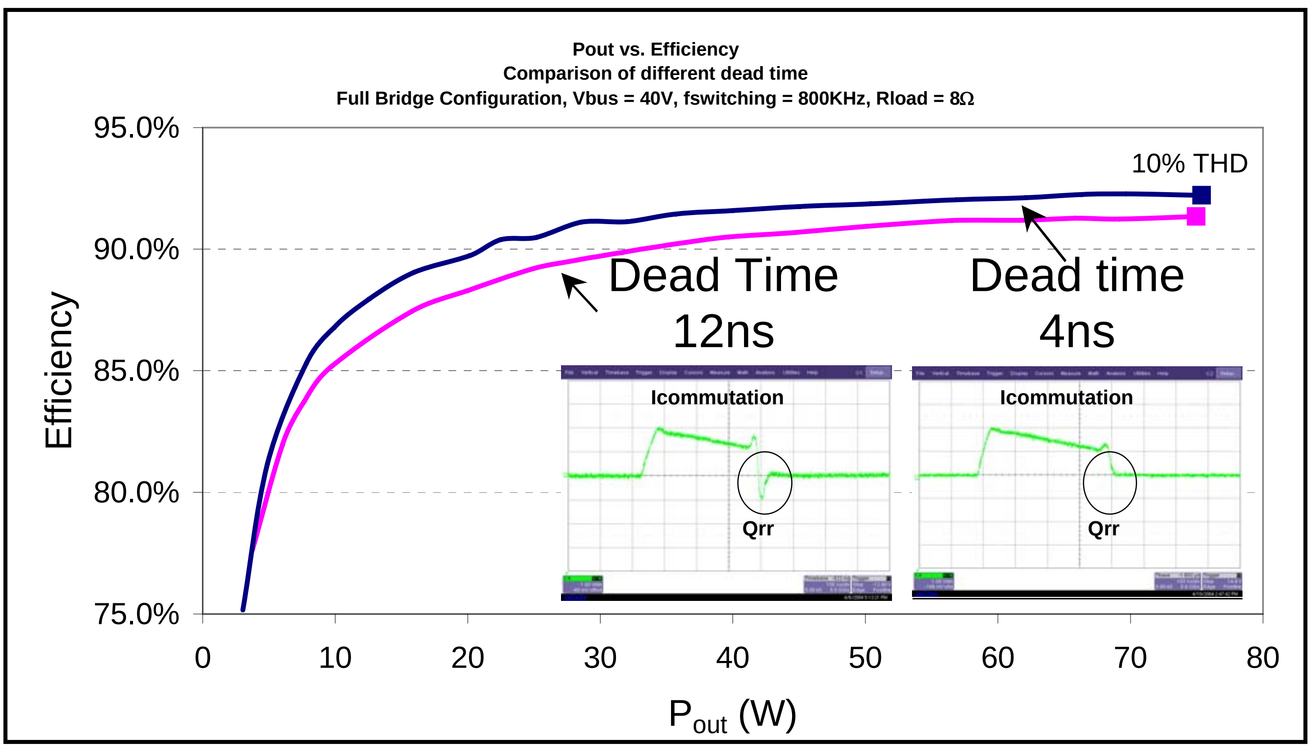


Figure 9. Amplifier efficiency at different dead times.

- Internal Gate Resistance, $R_{G(int)}$.

Internal Gate Resistance $R_{G(int)}$ is a temperature dependent parameter, increasing when temperature increases. This parameter affects MOSFET on and off switching times. Higher $R_{G(int)}$ increases total Gate resistance, decreases Gate current (as shown in Figure 10), increases switching times, and thus, MOSFET switching losses. Furthermore, a large variation of $R_{G(int)}$ affects dead time control. Therefore, $R_{G(int)}$ parameter distribution should be taken in consideration for amplifier performance tolerances.

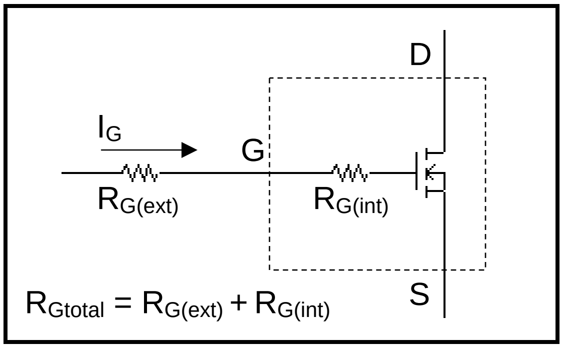


Figure 10. Total Gate resistance, $R_{Gtotal} = R_{G(ext)} + R_{G(int)}$.

- MOSFET Package.

The selection of MOSFET package is of particular importance because it can significantly affects the amplifier performance and cost. Packages characteristics such as dimensions, power dissipation capability, current capability, internal inductance and resistance, electrical isolation and mounting process can all be significant to define PCB and heatsink size, assembly process, and MOSFET electrical parameters.

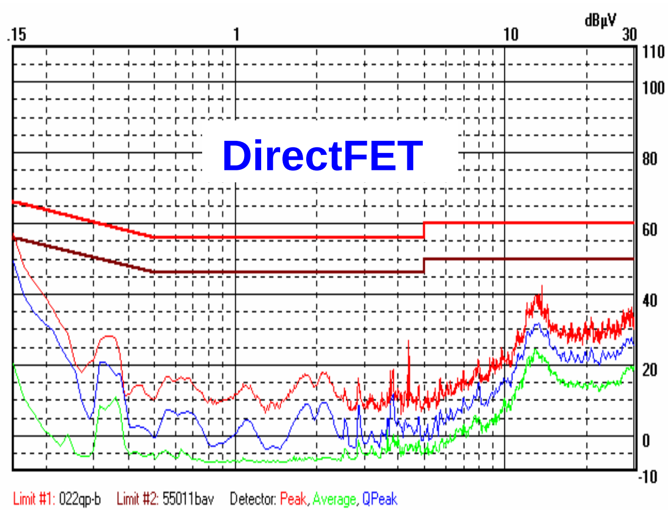
It is well known the importance of package thermal resistance $R_{\theta JC}$ in MOSFET performance. Mainly, because lower $R_{\theta JC}$ reduces MOSFET junction temperature T_J during operation, improving the MOSFET reliability and performance.

$P_{max} = \Delta T_J / R_{\theta JC\ max}$

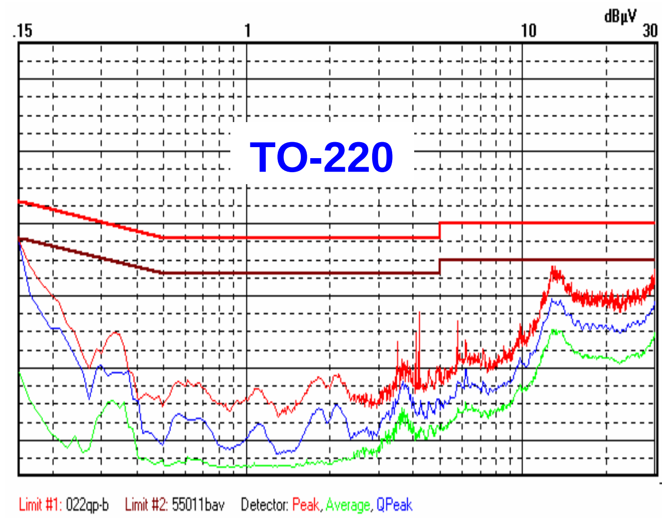
Again, stray inductances and capacitances in amplifier circuit affect EMI performance. Internal package inductance can make a significant difference in EMI noise generation. Figure 11 shows EMI noise comparison of two packages with same MOSFET die and different internal inductance, DirectFET^{TM} MOSFET (<1nH) vs. TO-220 (~ 12nH). It can be observed in this comparison that the DirectFET MOSFET shows better EMI performance. Approximately 9dB lower noise than TO-220, even when the DirecFET MOSFET rise and fall times are approximately three times faster than TO-220.

In summary, the right package selection improves amplifier reliability, performance and cost

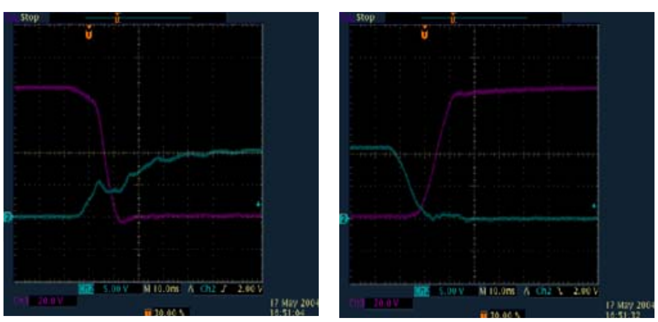
Test Conditions: Half-Bridge Configuration, No Heatsink, V_{bus} = +/- 35V,
f_{sw} = 395kHz, P_{out} = 12.5W, R_{load} = 4 Ohms,
Input = 250mV_{rms} Sinusoidal @ 1kHz
Note: Not shielded test room.
Both Packages are tested with the same MOSFET die



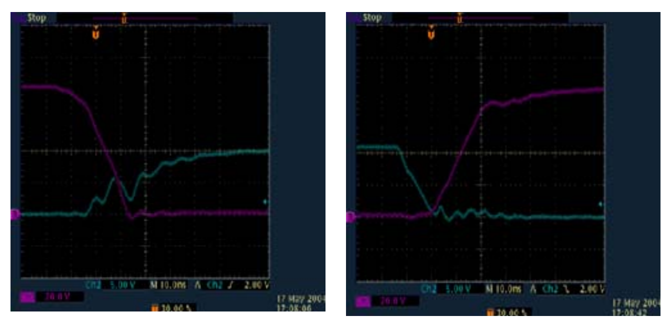
a) DirectFET package EMI noise.



b) TO-220 package EMI noise.



c) DirectFET V_{DS} rise and fall times



d) TO-220 V_{DS} rise and fall times

Figure 11. Amplifier conducted EMI performance comparison. DirectFET vs. TO-220

- Maximum Junction Temperature, T_J.

The maximum Junction Temperature $T_{J\ max}$ is a parameter that is not directly related with the amplifier performance. However, special highlight is done because it is significant to define heatsink size. MOSFET devices with higher $T_{J\ max}$, allow handling higher power losses, and hence, allow smaller heatsink reducing amplifier size and cost.

International Rectifier Digital Audio MOSFET.

IR Digital Audio MOSFETs are devices specifically designed for class D audio amplifier applications. Its parameters are optimized to improve amplifier performance and this goal is achieved by selecting the right die size for specific amplifier specifications.

As mentioned before, $R_{DS(on)}$ and Q_g are key parameters that determine MOSFET power losses. These parameters are related to MOSFET die size and there is a tradeoff between them. A larger MOSFET die size means lower $R_{DS(on)}$ and higher $Q_{g,}$ and vice versa.

Bigger Die Size $\Rightarrow$ Lower $R_{DS(ON)}$ & Higher Q_g $\Rightarrow$ Lower $P_{CONDUCTION}$ & Higher $P_{SWITCHING}$

Smaller Die Size $\Rightarrow$ Higher $R_{DS(ON)}$ & Lower Q_g $\Rightarrow$ Higher $P_{CONDUCTION}$ & Lower $P_{SWITCHING}$

Therefore, the optimal die size will results in lower MOSFET power losses. An example of this is illustrated in Figure 12.

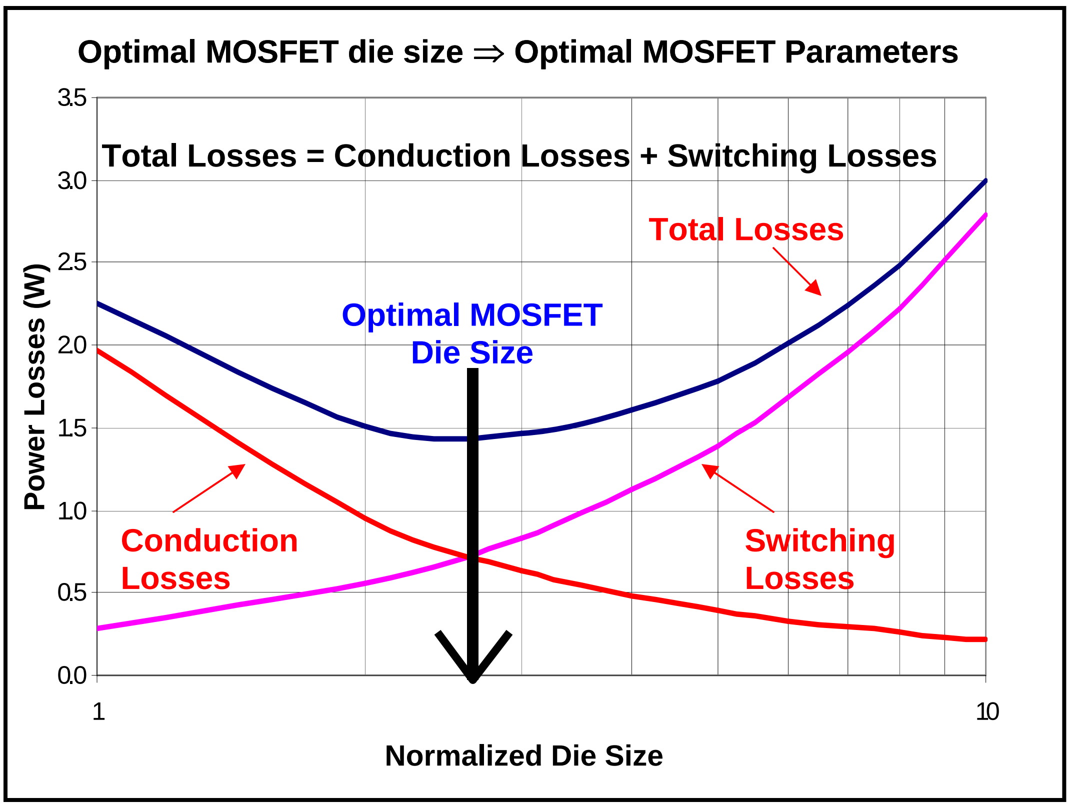


Figure 12. Example of IR Digital Audio MOSFET die size selection.

Furthermore, IR Digital Audio MOSFETs have a guaranteed maximum $R_{G(int)}$, low Q_{rr}, a 175°C maximum T_J, and are assembled in most efficient packages such as DirectFET MOSFET. These features combine to make this MOSFET a highly efficient, robust, and reliable device for class D audio amplifier applications.

Conclusions

There are key MOSFET parameters such as B_{VDSS}, $R_{DS(on)}$, Q_g, Q_{rr}, $R_{G(int)}$, $T_{J\ max}$ and packaging that are related with Class D audio amplifier performance, size and/or cost. The right selection of these parameters can improve the amplifier performance and reduce its size and/or cost. IR Digital Audio MOSFETs are devices in which those key parameters have been optimized to achieve the best overall amplifier performance.

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