Power MOSFET Switching Loss Precise Analysis

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Introduction

Power MOSFET is widely used in the power converter; DC-DC and AC-DC converters have a lot of power MOSFETs. Efficiency is the most important characteristic in the DC-DC and AC-DC converters' application and is always decided by the power MOSFET characteristics, like drain-source on-state resistance, rise time, and fall time. However, in the typical oscilloscope, the power loss calculating function is not common, and an extra method is needed to calculate the power consumption. In this article, a mathematic method is applied to estimate the power consumption.

Power MOSFET Efficiency

The power efficiency of power MOSFET can be divided into two parts: conduction loss and switching loss. The total power loss can be calculated by combining the conduction loss and the switching loss as shown in the Eq. (1).

$$P_{total} = P_{conduction\_loss} + P_{switching\_loss} \qquad (1)$$

The conduction loss is simply decided by the loading current and the drain-source on-state resistance, and the difference between an experiment and a calculation can be very close. Eq. (2) shows the conduction loss formula.

$$P_{Conduction} = I^2 \times R_{DS(on)} \qquad (2)$$

But for switching loss, the calculation becomes very complex because of the parasitic capacitances.

Switching Power Loss by Linear Approximation

In this article, the primary side power MOSFET of Flyback converter is analyzed as shown in the fig.1. NIKOS P7105ATF is used in the AC-DC converter priority side, and the switching waveform is shown in the fig. 2 and fig. 3. Fig. 2 is the rising edge waveform, and fig. 3 is the falling edge waveform.
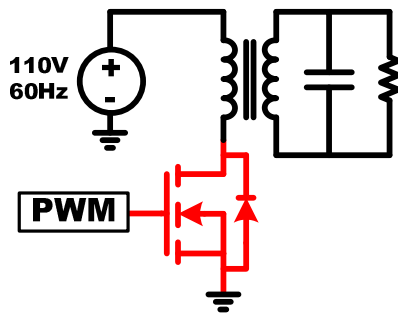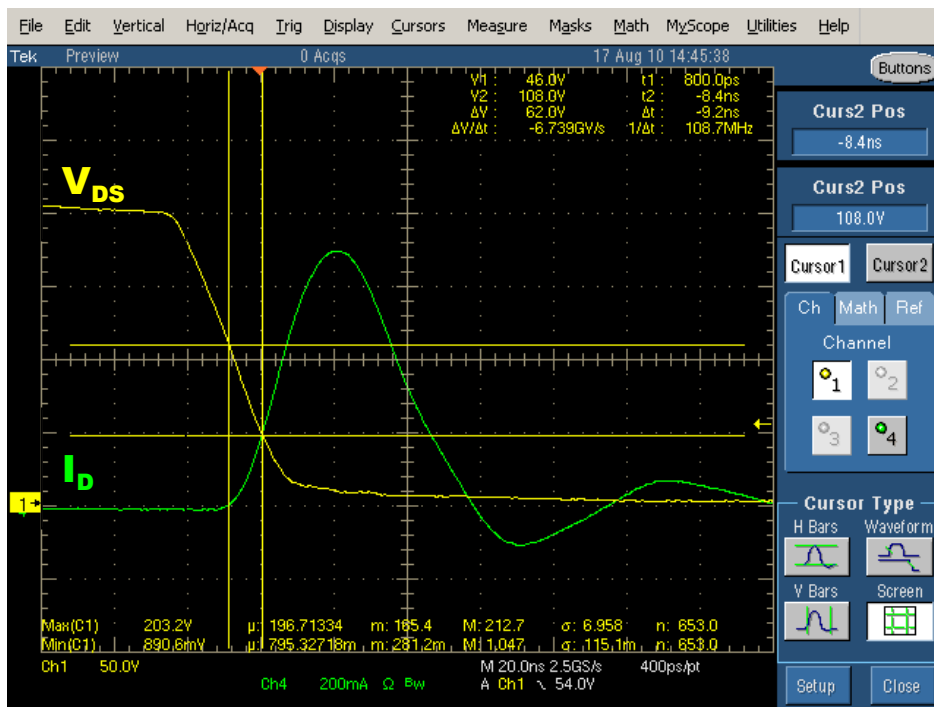

Fig.1 Flyback Converter

Fig.2 Rising Edge Waveform

Assume the drain current and drain-source voltage are linear during rising and falling edge, and the waveform can be approximated as fig. 4.
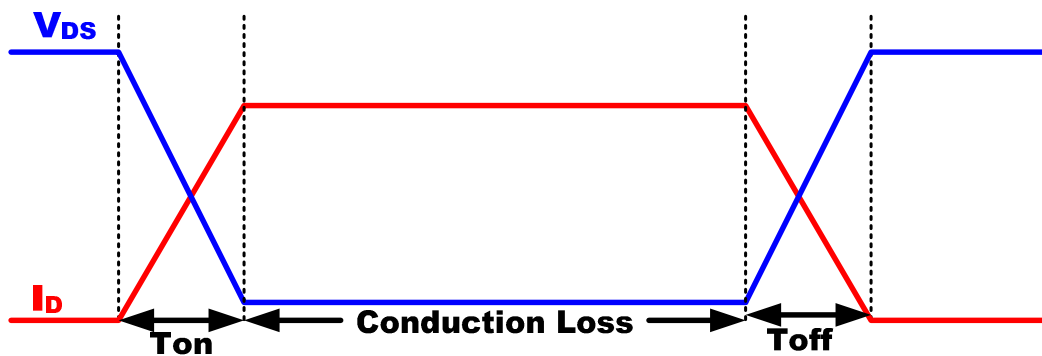

Fig. 3 Falling Edge Waveform

Fig. 4 MOSFET Ideal Waveform

In the linear approximation, the drain current can be decided by the formula (3), and the drain-source voltage can be decided by the formula (4) during the rising edge.

$$i_D(t) = I_D \frac{t}{T_{on}} \tag{3}$$

$$v_{DS}(t) = V_{DS}(1 - \frac{t}{T_{on}}) \tag{4}$$

Where Ton is the rising time, I_D is the rated current, and V_{DS} is the drain-source voltage. The power consumption can be decided by multiplying current and voltage as shown in the formula (5).

$$P(t) = i_D(t) \times v_{DS}(t) = \frac{V_{DS} I_D}{T_{on}} t(1 - \frac{t}{T_{on}}) \tag{5}$$

The energy can be shown in the formula (6).

$$W_{rising} = \int_0^{T_{on}} P(t)dt$$

$$= \int_0^{T_{on}} \frac{V_{DS} I_D}{T_{on}} t(1 - \frac{t}{T_{on}})dt$$

$$= \frac{V_{DS} I_D T_{on}}{6} \tag{6}$$

Similarly, the energy during the falling edge can be decided in the formula (7) where T_{off} is the falling time.

$$W_{falling} = \frac{V_{DS} I_D T_{off}}{6} \tag{7}$$

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The switching loss can be found by formula (8).

$$W_{switching} = W_{rising} + W_{falling}$$

$$= \frac{V_{DS}I_D}{6}[T_{on} + T_{off}] \qquad (8)$$

The power consumption can be found by multiplying the switching frequency fs. However, in actual, the waveform is not a linear because of capacitors. Another method is needed to analyze correctly.

Switching Power Loss by Riemann Sum

The linear approximation is not a very precise method to analyze the switching loss of power MOSFET, so Riemann Sum is recommended. In mathematic, a Riemann sum is a method for approximating the total area underneath a curve on a graph, otherwise known as an integral. It may also be used to define the integration operation. In this article, the rising edge is divided into six sections as shown in the fig. 5.
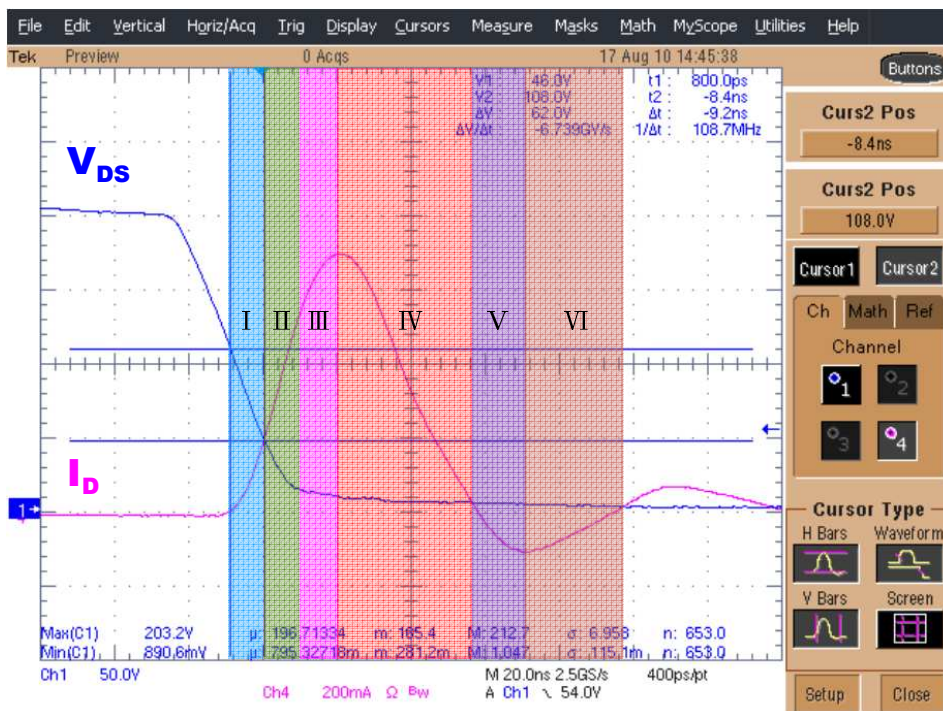
Fig. 5 Riemann Sum Six Sections of Rising Edge

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In very section, the voltage and the current can be decided by the formula (9) and (10).

$$v(t) = \frac{V_2 - V_1}{t_2 - t_1}(t - t_1) + V_1 \tag{9}$$

$$i(t) = \frac{I_2 - I_1}{t_2 - t_1}(t - t_1) + I_1 \tag{10}$$

Where V_2 and V_1 is the voltage at time t_2 and t_1 and I_2 and I_1 is the current at time t_2 and t_1. The power can be found by multiplying current can voltage, and the energy can be decided by integral power as shown in the formula (11).

$$W_{rising} = \int_{t_1}^{t_2} v(t) \times i(t) dt \tag{11}$$

The energy of the six segments shows as below:

Section I : $(V_1, V_2) = (108V, 46V)$, $(I_1, I_2) = (0, 0.2A)$, $(t_1, t_2) = (0, 9.2ns)$

$$
\begin{aligned}
W_{\mathrm{I}} &= \int_0^{9.2n} (\frac{-62}{9.2n}t + 108) \times (\frac{0.2}{9.2n}t) dt \\
&= 6.133 \times 10^{-8}(J)
\end{aligned}
\tag{12}
$$

Section II : $(V_1, V_2) = (46V, 16V)$, $(I_1, I_2) = (0.2A, 0.4974A)$, $(t_1, t_2) = (9.2n, 17.2ns)$

$$
\begin{aligned}
W_{\mathrm{II}} &= \int_{9.2n}^{17.2n} [\frac{-30}{8n}(t - 9.2n) + 46] \times [\frac{0.2974}{8n}(t - 9.2n) + 0.2] dt \\
&= 8.05296 \times 10^{-8}(J)
\end{aligned}
\tag{13}
$$

Section III : $(V_1, V_2) = (14.37V, 7.88V)$, $(I_1, I_2) = (0.4974A, 0.7044A)$, $(t_1, t_2) = (17.2n, 39.6ns)$

$$
\begin{aligned}
W_{\mathrm{III}} &= \int_{17.2n}^{39.6n} [\frac{-6.49}{12.4n}(t - 17.2n) + 14.37] \times [\frac{0.207}{12.4n}(t - 17.2n) + 0.4974] dt \\
&= 1.22244 \times 10^{-7}(J)
\end{aligned}
\tag{14}
$$

Section Ⅳ: $(V_1, V_2) = (7.88V, 4.67V)$, $(I_1, I_2) = (0.7044A, 0A)$, $(t_1, t_2) = (39.6n, 75.2ns)$

$$W_{\text{IV}} = \int_{39.6n}^{75.2n} [\frac{3.21}{35.6n}(t-39.6n)+7.88] \times [\frac{-0.7044}{35.6n}(t-39.6n)+0.7044]dt$$
$$= 8.5386 \times 10^{-8}(J) \tag{15}$$

Section Ⅴ: $(V_1, V_2) = (4.67V, 2.96V)$, $(I_1, I_2) = (0A, -0.087A)$, $(t_1, t_2) = (75.2n, 90.8ns)$

$$W_{\text{V}} = \int_{75.2n}^{90.8n} [\frac{-1.71}{15.6n}(t-75.2n)+4.67] \times \frac{-0.098}{15.6n}(t-75.2n)dt$$
$$= 2.69833 \times 10^{-9}(J) \tag{16}$$

Section Ⅵ: $(V_1, V_2) = (2.96V, 0.153V)$, $(I_1, I_2) = (-0.098A, 0A)$, $(t_1, t_2) = (90.8n, 116.4ns)$

$$W_{\text{VI}} = \int_{90.8n}^{116.4n} [\frac{-2.807}{25.6n}(t-90.8n)+2.96] \times [\frac{0.098}{25.6n}(t-90.8n)-0.098]dt$$
$$= 2.53932 \times 10^{-9} \tag{17}$$

The energy can be found by adding form (12) to (17), and then multiplying the switching frequency about 60kHz to get the switching power loss as shown in the formula (18).

$$P_{ri\sin g} = (W_{\text{I}} + W_{\text{II}} + W_{\text{III}} + W_{\text{IV}} + W_{\text{V}} + W_{\text{VI}}) \times 60k \approx 0.02W \tag{18}$$

Similarly, the power loss of falling edge can be found. In this article, the falling edge is divided into two parts as shown in the fig. 6. The energy of the three segments shows as below:

Section Ⅰ: $(V_1, V_2) = (0.16V, 18.98V)$, $(I_1, I_2) = (1.127A, 1.127A)$, $(t_1, t_2) = (0, 52ns)$

$$W_{\text{I}} = \int_{0}^{52n} (\frac{18.82}{52n}t+0.16) \times 1.127dt$$
$$= 5.6084 \times 10^{-7} \tag{19}$$

Section Ⅱ: $(V_1, V_2) = (18.98V, 263.8V)$, $(I_1, I_2) = (1.127A, 0.52A)$, $(t_1, t_2) = (52n,$ 116ns)

$$W_{II} = \int_{52n}^{116n} [\frac{244.82}{64n}(t-52n)+18.98] \times [\frac{-0.607}{64n}(t-52n)+1.127]dt$$
$$= 6.65925 \times 10^{-6}(J) \tag{20}$$

Section Ⅲ: $(V_1, V_2) = (263.8V, 263.8V)$, $(I_1, I_2) = (0.52A, 0A)$, $(t_1, t_2) = (116n,$ 144.8ns)

$$W_{III} = \int_{116n}^{144.8n} 263.8 \times [\frac{-0.52}{28.8n}(t-116n)+0.52]dt$$
$$= 1.97533 \times 10^{-6}(J) \tag{21}$$

The energy can be found by adding form (19) to (21), and then multiplying the switching frequency about 60kHz to get the switching power loss as shown in the formula (18).

$$P_{falling} = (W_I + W_{II} + W_{III}) \times 60k \approx 0.55W \tag{18}$$
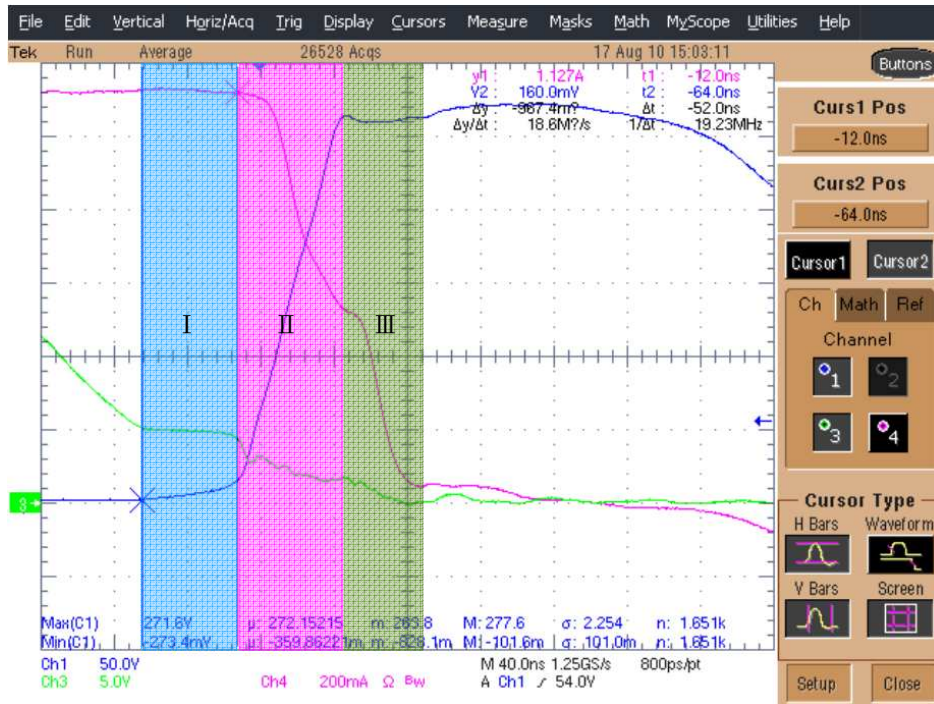

Fig. 6 Riemann Sum Three Sections of Falling Edge

Conclusion

In this article, the precise mathematic analysis is presented to analyze the switching loss of a power MOSFET. In theorem, if the waveform can be divided into more sections, the results can be more accurate.