Calculation of on-state and switching losses in a PWM DC/AC or DC/DC converter

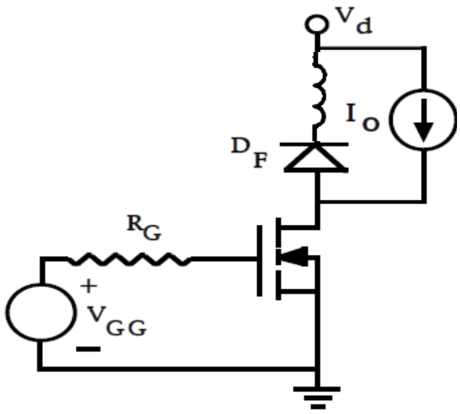

Figure 1 Equivalent switching circuit for a MOSFET/diode pair

The circuit above is considered when calculating losses in one switching device, e.g. MOSFET. Switching in most basic voltage source converters involves commutation of current between a diode and a MOSFET (or other switching devices). The waveform for a typical switching sequence is shown in Figure 2.

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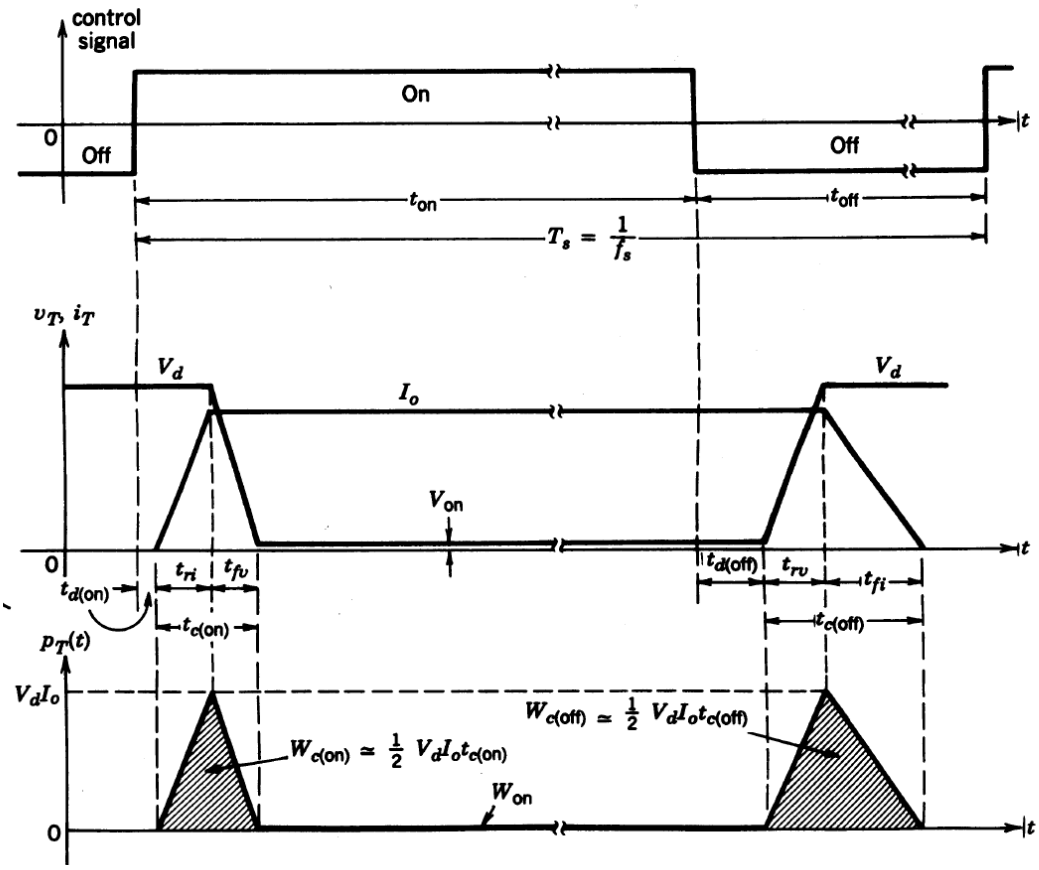

Figure 2 Switching sequence

The power loss during on-state is calculated as:

$$P_{on} = V_{on}I_o\frac{t_{on}}{T_s} = r_{on}I_o^2\frac{t_{on}}{T_s}$$

Equation 1

Here Io is the actual current during the conduction interval. For a simplified calculation Io can be considered as the total rms current (Iv) through the inductance L. The factor $\frac{t_{on}}{T_s}$ equals the duty cycle D of a DC/DC converter.

$$P_{on(\frac{DC}{DC})} = r_{on}I_{v,rms}^2D$$

Equation 2

For a DC/AC converter the duty cycle is varying between a small and a large value when the control signal is in the positive or negative half cycle, as shown in Figure 3(b).

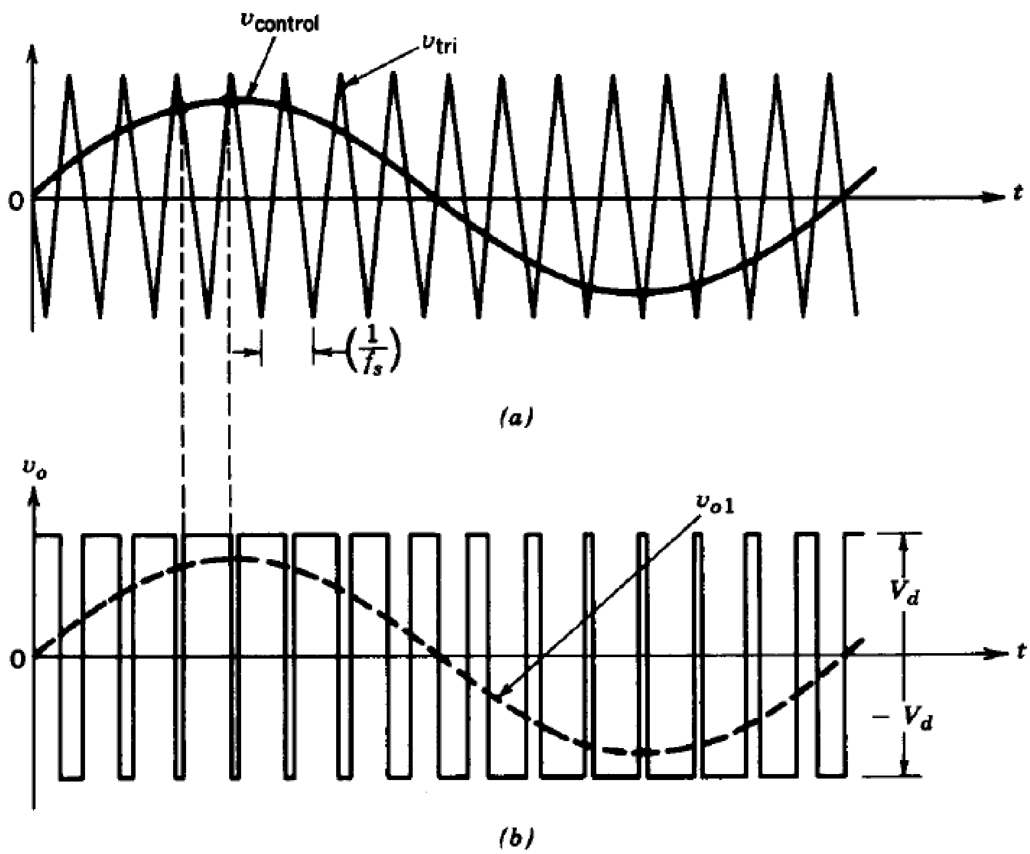

Figure 3 DC/AC converter PWM

Defining the amplitude ratio, ma, between amplitudes of the control signal and PWM triangular wave defined as:

$$m_a = \frac{\hat{V}_{control}}{\hat{V}_{tri}}$$

The max and min duty cycle can be defined as:

$$D_{max} = 0.5 + \frac{m_a}{2}, D_{min} = 0.5 - \frac{m_a}{2}$$

Consequently, on average, the duty cycle in an DC/AC converter can be considered as 0.5.

$$P_{on(\frac{DC}{AC})} = \frac{1}{2} r_{on} I_{v,rms}^2$$

Equation 3

Switching losses

The power losses during switching is defined as:

$$P_s = \frac{1}{2} V_d I_o f_s \left(t_{c(on)} + t_{c(off)}\right)$$

Equation 4

The time delays for turn-on and turn-off can be estimated using the capacitor equivalent of the MOSFET and a gate drive represented as a voltage source V_{GG} in series with a resistance R_G.

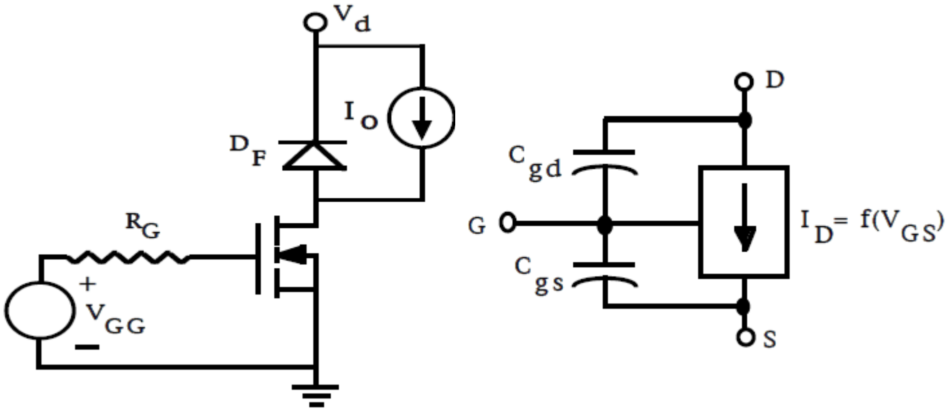

Figure 4

Four time delays are used to define the wave forms of current and voltage during switching:
Turn-on:

- **t_{ri}**: Rise time of current
- **t_{fv}**: Fall time of voltage

Turn-off

- **t_{rv}**: Rise time of voltage
- **t_{fi}**: Fall time of current

Based on the definition of time delays for MOSFET turn-on and turn-off from [1] per Figure 5 below, the four time delays above can be determined.

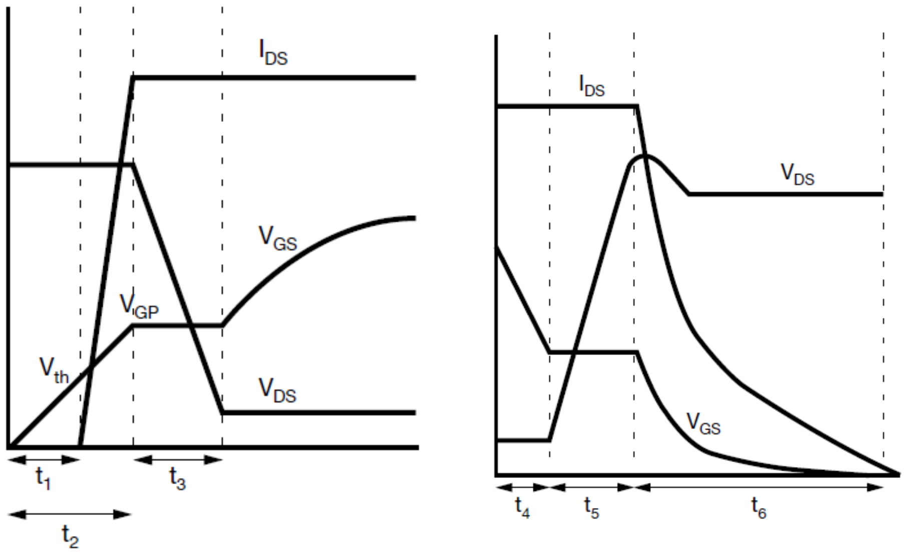

Figure 5 MOSFET turn-on and turn-off waveforms

$\mathbf{t_{ri} = t_2 - t_1}$

$\mathbf{t_{fv} = t_3}$

$\mathbf{t_{rv} = t_5}$

$\mathbf{t_{fi} = t_6}$

For the MOSFET based converter used in Lab 3 the following parameters are used:

Rgon = 1000 ohm
Rgoff = 10 ohm
VGG(on) = 15V
VGG(off) = 1.2V (incl schottky diode voltage and output voltage of driver)
Vgs(th-on) = 4V (MOSFET gate threshold at turn-on)
Vgs(th-off) = 2V (MOSFET gate threshold at turn-off)
VGP = 4.2 V (Miller plateau voltage of Vgs)
Ciss = 1700 pF @ Vds=25V
Ciss = 2500 pF @ Vds=0V
Crss = 200 pF @ Vds=10V
Crss = 500 pF @ Vds=2.5V

$$t_1 = R_{gon}(C_{gs} + C_{gd}) ln\left(\frac{1}{1-\frac{V_{gs(th-on)}}{V_{GG(on)}}}\right); C_{gs} + C_{gd} = C_{iss} @ V_{ds} = 25V$$
$$t_2 = R_{gon}(C_{gs} + C_{gd}) ln\left(\frac{1}{1-\frac{V_{GP}}{V_{GG(on)}}}\right); C_{gs} + C_{gd} = C_{iss} @ V_{ds} = 25V$$
$$t_3 = R_{gon} C_{gd} \frac{V_{ds}}{V_{GG(on)}-V_{GP}}; C_{gd} = C_{rss} @ V_{ds} = 2.5V$$
$$t_5 = R_{goff} C_{gd} \frac{V_{ds}}{V_{GP}}; C_{gd} = C_{rss} @ V_{ds} = 2.5V$$
$$t_6 = R_{goff}(C_{gs} + C_{gd}) ln\left(\frac{V_{GP}}{V_{gs(th-off)}}\right); C_{gs} + C_{gd} = C_{iss} @ V_{ds} = 0V$$

The MOSFET time delays are calculated as:

t1 = 527 ns
t2 = 565 ns
t3 = 690 ns
t5 = 24 ns
t6 = 32 ns

This gives the following values of the time delays:

t_{ri} = 38 ns
t_{fv} = 690 ns
t_{rv} = 24 ns
t_{fi} = 32 ns

Consequently, the total switching losses can be calculated as:

$$P_s = \frac{1}{2} V_d I_o f_s (t_{ri} + t_{fv} + t_{rv} + t_{fi}) = V_d I_o f_s 0.39\ \mu W$$

Where I_o should be the MOSFET current at the actual switching for detailed result. To simplify calculations the average MOSFET current can be used instead.

$$I_{o(\frac{DC}{DC})} = I_{v,av}$$

For a DC/AC converter the average of a sinusoidal current can be used as:

$$I_{o(\frac{DC}{AC})} = \frac{2\sqrt{2}}{\pi} I_{v,rms}$$

References

[1] Application Note 608, Power MOSFET Basics: Understanding Gate Charge and Using it to Assess Switching Performance, VISHAY Siliconix