开关稳压器 IC 系列

功率损耗的计算方法（同步整流型）

此应用手册用来说明半导体器件，计算温度时使用的功率损耗。产品的温度管理关系到是否可以确保可靠性，故非常重要。

Figure 1 为同步整流 DC/DC 转换器的回路图。Figure 2 为开关节点的电压波形与电感电流波形中，损耗发生的位置。

IC 的功率损耗主要有如下 5 个因素。

1. MOSFET 的 ON 电阻造成的导通损耗 P_{ON-L}, P_{ON-H}
2. MOSFET 的开关损耗 P_{SW-H}
3. Deadtime 损耗 P_D
4. MOSFET 的 Gate 电荷损耗 P_G
5. IC 控制回路的工作损耗 P_{IC}

导通损耗

导通损耗为 Figure 2 波形中 A 区间与 B 区间的部分。A 区间时高边 MOSFET ON，低边 MOSFET OFF，损耗可由输出电流、ON 电阻及 ON 占空比算出。B 区间，高边 MOSFET OFF，低边 MOSFETON，损耗可有输出电流、ON 电阻及 OFF 占空比算出。
导通损耗 P_{ON-H} 与 P_{ON-L} 由下式可算出。

高边 MOSFET

$$P_{ON-H} = I_O^2 \times R_{ON-H} \times \frac{V_O}{V_{IN}} \quad [W] \qquad (1)$$

低边 MOSFET

$$P_{ON-L} = {I_O}^2 \times R_{ON-L} \times \left(1 - \frac{V_O}{V_{IN}}\right) \quad [W] \qquad (2)$$

I_O: 输出电流 $[A]$
R_{ON-H}: 高边 MOSFET ON 电阻 $[\Omega]$
R_{ON-L}: 低边 MOSFET ON 电阻 $[\Omega]$
V_{IN}: 输入电压 $[V]$
Vo: 输出电压 $[V]$

开关损耗

开关损耗为 Figure 2 波形中 C 区间与 D 区间的计算。高边、低边 MOSFET 交替 ON/OFF 时，切换 ON 的过程中，产生损耗。由于计算 2 个三角形面积与波形上升、下降过程中功率损耗求法近似，所以该计算可以近似为单纯的图形面积计算。
开关损耗 P_{SW-H} 如下式求得。

高边 MOSFET

$$P_{SW-H} = \frac{1}{2} \times V_{IN} \times I_O \times (t_r + t_f) \times f_{SW} \quad [W] \qquad (3)$$

V_{IN}: 输入电压 $[V]$
I_O: 输出电流 $[A]$
t_r: *高边* MOSFET 开通上升时间 $[sec]$
t_f: 高边 MOSFET 关断下降时间 $[sec]$
f_{SW}: 开关频率 $[Hz]$

低边 MOSFET，在体二极管通电期间开通，下个一 Gate 信号来时关断，负载电流沿着体二极管相同方向续流，Drain 电压保持在低电压。所以开关损耗极少。

DeadTime 损耗

高边与低边 MOSFET 同时 ON 的话，VIN—GND 间形成短路，发生非常大的电流尖峰，所以，设置两 MOSFET 均为 OFF 的死区时间来防止短路。电感电流继续流动，死区时间内电感电流流经低边 MOSFET 的体二极管。Deadtime 损耗 P_D 可用 Figure 2 波形中 E 区间与 F 区间来计算，由下式可算出。

$$P_D = V_D \times I_O \times (t_{Dr} + t_{Df}) \times f_{SW} \quad [W] \qquad (4)$$

V_D: 低边 MOSFET 的
提二极管正向压降 $[V]$
I_O: 输出电流 $[A]$
t_{Dr}: 上升沿时 Deadtime $[sec]$
t_{Df}: 下降沿时 Deadtime $[sec]$
f_{SW}: 开关频率 $[Hz]$

Gate 电荷损耗

Gate 电荷损耗是 MOSFET Gate 充电引起的功率损耗。该损耗与高边及低边 MOSFET 的 Gate 电荷数(亦或 Gate 电容)有关，故 Gate 电荷损耗如下式算出。

$$P_G = \left(Q_{g-H} + Q_{g-L}\right) \times V_{gs} \times f_{SW} \quad [W] \qquad (5)$$

或

$$P_G = \left(C_{g-H} + C_{g-L}\right) \times {V_{gs}}^2 \times f_{SW} \quad [W] \qquad (6)$$

Q_{g-H}: 高边 MOSFET 的 Gate 电荷数 $[C]$
Q_{g-L}: 低边 MOSFET 的 Gate 电荷数 $[C]$
C_{g-H}: 高边 MOSFET 的 Gate 电容 $[F]$
C_{g-L}: 低边 MOSFET 的 Gate 电容 $[F]$
V_{gs}: Gate 驱动电压 $[V]$
f_{SW}: 开关频率 $[Hz]$

IC 的工作损耗

IC 的控制回路造成的功率损耗 P_{IC} 如下式算出。

$$P_{IC} = V_{IN} \times I_{CC} \quad [W] \qquad (7)$$

V_{IN}: 输入电压 $[V]$
I_{CC}: IC 的工作电流 $[A]$

全功率损耗

IC 的功率损耗 P，将上述损耗全部相加。

$$\mathrm{P} = P_{ON-H} + P_{ON-L} + P_{SW-H} + P_D + P_G + P_{IC} \quad [W] \qquad (8)$$

P_{ON-H}: 导通损耗(高边) $[W]$
P_{ON-L}: 导通损耗(低边) $[W]$
P_{SW-H}: Switching 损耗(高边) $[W]$
P_D: Deadtime 损耗 $[W]$
P_G: Gate 电荷损耗 $[W]$
P_{IC}: ＩＣ的工作损耗 $[W]$

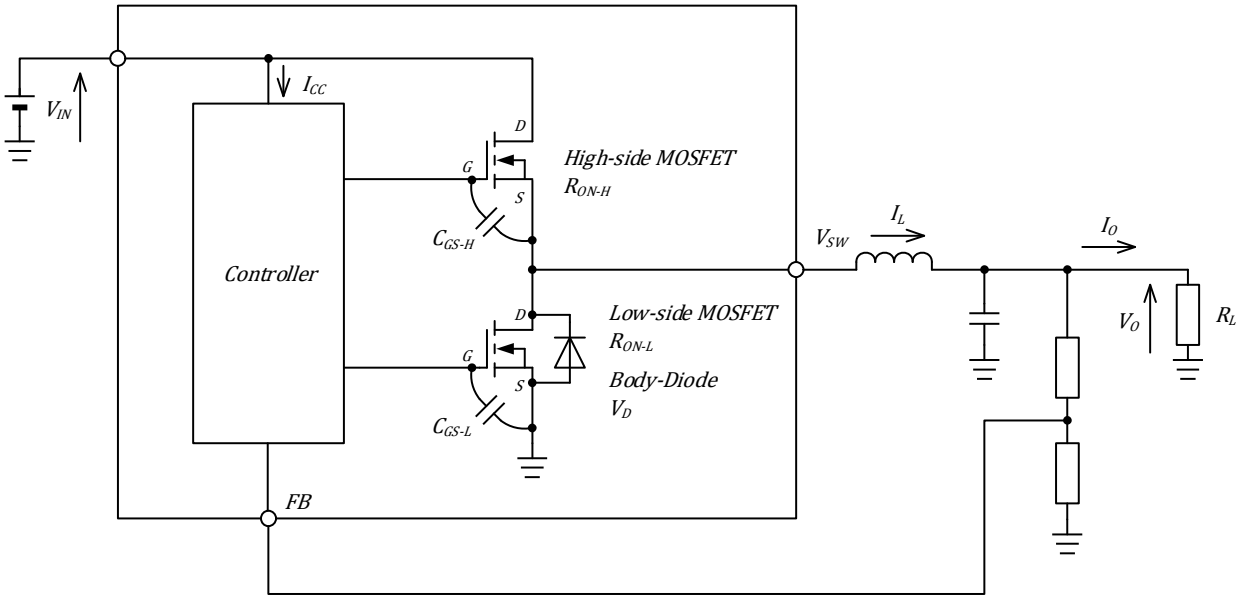

Figure 1. 同步整流型 DC/DC 变换器回路图

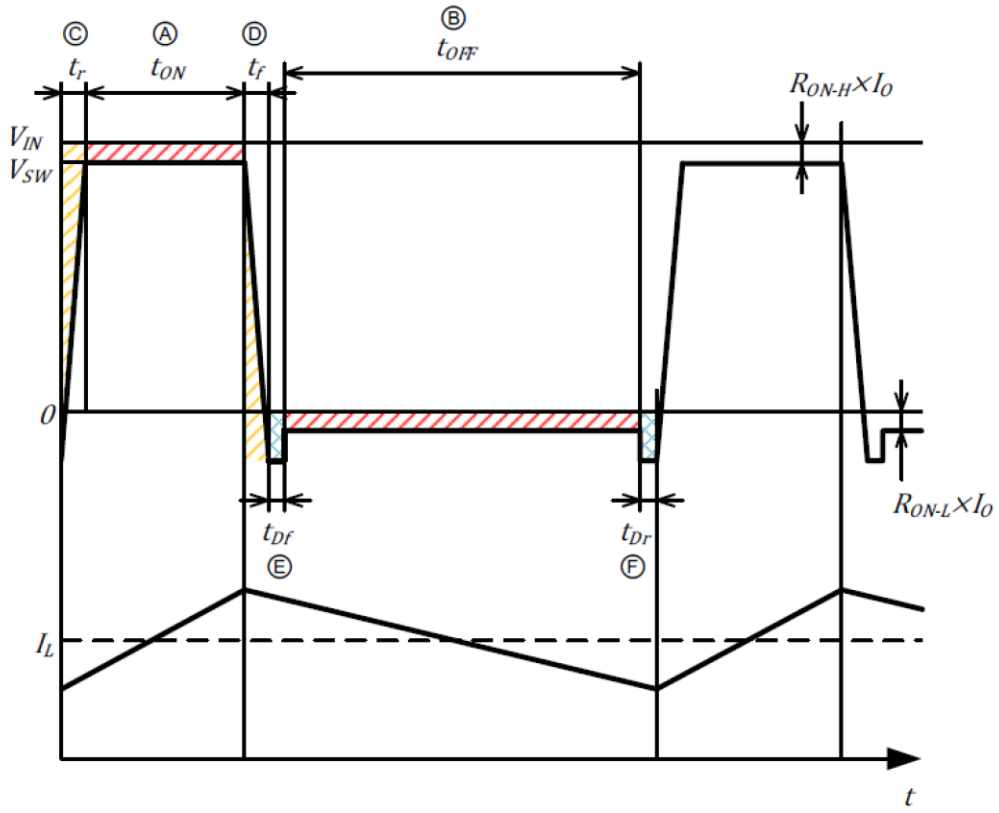

Figure 2. Switching 波形与损耗

计算例

计算式	Parameter	结果
1. 导通损耗 $P_{ON-H} = {I_O}^2 \times R_{ON-H} \times \frac{V_O}{V_{IN}}$ $P_{ON-L} = {I_O}^2 \times R_{ON-L} \times \left(1 - \frac{V_O}{V_{IN}}\right)$	V_{IN}: 输入电压 12 V V_O: 输出电压 5.0 V I_O: 输出电流 3.0 A R_{ON-H}: 高边 MOSFET ON 电阻 100 $m\Omega$ R_{ON-L}: 低边 MOSFET ON 电阻 70 $m\Omega$	375 mW 367.5 mW
2. Switching 损耗 $P_{SW-H} = \frac{1}{2} \times V_{IN} \times I_O \times (t_r + t_f) \times f_{SW}$	f_{SW}: 开关频率 2.0 MHz t_r: 高边 MOSFET 上升沿时间 4 $nsec$ t_f: 高边 MOSFET 下降沿时间 6 $nsec$	360 mW
3. Deadtime 损耗 $P_D = V_D \times I_O \times (t_{Dr} + t_{Df}) \times f_{SW}$ [W]	V_D: 低边 MOSFET 体二极管正向压降 0.5 V t_{Dr}: 上升沿时 Deadtime 30 $nsec$ t_{Df}: 下降沿时 Deadtime 30 $nsec$	180 mW
4. Gate 电荷损耗 $P_G = (Q_{g-H} + Q_{g-L}) \times V_{gs} \times f_{SW}$ $P_G = (C_{g-H} + C_{g-L}) \times {V_{gs}}^2 \times f_{SW}$	Q_{g-H}: 高边 MOSFET 的 Gate 电荷数 1 nC Q_{g-L}: 低边 MOSFET 的 Gate 电荷数 1 nC C_{g-H}: 高边 MOSFET 的 Gate 电容 200 pF C_{g-L}: 低边 MOSFET 的 Gate 电容 200 pF V_{gs}: Gate 驱动电压 5.0V	20 mW
5. IC 的工作损耗 $P_{IC} = V_{IN} \times I_{CC}$	I_{CC}: IC 的消费电流 1.0 mA	12 mW
全功率损耗 $P = P_{ON-H} + P_{ON-L} + P_{SW-H} + P_D + P_G + P_{IC}$		1.31 W

MOSFET 的 Gate 电容及体二极管正向压降等，IC 的内部参数一般厂商未必公开。该情况下，使用计算例里的值，可以进行大致的估算。

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