开关式稳压电源系列

降压转换器 IC 的缓冲电路

降压转换器 IC 的开关节点容易产生很多高次谐波噪声。缓冲电路作为除去这些高次谐波噪声的手段之一。这个应用手册阐述了 RC 缓冲电路的设定方法。

RC 缓冲电路

降压开关转换器电路如 Figure 1 所示，但是实际上如 Figure 2 所示会存在很多寄生电感 L_P 和寄生电容 C_P。高边开关在导通和关断时，由于寄生电感蓄积的能量，在输入环路里会产生共振。因为寄生参数的值由于非常小，所以共振频率可以达到数百 MHz 以上，会导致 EMI(电磁干扰)特性恶化(Figure 3)。

众所周知 RC 缓冲电路是用来去除高次谐波噪声的方法。Figure 4 所示在开关节点只需追加 RC 网络就可以实现降低高次谐波噪声。

Figure 5 展示了缓冲电路的动作过程。当高边开关导通时，寄生电感蓄积的能量通过缓冲电容 C_{SNB}，作为静电能量存储在电容里。开关节点电位会上升到输入电压 V_{IN}、当充电到 V_{IN} 时，电容储存了$1/2 \times C_{SNB} \times V_{IN}{}^2$能量。这时候缓冲电阻 R_{SNB} 里会产生与充电能量相同的$1/2 \times C_{SNB} \times V_{IN}{}^2$阻抗损耗。当低边开关导通时，开关节点会降低到 GND 电位，所以缓冲电容 C_{SNB} 蓄积的能量会通过缓冲电阻(阻尼电阻)放电。这时候缓冲电阻 R_{SNB} 会消耗$1/2 \times C_{SNB} \times V_{IN}{}^2$能量。作为这个公式的补充说明，充电后电容电荷$Q$由$C_{SNB} \times V_{IN}$求得，电源供电功率为$V_{IN} \times Q = C_{SNB} \times V_{IN}{}^2$。电容蓄积能量和释放能量在充放电周期 CR 常数设定足够长的话，只由电容容量和电压决定。充电时电源有一半能量由于电阻变成了焦耳热，剩下的一半作为静电容量储存在电容里。放电时蓄积的一半静电能量由于电阻变成了热能。即使电阻值变化，只会充放电所需时间发生变化，但是这个比例是一定的。

开关一个周期合计会由电阻产生$C_{SNB} \times V_{IN}{}^2$损耗，仅开启关断的次数就会产生损耗，所以产生损耗由$C_{SNB} \times V_{IN}{}^2 \times f_{SW}$求得。即使无负载，只要有开关动作，缓冲电路就会产生损耗，所以成了降低效率的要因。

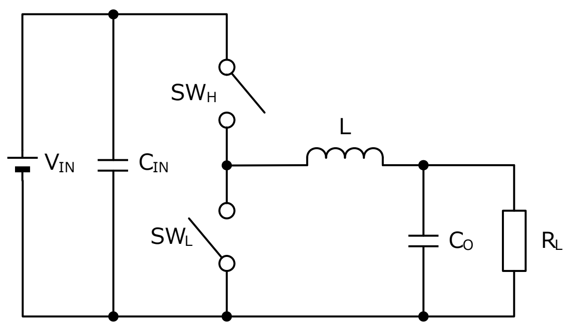

Figure 1. 降压开关转换器电路

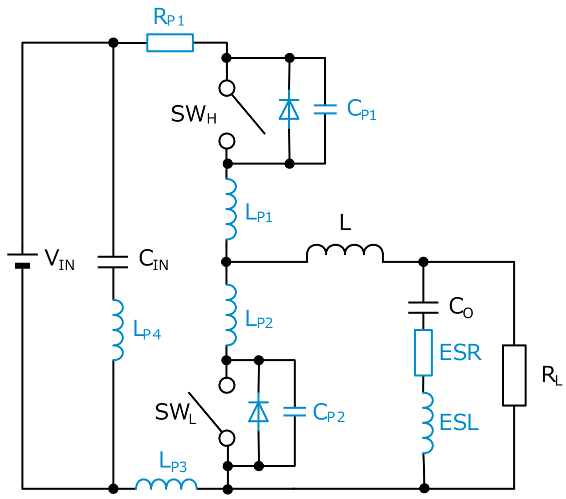

Figure 2. 考虑寄生参数的电路

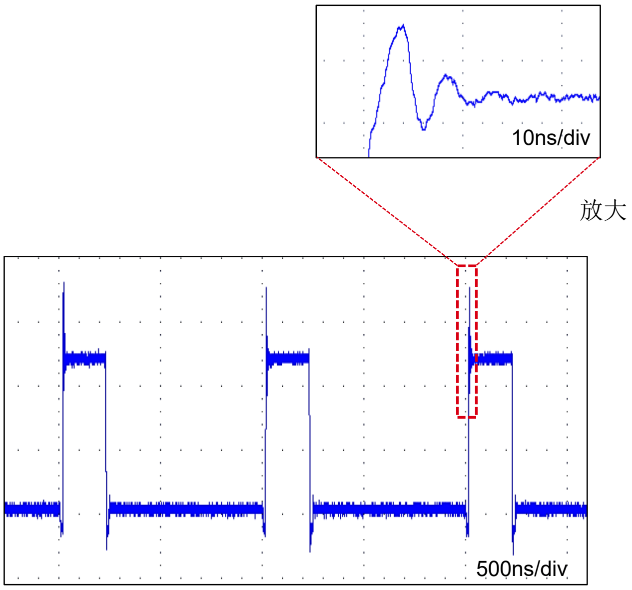

Figure 3. 开关节点振铃波形

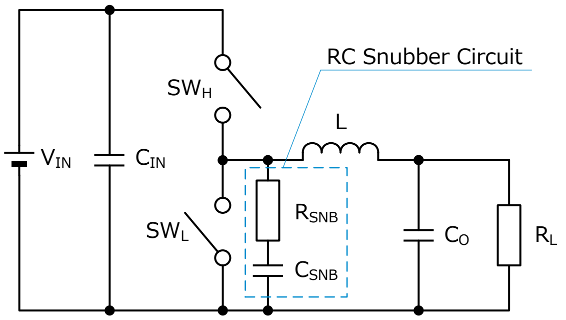

Figure 4. RC 缓冲电路

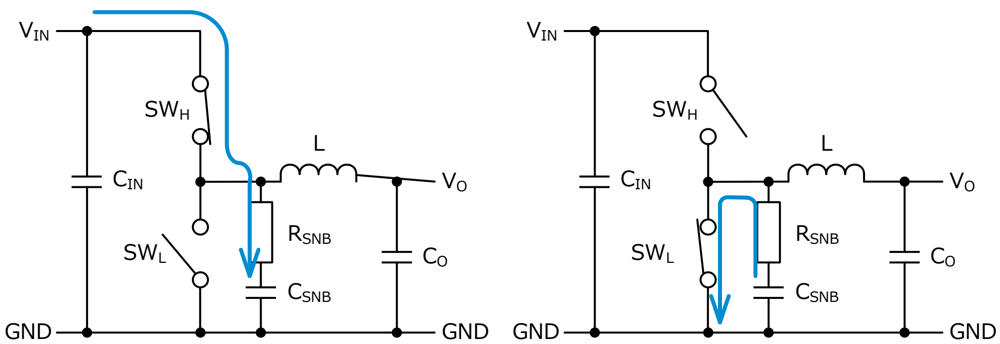

Figure 5. 缓冲电路的动作过程

计算 RC 值

文献『K. Harada, T. Ninomiya, M. Kohno, "Optimum Design of RC snubbers for Switching Regulators", IEEE Transactions of Aerospace and Electronics Systems, Vol.AES-15, No.2, March 1979』介绍了消除振铃的缓冲电路 RC 值由下面两个公式求得。

$$R_{SNB} = 0.65 \times \sqrt{\frac{L_P}{C_{P2}}} \tag{1}$$

$$C_{SNB} = 8 \times C_{P2} \tag{2}$$

但是，L_P 或 C_{P2} 是寄生参数，有厂商不公开该信息，或值太小难以进行参数计算。本手册按照一边在实机上测量实际的开关波形，一边计算相关参数的方法进行说明。首先简单的计算步骤如下所示。

RC 值计算步骤

1. 使用示波器测得振铃频率 f_r。
2. 在开关节点和 GND 之间接入电容 C_{P0}，求得振铃频率变为 1/2 时的电容值。
3. 电容容值 C_{P0} 的 1/3 即是寄生容量 C_{P2}。

$$C_{P2} = \frac{C_{P0}}{3} \quad [F] \tag{3}$$

4. 由寄生容量 C_{P2} 求得寄生电感 L_P。

$$L_P = \frac{1}{(2\pi f_r)^2 \times C_{P2}} \quad [H] \tag{4}$$

5. 求得共振的特性阻抗。

$$Z = \sqrt{\frac{L_P}{C_{P2}}} \quad [\Omega] \tag{5}$$

6. 缓冲电阻 R_{SNB} 设为和特性阻抗 Z 同等程度的值。

$$R_{SNB} \geq Z \quad [\Omega] \tag{6}$$

7. 缓冲容量 C_{SNB} 设为寄生容量 C_{P2} 的 1～4 倍。

$$C_{SNB} = (1\sim4) \times C_{P2} \quad [F] \tag{7}$$

8. 求得缓冲电阻 R_{SNB} 的消耗功率。

$$P_{RSNB} = C_{SNB} \times V_{IN}{}^2 \times f_{SW} \quad [W] \tag{8}$$

额定功率需选择消耗功率 2 倍以上的电阻。

RC 值的计算例子

这里一边进行实际测量一边按照 RC 值计算步骤进行说明。

1. 因为需要使用示波器来测量振铃频率，所以在测试点的开关节点处一定要会使用探头。为了降低探头附加在开关节点处的寄生容量，将探针前端的挂钩尖端除去，使探头直接接触开关节点。因为接地引线会附加电感成分所以去掉。取而代之的是安装接地引线适配器，使接地长度最小化(Figure 6)。

   放大振铃波形，测定频率(Figure 7)。该例观测到了 217.4MHz。

Figure 6. 探头设置

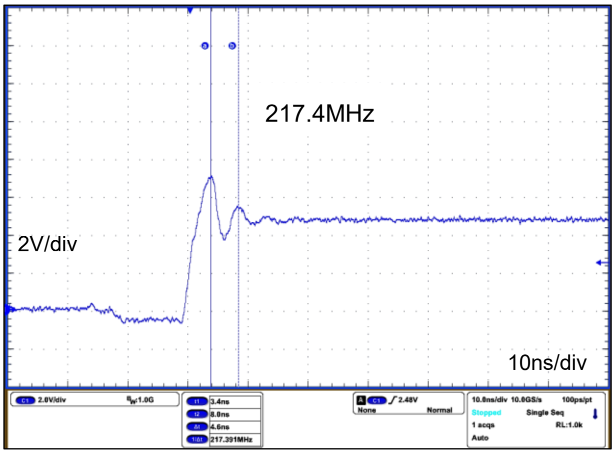

Figure 7. 测定振铃频率

2. 如 Figure 8 所示，在开关节点和 GND 间接入电容 C_{P0}，求得振铃频率变为 1/2 时的电容值。该例将 217.4MHz 的一半 108.7MHz 作为目标，实验结果显示当追加 680pF 电容时，振铃频率约为 108.7MHz (Figure 9)。

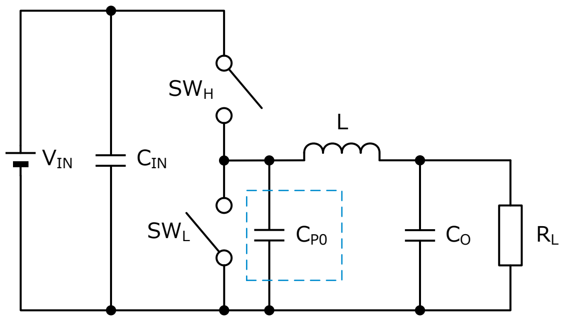

Figure 8. 追加 C_{P0}

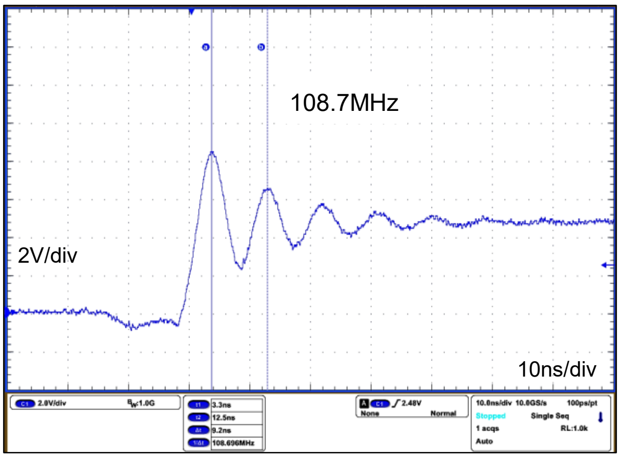

Figure 9. 将 C_{P0} 设为 680pF 时的振铃频率

3. 振铃共振频率由 $f_r = \frac{1}{2\pi\sqrt{L_P \cdot (C_{P2}+C_{P0})}}$ 决定，因此容量值变为 4 倍的话，频率降为一半。也就是可以推测寄生容量 C_{P2} 为附加电容 C_{P0} 的 1/3。C_{P0} 为 680pF 时，寄生容量 C_{P2} 就如下所示求得。

$$C_{P2} = \frac{C_{P0}}{3} = \frac{680pF}{3} = 227 \ \ \text{pF}$$

4. 寄生容量 C_{P2} 判定后，共振频率公式 $f_r = \frac{1}{2\pi\sqrt{L_P \cdot C_{P2}}}$ 变形可以求得寄生电感 L_P。振铃频率 f_r 为 217.4MHz，寄生容量 C_{P2} 为 227pF，那么

$$L_P = \frac{1}{(2\pi f_r)^2 \times C_{P2}} = \frac{1}{(2\pi \times 217.4MHz)^2 \times 227pF} = 2.36 \ \ nH$$

5. 求得共振特性阻抗。为了简化计算未考虑传输线路损耗，由理想的实际数值计算。

$$Z = \sqrt{\frac{L_P}{C_{P2}}} = \sqrt{\frac{2.36nH}{227pF}} = 3.22 \ \ \Omega$$

6. 为了衰减振铃，有必要将缓冲电阻 R_{SNB} 设为和共振特性阻抗 Z 同等大小。

$$R_{SNB} \geq Z \qquad [\Omega]$$

这里例子选择了 3.3Ω。

7. 缓冲容量 C_{SNB} 设定为寄生容量 C_{P2} 的 1～4 倍。

$$C_{SNB} = (1\sim4) \times C_{P2} \qquad [F]$$

计算结果为 227pF、454pF、681pF、908pF，实物容值为 220pF、470pF、680pF、1000pF。依次改变这些容量，观测振铃波形。结果为 Figure 10～14 所示，可以判断出当容值为 680pF 时，可以获得无振铃的良好波形。当振铃不消失时，将容量值进一步增加到 10 倍程度观测波形。但是容量值越大功率损耗就越增加，效率就低下。

8. 缓冲电阻 R_{SNB} 的消耗功率由如下公式求得。这个例子输入电压 V_{IN} 为 5V、开关频率 f_{SW} 为 1MHz，因此

$$P_{RSNB} = C_{SNB} \times {V_{IN}}^2 \times f_{SW} = 680\text{pF} \times 5^2 \times 1\text{MHz} = 17\text{mW}$$

缓冲电阻产生了 17mW 损耗。这个例子损耗虽然小，但是输入电压高的时候损耗也变大，因此不注意电阻的额定功率的话，缓冲电阻就会烧毁。缓冲电阻推荐使用额定功率是消耗功率 2 倍以上的电阻。
例如输入电压 V_{IN} 为 24V、开关频率 f_{SW} 为 1MHz 时、

$$P_{RSNB} = 680\text{pF} \times 24^2 \times 1\text{MHz} = 0.39\text{W}$$

产生了 0.39W 消耗功率，因此需要使用额定功率 1W，尺寸为 6432 (2512 inch)的电阻。

这个例子虽然选择了 3.3Ω と 680pF 常数，但是这个只对一开始测定的振铃频率有效，还得必须考虑输入电压或负载电流变化时这些参数也会变化的可能性，不管哪种条件都需要将最大程度减弱振铃作为目标值。

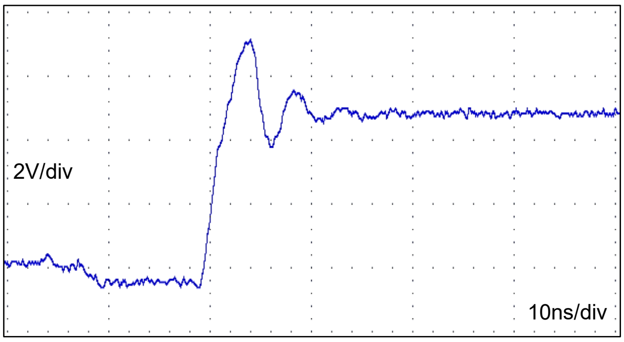

Figure 10. 无缓冲电路

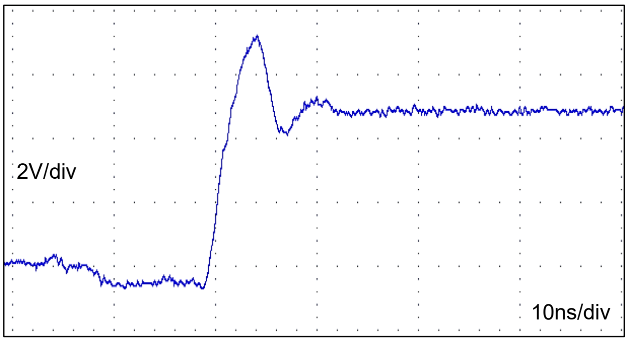

Figure 11. R_{SNB}=3.3Ω、C_{SNB}=220pF

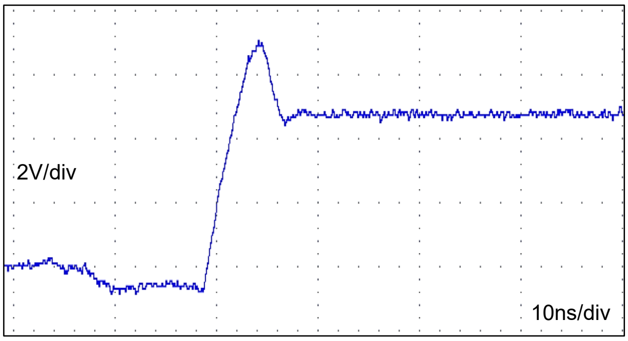

Figure 12. R_{SNB}=3.3Ω、C_{SNB}=470pF

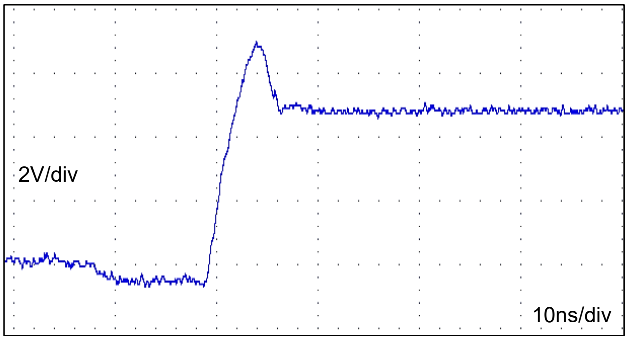

Figure 13. R_{SNB}=3.3Ω、C_{SNB}=680pF

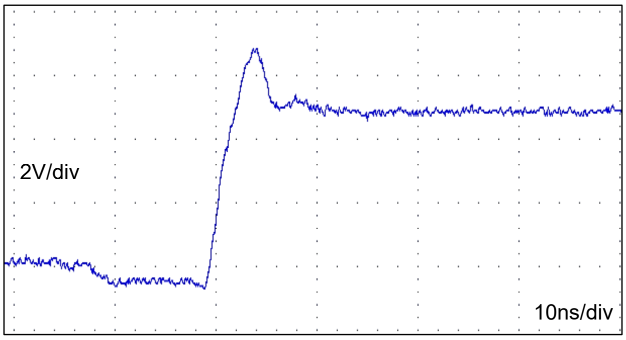

Figure 14. R_{SNB}=3.3Ω、C_{SNB}=1000pF

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