

Switch Mode Power Supply (SMPS) Design

Introduction

During my work at Edwards, one of the most exciting things I worked on was the design and test of a high voltage switch mode power supply. The below equations were used to design a SMPS, where the most important factor was to calculate the RMS (ripple) current through the capacitors and transformer in a power supply design, which was used to run a high voltage (3KV) circuit. The results of the calculations appropriate to the design have provided the answers for the specifications of the capacitors and transformer needed to achieve a functional hardware design. Once the hardware prototypes were built, the test results matched with the calculations, thus proving the board to be fully functional. The design process was done as described below:

Part 1: Extracting the whole necessary data.

Before starting the design the below points need to be taken into consideration:

- Maximum conduction time for the transformer
- Maximum switching duty cycle
- Maximum switching frequency

Equation one (Eq1) is used to find the longest time (t) that the transformer will be conducting during the worst case input voltage. The transformer has a maximum allowed time to conduct and if that time is exceeded it saturates (stops conducting). The off time has to be such that it allows for the transformer to cool off.

$$I(t) = \frac{1}{L} \int_0^T V_L(t) dt \quad \text{Eq1}$$

$$I_{pk} = \frac{1}{L} * V_{min} * t$$

$$t = \frac{I_{pk} * L}{V_{min}}$$

Once t is known then:

The duty cycle (suggested between 10-15%) determines the minimum period.

$$D = \frac{t}{T} \quad \text{Thus giving: } T = \frac{t}{D} \quad \text{Eq2}$$

Frequency needed to stably operate is found by:

$$f = \frac{1}{T} \quad \text{Eq3}$$

Frequency of the switching device is determined by the values of the resonance resistor and capacitor.

So having found the frequency, then R and C can be found by:

$$f = \frac{x}{R * C} \rightarrow R * C = \frac{x}{f} \quad \text{Eq4}$$

Note: In the above equation there are 2 unknowns. The datasheet of the switching device would provide suggested values for R, C or both of them. So, one of them can be chosen as an appropriate or suggested value, and then used to calculate the other one. Eq4 was extracted from the switching IC's datasheet.

Part 2: Calculating the current through the Transformer and Capacitors.

a) Current through the transformer:

$$I(t) \rightarrow I_{pk} * \frac{t}{t_1} \quad \text{For } t < t_1 \quad \text{Eq5}$$

$$I_{rms} = \sqrt{\frac{1}{T} \int_0^T I(t)^2 dt} = \sqrt{\frac{1}{T} \int_0^{t_1} (I_{pk} * \frac{t}{t_1})^2 dt} = \sqrt{\frac{I_{pk}^2}{T * t_1^2} \int_0^{t_1} t^2 dt} \quad \text{Eq6}$$

$$= \sqrt{\frac{I_{pk}^2}{T * t_1^2} * \frac{t_1^3}{3}} = \sqrt{\frac{I_{pk}^2 * t_1}{T * 3}}$$

The ripple current can then be used as a specification for the choice of the transformer

b) Current through the capacitor:

$$I_{rms} = \sqrt{\frac{1}{T} \int_0^T I(t)^2 dt} \quad \text{Eq7}$$

$$I(t) \rightarrow \frac{I_{pk} * t}{t_1} - I_{av} \quad \text{For } t < t_1$$

$$- I_{av} \quad \text{Otherwise} \quad \text{Eq8}$$

$$\begin{aligned}
I_{rms} &= \sqrt{\frac{1}{T} \int_0^T I(t)^2 dt} = \sqrt{\frac{1}{T} \int_0^{t_1} (I_{pk} * \frac{t}{t_1} - I_{av})^2 dt + \frac{1}{T} \int_{t_1}^{t_2} (-I_{av})^2 dt} \\
&= \sqrt{\frac{1}{T} \int_0^{t_1} (\frac{I_{pk}}{t_1})^2 * t^2 - 2 * I_{pk} * \frac{I_{av}}{t_1} * t + I_{av}^2 dt + \frac{1}{T} \int_{t_1}^T I_{av}^2 dt} \\
&= \sqrt{\left[\frac{I_{pk}^2}{t_1^2} * \frac{t^3}{3} - I_{pk} * \frac{I_{av}}{t_1} * t^2 + I_{av}^2 * t \right]_0^{t_1} + I_{av}^2 * (T - t_1)} * \frac{1}{T} \\
&= \sqrt{\left[\frac{I_{pk}^2 * t_1}{3} - I_{pk} * I_{av} * t_1 + I_{av}^2 * t_1 + I_{av}^2 * (T - t_1) \right]} * \frac{1}{T} \\
&= \sqrt{\left[\frac{I_{pk}^2 * t_1}{3} - I_{pk} * I_{av} * t_1 \right]} * \frac{1}{T} + I_{av}^2 \\
&= \sqrt{\frac{I_{pk} * t_1}{T} \left[\frac{I_{pk}}{3} - I_{av} \right]} + I_{av}^2
\end{aligned}$$

The ripple current can then be used as a specification for the choice of the capacitor(s). The specifications for the capacitor can be checked in its datasheet. If more than one capacitor is used that the ripple required for each capacitor will be:

$$I_{rmsn} = \frac{I_{rms}}{n} \quad \text{Eq9}$$

Where n is the number of capacitors.

Figure 1 shows the voltage across the capacitors after the prototype board was built. As expected the capacitor charges during the short on time and then conducts a small amount of current during the off time (fly-back of the transformer).

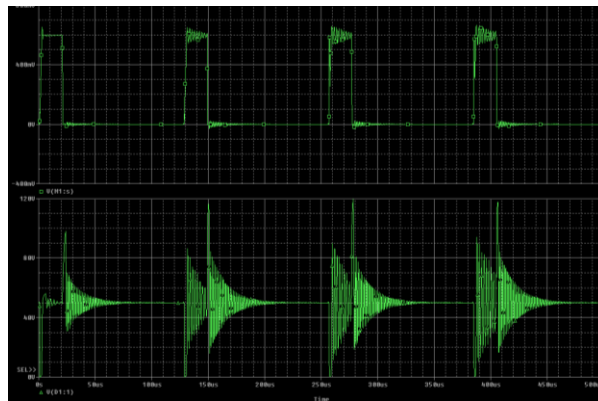


Figure 1: Voltage indicating the duty cycle (upper graph) and voltage through the transformer (lower graph).

Conclusion

After spending a long time researching and designing power supply circuit, the most interesting bit is when the actual built product speaks for itself. This whole process doesn't only teach you how to work out your way in designing power circuits, but shows how amazing engineering is. The whole mathematical equations which you learn at school starts to make sense when applied in engineering. And, that is probably when you really start enjoying and appreciating maths.

Appendix

I (t)	current (Amps)	t	time (Seconds)
I _{pk} (t)	maximum current (Amps)	t ₁	on time (Seconds)
I _{av}	average current during off time (Amps)	t ₂	off time (Seconds)
I _{rms}	ripple current (Amps)	R	resistor (Ohms)
L	inductance of the transformer (Henry)	C	capacitor (Farads)
VL	voltage (Volts)	f	frequency (Hertz)
n	number of capacitors	T	period (Seconds)
x	frequency factor (1 if not specified in the datasheet)	D	duty cycle (%)