Temperature-related power loss modeling for buck converter

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Abstract: The power loss modeling is a key procedure during designing the converter, especially in high temperature operation. This letter presents a practical method for predicting the temperature-related power losses for buck converter. In order to build the loss model, the datasheet driven method is adopted which requires only the information in device datasheets. The accuracy of the proposed model is demonstrated by the experiment. Experimental results are consistent with the theoretical analysis over the entire temperature range.

Keywords: high temperature, power losses, modeling, buck converter

Classification: Electron devices, circuits and modules

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1 Introduction

The power losses should be estimated to optimally design the switching converter. The accurate loss analysis and distribution of the converter are beneficial to improve the efficiency and save the cost. In the operation process of power converters, the loss of IGBT is one of the main power dissipation. Hence, accurate loss evaluation and loss measurement of IGBT becomes to be an important issue in designing higher power density converters. Conduction losses as well as switching losses are included in the calculation using a simplified model, based on power semiconductor data sheet in [1, 2].

There are lots of papers on DC-DC power converter loss investigation such as [3, 4, 5]. However the temperature-related accurate design-oriented loss modeling is seldom analyzed. And many recent researches are either too complicated or inaccurate such as [6, 7, 8]. Since it is desired to use only datasheet information with minimal measurements, the proposed method is independent of circuit models with decent accuracy and simulation speed. This proposed model divides the power losses of buck converter into four different parts, considering the relation of each component to temperature variation.

2 Temperature-related power loss modeling

The buck converter circuit and its waveform are in Fig. 1. $U_A$ means the IGBT conduction voltage, $u_{\text{drive}}$ means its drive signal and $U_F$ means the diode conduction voltage. The power losses for a buck converter are mainly caused by IGBT, diode, filter inductance and capacitance.

![Fig. 1. (a) Buck converter circuit; (b) Voltage and current waveform](image)

2.1 Diode loss thermal modeling

The schottky diode in buck converter acts as freewheel diode whose loss mainly consists of conduction loss. The conduction loss can be expressed as:

$$P_{D,\text{con}} = I_{D,\text{rms}} \times V_{F,\text{rms}}$$

(1)
where $I_{D_{\text{rms}}}$ is the effective conduction current and $V_{F_{\text{rms}}}$ is the effective conduction voltage. They are given by

$$I_{D_{\text{rms}}} = \sqrt{(1-D)(I^2_C + \Delta I^2)}$$

and

$$V_{F_{\text{rms}}} = \sqrt{(1-D)V_F^2}.$$  

Then the conduction loss is given by:

$$P_{D_{\text{con}}} = (1-D)V_F \times \sqrt{I^2_C + \Delta I^2}$$  

When temperature increases, the forward conduction voltage drops. According to the datasheet [9], $V_{F0}$ is 0.55 V and its change rate is $-1 \text{ mV/°C}$. $V_{FT}$ is given by:

$$V_{FT} = V_{F0}(1 - 0.001(T - T_0))$$  

The correction formula of the conduction loss is obtained as Eq. (4).

$$P_{D_{\text{con}}} = (1-D)V_{FT} \times \sqrt{I^2_C + \Delta I^2}$$  

### 2.2 IGBT loss thermal modeling

The total losses of IGBT include three aspects: 1) the switching loss during the process of turn on and turn off; 2) the conduction loss during the state of conducting; 3) the turn-off loss during the turned off state. The turn-off loss can be ignored.

IGBT switching losses can be expressed as Eq. (5).

$$P_{S_{\text{SW}}} = (E_{S_{\text{on}}} + E_{S_{\text{off}}}) \cdot f_s$$  

where $E_{S_{\text{ON}}}$ and $E_{S_{\text{OFF}}}$ respectively represent turn-on switching energy and turn-off switching energy, and $f_s$ represents the switching frequency. The numerical value $E_{S_{\text{ON}}}$ and $E_{S_{\text{OFF}}}$ vs. collector current at ambient temperature of 25°C is provided in the datasheet. Using the curve fitting method, the turn-off switching energy and turn-on switching energy can be expressed respectively as a linear function and a quadratic function of collector current $I_C$:

$$E_{S_{\text{off}}} = 0.051I_C - 0.011$$  

$$E_{S_{\text{on}}} = 0.0011 \times I_C^2 - 0.0084 \times I_C + 0.0836$$  

Temperature changes will affect corresponding parameters of IGBT and will inevitably affect the IGBT switching losses. The switching losses are calculated under varying temperatures in the datasheet [10] in Fig. 2 when $I_C$ is kept constant.

The relationship between the switching losses and ambient temperature can be expressed as Eq. (8). We can calculate $k$ and $b$ coefficient from the curve below that $k = 0.00405$ and $b = -0.668$. So the numerical model of IGBT switching losses and switching power dissipation vs. temperature can be expressed as Eq. (9)–(10).

$$\lg E_{\text{total}} = kT + b$$  

$$E_{\text{total}}_T = 10^{0.00405T - 0.668}$$  

$$P_{S_{\text{SW}}} = E_{\text{total}}_T \cdot f_s$$  

The conduction loss of IGBT can be expressed as Eq. (11).

$$P_{S_{\text{con}}} = I_{S_{\text{rms}}} \times V_{F_{\text{rms}}}$$
where $I_{S\text{-rms}}$ is the effective conduction current, and $V_{A\text{-rms}}$ is the effective conduction voltage. They are given by: 

$$I_{S\text{-rms}} = \sqrt{D(I_L^2 + \frac{\Delta I_L^2}{12})}, \quad V_{A\text{-rms}} = \sqrt{D^2}.$$ 

So the conduction loss is obtained as Eq. (12).

$$P_{S\text{-con}} = DV_{A\text{-rms}} \times \sqrt{I_L^2 + \frac{\Delta I_L^2}{12}} \tag{12}$$

The voltage value can be obtained by simulation under different temperature in a text circuit. Using curve fitting method, the relationship between conduction voltage and temperature is given by Eq. (13) and the correction formula is obtained:

$$V_{AT} = -0.003T + 1.886 \tag{13}$$

$$P_{S\text{-con}} = DV_{AT} \times \sqrt{I_L^2 + \frac{\Delta I_L^2}{12}} \tag{14}$$

### 2.3 Capacitor loss thermal modeling

The output filter capacitor loss is mainly caused by the ripple current flowing through its equivalent series resistance (ESR).

According to the definition of effective current, the ripple current flowing through output filter capacitor can be represented as:

$$I_{C\text{-rms}} = \sqrt{\frac{1}{T_s} \left[ \int_0^{DT_s} \left(-\frac{\Delta I_L}{2} + \frac{\Delta I_L}{D T_s} t\right)^2 dt + \int_0^{(1-D)T_s} \left(\frac{\Delta I_L}{2} - \frac{\Delta I_L}{(1-D)T_s} t\right)^2 dt \right]}$$

$$= \sqrt{\frac{\Delta I_L^2}{12}} \tag{15}$$

So the power loss of the capacitor is given by:

$$P_C = I_{C\text{-rms}}^2 \cdot ESR = \frac{\Delta I_L^2}{12} \cdot ESR \tag{16}$$

Using curve fitting method, the ESR can be expressed as a linearity function of temperature according to the datasheet:

$$ESR_T = ESR_0(1 + TR(T - T_0)) \tag{17}$$

where $T_0 = 25^\circ\text{C}$, $ESR_0 = 0.2\ \Omega$ and $TR$ is a linear temperature coefficient of ESR. Using curve fitting method, $TR = -0.0039$. So the ESR vs. temperature can be represented as:
$$ESR_T = 0.2 \times (1 - 0.0039 \times (T - 25)) = (0.2195 + 0.00078 \times T) \Omega \quad (18)$$

The correction formula of the output filter capacitor loss is obtained as follow:

$$P_C = \Delta f_L \cdot ESR_T/12 \quad (19)$$

### 2.4 Inductance loss thermal modeling

The inductance losses include two aspects: the iron loss and the copper loss. The Steinmetz empirical formula for iron loss is given by [11]:

$$P_v = C_m f^n B_m^p (a \cdot T^2 - b \cdot T + c) \quad (20)$$

where $P_v$ refers to the iron loss of per unit volume, $f$ is the magnetization frequency, $B_m$ is the amplitude value of the magnetic flux density, $T$ is the core temperature and $C_m$, $\alpha$, $\beta$, $a$, $b$, $c$ are correlation coefficients that can be found in the datasheet of the magnetic components.

This empirical formula is only applied to the condition of sine excitation so it should be amended for application of rectangular wave signal. Research has shown that the iron loss is related to the magnetization rate $dM/dt$ rather than the magnetization frequency $f$ [12]. $dM/dt$ is in proportion to the changing rate of magnetic flux density $dB/dt$. The average changing rate of magnetic flux density can be expressed as:

$$\frac{\langle dB \rangle}{dt} = \frac{1}{T} \int_0^T |B_m \omega \cos \omega t| dt = 4B_m f \quad (21)$$

Under non-sine voltage excitation, $dB/dt$ is not a simple linear relationship with $f$. In a magnetization cycle, the average $dB/dt$ in the direction of $B$ is given by:

$$\langle dB/dt \rangle = \frac{1}{\Delta B} \int dB/dt dB = \frac{1}{\Delta B} \int_0^T \left(\frac{dB}{dt}\right)^2 dt \quad (22)$$

where $\Delta B = B_{\text{max}} - B_{\text{min}}$. By substituting $B = B_m \sin \omega t = \frac{\Delta B}{2} \cdot \sin \omega t$ into Eq. (22), the average changing rate of magnetic flux density is obtained as follow:

$$\langle dB/dt \rangle = \frac{\pi^2}{2} \cdot \Delta B \cdot f_{\text{sin}} \quad (23)$$

$$\langle dB/dt \rangle = \frac{1}{\Delta B} \int_0^T \left(\frac{dB}{dt}\right)^2 dt = \frac{\pi^2}{2} \cdot \Delta B \cdot f_{\text{eq}} \quad (24)$$

So the equivalent magnetization frequency $f_{\text{eq}}$ can be expressed as:

$$f_{\text{eq}} = \langle dB/dt \rangle = \frac{2}{\Delta B^2 \cdot \pi^2} \int_0^T \left(\frac{dB}{dt}\right)^2 dt \quad (25)$$

So the correction form of the Steinmetz empirical formula is:

$$P_v = C_m f_{\text{eq}}^{\alpha-1} B_m^p f(a \cdot T^2 - b \cdot T + c) \quad (26)$$

According to the Faraday’s law of electromagnetic induction, the voltage is:

$$U_L = N \frac{d\Phi}{dt} = NA_e \frac{dB}{dt} \quad (27)$$
where $\Phi$ is the magnetic flux, $N$ is the number of coil and $A_e$ is the core effective cross-sectional area. So the equivalent magnetization frequency $f_{eq}$ is given by:

$$
\frac{dB}{dt} = \begin{cases} 
\frac{U_i - U_o}{NA_e} & 0 < t < DT \\
-\frac{U_o}{NA_e} & DT < t < T 
\end{cases} 
$$

(28)

$$
f_{eq} = \frac{2}{\Delta B^2} \cdot \frac{\pi}{2} \int_0^T \left( \frac{dB}{dt} \right)^2 dt = \frac{2f}{D(1-D)\pi^2} 
$$

(29)

where $D = 0.5$ and $f_{eq} = \frac{8f}{\pi^2}$.

The copper loss can be expressed as:

$$
P_{cu,loss} = I_{L,\text{rms}}^2 \cdot R_{cu} 
$$

(30)

where $I_{L,\text{rms}}$ is the effective current of the inductor and $R_{cu}$ is the resistance of the winding wire. Recording to the calculation formulas, $I_{L,\text{rms}}$ can be expressed as:

$$
I_{L,\text{rms}} = \left\{ \frac{1}{T_s} \left[ \int_0^{DT_s} \left( \left( I_L - \frac{\Delta I_L}{2} \right) + \frac{\Delta I_L}{DT_s} t \right)^2 \right] dt \\
+ \int_0^{T_s(1-D)} \left( \left( I_L + \frac{\Delta I_L}{2} \right) - \frac{\Delta I_L}{(1-D)T_s} t \right)^2 dt \right\}^{\frac{1}{2}} = \sqrt{I_o^2 + \frac{\Delta I_L^2}{12}} 
$$

(31)

In addition, the resistance of the winding wire $R_{cu} = \rho_{cu} \frac{l}{S}$. The resistivity of copper wire $\rho_{cu} = 1.85 \times 10^{-8} \Omega \cdot m$, the cross-sectional area of the wire $S = 1 \times 10^{-6} \text{m}^2$ and $l$ is the total length of the winding wire. The relationship between $R_{cu}$ and temperature is given by:

$$
R_{cu,T} = R_{cu} \times (1 + \alpha(T - T_0)) 
$$

(32)

where $\alpha$ is the temperature parameter and $\alpha = 0.00393/\text{°C}$ when $T_0 = 25\text{°C}$. So the correction formula of the copper loss is obtained as follow:

$$
P_{cu,loss} = I_{L,\text{rms}}^2 \cdot R_{cu,T} 
$$

(33)

3 Simulation and analysis

By putting each part together, the temperature-related power loss model for buck converter can be built. The numerical simulation was carried out using Matlab in temperature ranging from $25\text{°C}$ to $125\text{°C}$ in Fig. 3. With ambient temperature increasing, the total losses of buck converter increase dramatically.
Through the loss analysis of each part, the output filter capacitor loss is so small that can be ignored. The percentage of each part in ambient temperature of 25°C, 75°C and 125°C is shown respectively in Fig. 4.

As the figures show, with ambient temperature increasing, the proportion of IGBT conduction loss and diode loss reduces, the proportion of inductance loss remains stable and the proportion of IGBT switching loss increases dramatically.

4 Experimental verification

In order to verify the proposed loss model, an experiment platform is built as shown in Fig. 5. The specifications of the buck converter are shown in Table I. The complete power stage is placed in the thermostat with the control board placed outside. The converter is tested for ambient temperatures of 25°C to 125°C. Each temperature stays constant for 20 min.

Table I. Circuit performance indicators of the buck converter

|                         | \( U_i \) | 48 V |
|-------------------------|-----------|------|
| Input voltage           | \( U_i \) | 24 V |
| Output voltage          | \( U_o \) | 24 V |
| Rated power             | \( P_N \) | 100 W|
| Output voltage ripple coefficient | \( Y_u \) | 1%   |
| Inductor current ripple coefficient | \( Y_a \) | 20%  |
| Switching frequency     | \( f_s \) | 5 kHz|

The measured results are compared to the analysis model. As shown in Fig. 6, the IGBT and diode conduction voltage drops with ambient temperature increasing.
The calculated results based on the analysis model almost coincides with the experiment results under a wide range of temperature.

The input and output parameters are measured to calculate the efficiency. Fig. 7 shows the calculated efficiency based on the proposed loss analysis model and the measured efficiency of the buck converter. As shown in Fig. 7, the calculated efficiency based on the loss analysis model almost coincides with the experiment efficiency under a wide range of temperature. The model efficiency is a little higher than experiment because it ignores the parasitic losses of the converter. Good agreement is achieved that verify the accuracy of the proposed model.

5 Conclusion

A temperature-related power loss model for buck converter is carried out using the information of datasheets. The consideration of temperature effect on the device characteristics and losses is recommended for high-temperature operation. The experiment results verified the accuracy of the proposed model. The temperature-related power loss modeling method in this letter can be applicable to predict IGBT or diode junction temperature and to design power converters’ heat dissipation system under high temperatures. It can be widely used in high temperature, high power density and high frequency systems.

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