Average Modeling of Fly-buck Converter

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Abstract: This document presents an average macro model for the fly-buck converter. The model can be used for both large and small signal modeling. Parasitic and lossy components are included in the model, and it is partially based on a conventional average switch model for a buck stage. For isolated output, the analytic solution of the average current in a secondary winding is proposed. The presented model is implemented in SPICE, and simulation results are compared to switching model simulation and experimental data.

1 INTRODUCTION

The fly-buck converter has become popular because it has several advantages, such as good cross regulation, line transient response, and low EMI (Fang and Meng, 2015; Karlsson and Persson, 2017; Gu and Kshirsagar, 2017; Choudhary, 2015; Nowakowski, 2012). It has a simple design and provides multiple isolated outputs. A small-signal analytical model for an ideal fly-buck converter was presented in (Wang et al., 2017), but the effects of component parasitics could not be predicted.

The proposed model can be used for both large and small signal analysis and can be simulated in time or frequency domains. The difficulty of developing such a model is that leakage inductance current has a pulsed shape and cannot be approximated with conventional small ripple approximation, (Erickson and Maksimovic, 2007). To overcome this issue, the current is calculated during the instantaneous switching period, and small ripple approximation is used for the transformer’s magnetizing inductance current and capacitor voltages. The model accounts for the losses and parasitics of semiconductors and magnets and has been implemented as a SPICE subcircuit. The following assumptions were considered: the model covers two isolated outputs, and the dead-time effect is negligible.

2 MODEL DERIVATION

The fly-buck converter’s basic structure is shown in Fig. 1. The MOSFETS Q₁ and Q₂ have on-state resistances Rₘ₁ and Rₘ₂, respectively. The transformer T₁ has secondary side-related leakage inductance Lₛ, magnetizing inductance Lₘ, primary winding resistance Rₚ, secondary winding resistance Rₛ, and turns ratio 1 : n. The diode D₁ is modeled with on-state resistance R₇ and forward bias voltage Vₛ. Components listed above are internal parts of the proposed model. The input voltage vₕ(t), output voltages vₜ₁(t) and vₜ₂(t), and the corresponding load networks (R₁/C₁ and R₂/C₂) are connected externally to the model.

The converter has switching frequency Fₛ = 1/T.

![Figure 1: Fly-buck converter with two outputs.](image)

The main waveforms are shown in Fig. 2. The switching period is divided into three parts, and the first interval d₁ is the time when leakage inductance Lₛ resets. The switch Q₁ is on, and the Q₂ is off. The diode D₁ is forward-biased. The second interval d₂ is the time when the diode D₁ blocks, Q₁ is on, and Q₂ is off. The third interval d₃ is the time...
when $Q_1$ is off, $Q_2$ is on, and $D_1$ conducts. The duty cycle is determined as $d = d_1 + d_2$ and $1 - d = d_3$.

![Figure 2: Waveforms of the fly-buck converter.](image)

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![Figure 3: Equivalent circuits of the converter for different time intervals.](image)

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By using the charge balance approach, the average currents for $C_1$ and $C_2$ can be found:

$$L_m \frac{di(t)}{dt} = \langle v_{in}(t) \rangle_T - \langle v_{out1}(t) \rangle_T - \langle v_{out2}(t) \rangle_T$$

where $\langle x(t) \rangle_T$ represents the average value of $x$ over the switching period $T$. The currents $i_{out2(d_1)}(t)$ and $i_{out2(d_3)}(t)$ are artificially shown in Fig. 2 separately, so $i_{out2}(t) = i_{out2(d_1)}(t) + i_{out2(d_3)}(t)$ due to $i_{out2(d_2)}(t) = 0$. The average values of these currents will be obtained later.

The input voltage source’s average current can be obtained as follows:

$$\langle i_{in}(t) \rangle_T = \langle i_2(t) \rangle_T - \langle i_{out2}(t) \rangle_T - \langle i_{out1}(t) \rangle_T$$

To build the final model, the average currents $\langle i_{out2(d_1)}(t) \rangle_T$ and $\langle i_{out2(d_3)}(t) \rangle_T$ must be obtained. It can be seen from Fig. 2 that current $i_{out2(d_3)}(t)$ is an exponential process of magnetizing leakage inductance $L_m$. Fig. 3c can be used to find an analytical solution for the $\langle i_{out2(d_1)}(t) \rangle_T$ average current. The transient process during one switching period is considered. Variables $i_2(t)$, $v_{out1}(t)$ and $v_{out2}(t)$ can be replaced with constant sources for one switching period due to the small ripple approximation. The initial current in
the Ls inductor is zero, so a solution for the peak and average currents can be found:

\[
\max(i_{out2})_T = \frac{E_d(t)}{R_{d3}n} \left(1 - e^{-\frac{nR_{d3}t}{L_s}}\right)
\]

(5)

\[
(i_{out2})_T = \frac{E_d(t)}{R_{d3}n} \left(1 - e^{-\frac{nR_{d3}t}{L_s}}\right) + t_{off},
\]

(6)

where \(R_{d3} = R_{on2}+R_{pri}+(R_s+R_D)/n^2\), \(t_{off} = (1-d)/F_{sw}\) and

\[
E_d(t) = (v_{out1}(t)) + (i_t(t)) \left(R_{on2}+R_{pri}\right) - \frac{(v_{out2}(t))+V_D}{n}.
\]

A similar approach can be used to find \((i_{out2})_T\)’s average current during the \(d_1\) interval. Transient process of the leakage inductance reset is also considered in one particular switching period. The initial current in the \(L_s\) inductor is \(\max(i_{out2})_T\), found from (5), and then it resets to zero current. Thus, the solution is obtained as follows:

\[
(i_{out2})_T = \frac{E_d(t) F_{sw} L_s}{n^3 R_{on1} R_{d3}} \left(1 - e^{-\frac{nR_{d3}t}{L_s}}\right) \left(1 - e^{-\frac{nR_{d3}t_{off}}{L_s}}\right),
\]

(7)

where \(E_d(t) = E_d(t) - (v_{in}(t)) - (i_t(t)) \left(R_{on2} + R_{on1}\right)\), \(R_{d1} = R_{on1} + R_{pri} + (R_s + R_D)/n^2\). Using (1)–(3), the schematic of the fly-buck converter model can be constructed as shown in Fig. 4. The \((i_{out2})_T\) and \((i_{out2})_T\) currents ((6) and (7)) and realization of (3) are implemented by the Gd1 and Gg2 arbitrarily behavior current sources. The E3 source, along with \(L_1\), realizes (1). The G3 source is responsible for (4), while the G4 source implements (2). The ideal diodes D1 and D2 improve the convergence of the model by blocking negative voltages on the second output.

The model has next pins to connect to external circuits: node ‘Vin’ — input voltage, node ‘Vout1’ — first output (non-isolated), node ‘Vout2’ — second output (isolated) and node ‘d’ — duty cycle control input (0.0...1.0 range). The reference zero potential for the primary side is connected to the global ‘0’ net, and the secondary side’s ground potential is connected using a GND SEC pin.

The sub-model netlist can be found in Fig. 5 and (Zaikin, 2019).

### 3 RESULTS

The proposed model was simulated and compared to switching modeling, along with proto-
type measurement. The parameters for simulation and testing were \( V_D = 1.8 \) V, \( R_D = 0.2 \) Ohm (C3D06060A two in series), \( R_{on1} = R_{on2} = 12 \) mOhm (IPB117N20NFD), \( f_s = 100 \) kHz, \( L_S = 7.5 \) uH, \( R_S = 0.07 \) Ohm, \( L_m = 3.8 \) uH, \( R_{pri} = 10 \) mOhm, and \( n = 5 \). The external circuit contained the input cable's 40 uH inductance, and capacitance at the input was 7.92 mF (25 mOhm ESR), \( R_1 = 100 \) kOhm, \( C_1 = 940 \) uF (35 mOhm ESR), \( R_2 = 75 \) Ohm, \( C_2 = 2.35 \) uF and the input voltage \( v_{in} = 50 \) V. The circuit for simulation and measurement is shown in Fig. 6. The simulation results are presented in Fig. 7 and Fig. 8.

The setup for testing is shown in Fig. 9. The measurement results are presented in Fig. 10.

![Switching model and Average model](image)

Figure 7: Simulation results. The \( v_{out2} \) step response on the duty cycle changed from 0.4 to 0.5.

![Magnitude and Phase](image)

Figure 8: Simulation results. The transfer function \( \frac{v_{out2}(f)}{d(f)} \) of the output voltage compared to a control.

4 CONCLUSION

The proposed model can be simulated for large and small signal modeling in time or frequency domains. The model accounts for parasitics of semiconductors and magnetics so losses and precise behavior can be predicted. A listing of the SPICE model was presented and it can be used for the static and dynamic behavior analysis of the fly-buck converter.

REFERENCES

