Section 3: Effect of Non-Ideal Switches And Components On DC-DC Converters

3.1 Introduction: Steady-State Equivalent Circuit

The foregoing analyses of DC-DC converter circuits were based on ideal devices (switch T and diode D) and components (L and C). As a result, the input and output power (DC) could be equated (loss-less converter) and this simplified the analyses considerably. Linear or straight-line transitions of currents in the inductors were also assumed.

We assumed: \[ P = V_d I_d = V_0 I_0 \] (3.1)

![Figure 3.1](image)

The input – output voltage ratio for converter circuits were given as

\[ V_0 = f(D)V_d \] (3.2)

\[ I_d = f(D)I_0 \] (3.3)
Table 3.1 indicate $f(D)$ for several converters

<table>
<thead>
<tr>
<th>Converter</th>
<th>$f(D)$ with CCM</th>
<th>$f(D)$ with DCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUCK</td>
<td>$D$</td>
<td>$\frac{2}{1 + \sqrt{1 - \frac{4K}{D^2}}}$</td>
</tr>
<tr>
<td>BOOST</td>
<td>$\frac{1}{1-D}$</td>
<td>$\frac{1 + \sqrt{1 + \frac{4D^2}{K}}}{2}$</td>
</tr>
<tr>
<td>BUCK-BOOST</td>
<td>$-\frac{D}{1-D}$</td>
<td>$-\frac{D}{\sqrt{K}}$</td>
</tr>
<tr>
<td>CUK</td>
<td>$-\frac{D}{1-D}$</td>
<td>$\frac{D}{1-D}$</td>
</tr>
<tr>
<td>SEPIC</td>
<td>$\frac{D}{1-D}$</td>
<td>$\frac{D}{1-D}$</td>
</tr>
</tbody>
</table>
Equations 3.1-3.3 are analogous to equations of an ideal AC transformer in the steady state.

\[ V_1 I_1 = V_2 I_2 \]
\[ I_2 = \frac{V_2}{Z_0} \]
\[ I_1 = aI_2 \quad \text{and} \quad V_2 = aV_1 \]

Thus, a DC-DC converter in the steady-state may be regarded as a DC transformer. It should thus be possible to transfer voltage, currents and circuit parameters across the two sides of a DC-DC converter just like an AC transformer, with the turn ratio “\(a\)” given by \(f(D)\). Any
resistance $R$ in the load side is transferred as $f_{(D)}^2 R$ into the input side, and any resistance $R_i$ in the input side becomes $\left(\frac{1}{f_{(D)}^2}\right)^2 R_i$ in the load side. Thus

![Diagram of DC-DC Converter]

![Diagram of Transformer]

![Diagram of Resistor]

The DC transformer representation allows the calculation of the output voltage ratio $V_o/V_d$ when the voltage drops in the switch, diode and inductor resistance are not negligible. These voltage drops are influenced by load current and temperature. Furthermore, the DC representation allows us to determine how losses due these voltage drops affect the efficiency of the converter.
3.2 The Buck Converter

3.2.1 When only $L$ is non-ideal

\[ V_0 = DV_d \frac{1}{1 + \frac{R_L}{R_0}} \]

Also,
Figure 3.6

\[ I_d = \frac{V_d}{R_L} + \frac{R_o}{D^2} = \frac{V_0}{R_0} D \]

Now, \[ V_d = \frac{R_L}{D^2} \cdot \frac{V_0}{R_0} D + \frac{V_0}{D} \]

\[ V_d = \frac{1}{D} \left( \frac{R_L}{R_0} + 1 \right) V_0 \]

\[ V_0 = DV_d \frac{1}{1 + \frac{R_L}{R_0}} \]
Analysis using volt-seconds balance for the above circuit:

From $v_L = \int_0^T i_L dt = 0$, assuming that the ripple in inductor current is zero,

during $0 - DT_s$,

$$v_L = V_d - I_o R_L - V_o$$

during $1 - DT_s$,

$$v_L = -I_o R_L - V_o$$

$$\left( V_d - I_o R_L - V_o \right) DT_s - \left( I_o R_L + V_o \right) (1 - D) T_s$$

Simplifying, and noting that $V_o = I_o R_o$ and $I_o = I_L$,

$$I_o = \frac{D V_d}{R_o + R_L}$$ which conforms with figure 3.5.

Using $I_d = DI_o = \frac{D^2 V_d}{R_o + R_L} = \frac{V_d}{R_o + \frac{R_L}{D^2}}$ which conforms

with figure 3.6.
3.2.2 When $L$ and $T$ are non-ideal

Using ideal transformer equivalent circuit,

\[ V_{d} = \frac{V_{0}}{R_{0}}D = DI_{0} \]

\[ I_{d} = \frac{V_{0}}{R_{0}}D = DI_{0} \]

\[ V_{a} = \frac{V_{0}}{R_{0}}DR_{ds} + V_{T} + \frac{R_{L}}{D^{2}} \frac{V_{0}}{R_{0}}D + \frac{V_{0}}{D} \]
\[ V_d = \frac{V_0}{R_0} DR_{ds} + V_T + \frac{R_L V_0}{R_0} + \frac{V_0}{D} \]

\[ V_d = V_T + V_0 \frac{D^2 R_{ds}}{DR_0} + \frac{R_L V_0}{R_0} + \frac{V_0}{D} \]

\[ V_d = V_T + \left( \frac{D^2 R_{ds}}{R_0} + \frac{R_L}{R_0} + 1 \right) \frac{V_0}{D} \]

\[ V_0 = \frac{DV_d - DV_T}{1 + \frac{R_L}{R_0} + \frac{D^2 R_{ds}}{R_0}} = \frac{DV_d - DV_T}{R_o} \frac{R_o}{R_o + R_L + D^2 R_{ds}} \]

![Diagram of circuit](image)
Using Volt-second balance of inductor voltage,

During $0 - DT_s$:  
$$V_L = V_d - V_T - I_L R_{ds} - I_L R_L - V_o$$

During $DT_s - T_s$, i.e., $(1 - D)T_s$:  
$$V_L = -(I_L R_L + V_o)$$

$$\left(V_d - V_T - I_L R_{ds} - I_L R_L - V_o\right)DT_s - (I_L R_L + V_o)(1 - D)T_s = 0$$

$$D V_d - D V_T - I_L R_{ds} D - I_L R_L D - V_o D$$
$$- I_L R_L - V_o + I_L R_L D + V_o D = 0$$

Noting that $I_L = I_o$, $V_o = I_o R_o$, and simplifying

$$I_o = \frac{D V_d - D V_T}{R_o + D R_{ds} + R_L}$$

$$V_o = \frac{D V_d - D V_T}{R_L + \frac{D R_{ds}}{R_0}}$$

Note that the analysis using volt-second balance gives a different expression for $I_o$ than the analysis of section 3.2.1. This implies that the ideal transformer representation cannot be applied to items which are part of the switching elements (T and D). Henceforth, we will only use the volt-seconds balance to analyse DC-DC converter circuits.
3.2.3 With diode voltage $V_D$, and $V_T$ included; $R_D$, $R_{ds}$ and $R_L$ neglected

Again, assuming ripple-free inductor current, from voltage-second balance across the inductor $L$,

$$V_d DT_s - V_T DT_s - V_0 DT_s - (V_0 + V_D)(1 - D)T_s = 0$$

$$V_d DT_s - V_T DT_s - V_0 DT_s - V_0 T_s - V_D T_s + V_0 DT_s + V_D DT_s = 0$$

$$DV_d - DV_T - V_0 - V_D(1 - D) = 0$$

$$V_0 = DV_d - DV_T - V_D(1 - D)$$

Analysis with diode resistance, $R_D$, included.

As before, using voltage-second balance across $L$,

$$V_d DT_s - V_T DT_s - (V_0 + V_D + I_L R_D) (1 - D) T_s = 0$$

$$V_d D - V_T D - V_0 D - V_0 - V_D - I_L R_D + V_0 D + V_D D + D I_L R_D = 0$$

$$V_0 = DV_d - DV_T - V_D(1 - D) - \frac{V_0}{R_0} R_D (1 - D)$$

$$V_0 \left\{ 1 + \frac{R_D}{R_0} (1 - D) \right\} = DV_d - DV_T - V_D(1 - D)$$

$$V_0 = \frac{DV_d - DV_T - V_D (1 - D)}{1 + \frac{R_D}{R_0} (1 - D)} = \frac{DV_d - DV_T - V_D (1 - D)}{R_o + (1 - D) R_D}$$
The above derivation also shows that elements which are shared between the input and the output circuits, such as $V_D$ and $R_D$ (or part of the switching elements T and D in the above case), are transferred differently from the concepts of the ideal transformer. Correct representation of these items must be determined from the volt-second and current balance principles.
3.2.4 Full representation

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.9}
\caption{Figure 3.9}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.10}
\caption{Figure 3.10}
\end{figure}

\[ v_L = V_d - I_d R_{ds} - V_T - I_L R_L - V_0 \]

\[ v_L \text{ during } T_{ON} = V_d - I_d R_{ds} - V_T - I_L R_L - V_0 \]

\[ v_L \text{ during } T_{OFF} = -(V_0 + I_o R_L + I_o R_D + V_D) \]

From volt-second balance

\[ (V_d - V_T - I_d R_{ds} - V_T - I_L R_L - V_o) DT_s \]
\[ -(V_0 + I_o R_L + I_o R_D + V_D)(1 - D) T_s = 0 \]
\[ DV_d - DV_T - V_D (1 - D) = V_0 + I_o DR_{ds} + I_o (1 - D)R_D + I_o R_L \]

\[ DV_d - DV_T - V_D (1 - D) = V_0 + D \frac{V_0}{R_0} R_{ds} + \frac{V_0}{R_0} R_D (1 - D) + \frac{V_0}{R_0} R_L \]

\[
V_0 = \left[ DV_d - DV_T - V_D (1 - D) \right] \frac{R_o}{DR_{ds} + R_D (1 - D) + R_L + R_0}
\]

Figure 3.11
3.2.5 Power loss

\[ P_{loss} = I_0^2 \left[ DR_{ds} + R_D (1 - D) + R_L \right] + I_0 \left[ DV_T + V_D (1 - D) \right] \]

Power output = \( V_0 I_0 = R_0 I_0^2 \)

Note: The current waveforms in \( R_{ds} \) and \( R_D \) are in fact pulsating, so their RMS values must be used in calculating the power dissipation. It should be noted the RMS currents in \( R_{ds} \) and \( R_D \) are \( I_o \sqrt{D} \) and \( I_o \sqrt{1-D} \), respectively, so that the above expression correctly give the power losses in \( R_{ds} \) and \( R_D \), under the assumption of ripple-free inductor current.

The total power loss must also include the switching power losses which are due to the overlap of voltage and current across the switch and the diode at each turn ON and OFF. Also losses in the series resistance of the capacitor (ESR) and in the snubber circuits, if used, must also be included.
3.2.6 The efficiency from DC analysis.

\[ \eta = \frac{P_{out}}{P_{out} + P_{loss}} = \frac{1}{1 + \frac{P_{loss}}{P_{out}}} \]

\[ \eta = \frac{1}{1 + \frac{I_0^2 [D R_{ds} + R_D (1 - D) + R_L]}{R_0 I_0^2} + I_0 \left[ D V_T + V_D (1 - D) \right]} \]

\[ \eta = \frac{1}{1 + \frac{1}{R_0} \left[ D R_{ds} + (1 - D) R_D + R_L \right] + \frac{1}{V_0} \left[ D V_T + (1 - D) V_D \right]} \]
3.3 The Boost Converter

3.3.1 When only L is non-ideal

Figure 3.12

Assuming CCM and negligible ripple in $i_L$ and $V_0$.

Figure 3.13
\[
\frac{V_d}{1-D} = I_0 R_0 + I_0 \frac{R_L}{(1-D)^2}
\]
\[
I_0 = \frac{V_d}{1-D} \frac{1}{R_0} + \frac{R_L}{(1-D)^2}
\]
\[
V_0 = I_0 R_0 = \frac{V_d}{1-D} \frac{R_0}{R_0} + \frac{R_L}{(1-D)^2}
\]
\[
V_0 = \frac{V_d}{1-D} \frac{1}{R_L/R_0} \left( 1 + \frac{R_L}{R_0} \right)
\]
\[
\frac{V_0}{V_d} = \frac{1}{1-D} \frac{1}{R_L/R_0} \left( 1 + \frac{R_L}{R_0} \right)
\]
\[
\eta = \frac{1}{1 + \frac{R_L}{R_0(1-D)^2}}
\]
3.3.2 Full representation

![Diagram](image)

Figure 3.14

During $T_{ON}$:  
\[ v_L = V_d - I_L R_L - V_T - I_L R_{ds}; \]
\[ I_C = -\frac{V_0}{R_0} \]

During $T_{OFF}$:  
\[ v_L = V_d - I_L R_L - V_D - I_L R_D - V_0; \]
\[ I_C = I_L - \frac{V_0}{R_0} \]

![Waveform](image)

Figure 3.15
From volt-second balance

\[
(V_d - I_L R_L - V_T - I_L R_{ds}) DT_s \\
+ (V_d - I_L R_L - V_D - I_L R_D - V_0) (1 - D) T_s = 0
\]

\[
V_d - I_L R_L - D V_T - D I_L R_{ds} \\
- (1 - D) V_D - I_L R_D (1 - D) - V_0 (1 - D) = 0
\]

\[
V_0 (1 - D) = V_d - D V_T - (1 - D) V_D \\
- I_L [R_L + R_D (1 - D) + D R_{ds}] \quad (eqn*)
\]

From current balance

\[
\frac{1}{T} \int_0^{T_s} i_c dt = 0
\]

\[
-\frac{V_0}{R_0} DT_s + (I_L - \frac{V_0}{R_0}) (1 - D) T_s = 0
\]

\[
-\frac{V_0}{R_0} D + I_L - \frac{V_0}{R_0} - D I_L + D \frac{V_0}{R_0} = 0
\]

\[
(1 - D) I_L = \frac{V_0}{R_0}
\]

\[
I_L = \frac{V_0}{R_0 (1 - D)} \quad (eqn**)\]
From (eqn*) and (eqn**):

\[
V_0(1 - D) = V_d - DV_T - (1 - D)V_D - \left[ \frac{V_0}{R_0(1 - D)} \right](R_L + R_D(1 - D) + DR_{ds})
\]

\[
V_0(1 - D) + \frac{V_0}{R_0(1 - D)}(R_L + R_D(1 - D) + DR_{ds}) = V_d - DV_T - (1 - D)V_D
\]

Dividing both sides by \(1 - D\)

\[
V_0 \left\{ 1 + \frac{1}{R_0(1 - D)^2} \left[ R_L + R_D(1 - D) + DR_{ds} \right] \right\} = \frac{V_d - DV_T - (1 - D)V_D}{1 - D}
\]

\[
V_0 = \frac{V_d - DV_T - (1 - D)V_D}{1 - D} \times \frac{1}{1 + \frac{1}{R_0(1 - D)^2} \left[ R_L + R_D(1 - D) + DR_{ds} \right]}
\]
\[ V_0 = \frac{V_d - DV_T - (1 - D)V_D}{1 - D} \]

\[
\times \frac{1}{1 + \frac{1}{R_0} \left[ \frac{R_L}{(1 - D)^2} + \frac{R_D}{(1 - D)} + \frac{DR_{ds}}{(1 - D)^2} \right]}
\]

\[
\frac{DR_{ds}}{(1 - D)^2} \quad \frac{DV_T}{1 - D} \quad V_D \quad \frac{R_D}{1 - D} \quad \frac{R_L}{(1 - D)^2}
\]

\[
\begin{array}{c}
\frac{V_d}{1 - D} \\
R_0
\end{array}
\]

**Figure 3.16**

### 3.3.3 Power loss

\[
P_{\text{loss}} = I_0^2 \left[ \frac{DR_{ds}}{(1 - D)^2} + \frac{R_D}{1 - D} + \frac{R_L}{(1 - D)^2} \right] + I_0 \left[ \frac{DV_T}{1 - D} + V_D \right]
\]

Power output = \( R_0 I_0^2 \)

Efficiency:

\[
\eta = \frac{P_{\text{out}}}{P_{\text{out}} + P_{\text{loss}}} = \frac{1}{1 + \frac{P_{\text{loss}}}{P_{\text{out}}}}
\]
\[ \eta = \frac{1}{1 + \frac{I_0^2}{R_0 I_0^2} \left[ \frac{D R_{ds}}{(1 - D)^2} + \frac{R_D}{1 - D} + \frac{R_L}{(1 - D)^2} \right] + I_0 \left[ \frac{D V_T}{1 - D} + V_D \right]} \]

\[ \eta = \frac{1}{1 + \frac{1}{R_0} \left[ \frac{D R_{ds}}{(1 - D)^2} + \frac{R_D}{1 - D} + \frac{R_L}{(1 - D)^2} \right] + \frac{1}{V_0} \left[ \frac{D V_T}{1 - D} + V_D \right]} \]
3.4 The Buck-Boost converter

During $T_{ON}$:  \[ v_L = V_d - V_T - R_{ds}I_L - I_L R_L ; \]

During $T_{OFF}$:  \[ v_L = -(V_0 + V_D + R_D I_L + I_L R_L) ; \]

From volt-second balance:

\[ \int_{0}^{T_s} v_L dt = 0 \]
\[
(V_d - I_L R_{ds} - V_T - I_L R_L)DT_s \\
-(V_0 + V_D + R_D I_L + I_L R_L)(1 - D)T_s = 0
\]

\[
DV_d - I_L DR_{ds} - DV_T - (1 - D)V_o \\
-(1 - D)V_D - I_L (1 - D)R_D - I_L R_L = 0
\]

In the steady-state DC condition, the switch current waveform is

\[
\begin{array}{c}
\text{I}_L \\
\hline
\text{DT}_s \\
\hline
\text{(1-D)T}_s
\end{array}
\]

\[I_d = DI_L\]

From current balance,

\[I_d + I_o = I_L\]

\[DI_L + I_o = I_L\]

\[I_o = (1 - D)I_L\]

\[I_L = \frac{I_o}{1 - D}\]
\[ I_d = \frac{D I_o}{1 - D} \]

\[ DV_d - DV_T - (1 - D)V_D = \frac{1}{1 - D} I_o D R_{ds} + (1 - D)V_o + \frac{I_o}{(1 - D)}(1 - D)R_D + \frac{1}{1 - D} I_o R_L \]

\[ I_o = \frac{DV_d - DV_T - (1 - D)V_D}{1 - D} \times \frac{1}{\left(\frac{D}{1 - D}\right) R_{ds} + (1 - D)R_o + R_D + \frac{1}{1 - D} R_L} \]

\[ V_0 = \frac{DV_d - DV_T - (1 - D)V_D}{1 - D} \times \frac{1}{1 + \frac{1}{R_0} \left[ \frac{D}{(1 - D)^2}R_{ds} + \frac{R_D}{1 - D} + \frac{1}{(1 - D)^2} R_L \right]} \]

\[ \frac{D}{(1 - D)^2} R_{ds} \quad \frac{D}{1 - D} V_T \quad V_D \quad \frac{R_D}{1 - D} \quad \frac{R_L}{(1 - D)^2} \]

Figure 3.19
3.4.1 Power loss

\[
P_{\text{loss}} = I_0^2 \left[ \frac{DR_{ds}}{(1 - D)^2} + \frac{R_D}{1 - D} + \frac{R_L}{(1 - D)^2} \right] + I_0 \left[ \frac{DV_{T}}{1 - D} + V_D \right]
\]

Power output = \(R_0 I_0^2\)

\[
\eta = \frac{P_{\text{out}}}{P_{\text{out}} + P_{\text{loss}}} = \frac{1}{1 + \frac{P_{\text{loss}}}{P_{\text{out}}}}
\]

\[
\eta = \frac{1}{I_0^2 \left[ \frac{DR_{ds}}{(1 - D)^2} + \frac{R_D}{1 - D} + \frac{R_L}{(1 - D)^2} \right] + I_0 \left[ \frac{DV_{T}}{1 - D} + V_D \right] + R_0 I_0^2}
\]

\[
\eta = \frac{1}{1 + \left[ \frac{DR_{ds}}{(1 - D)^2} + \frac{R_D}{1 - D} + \frac{R_L}{(1 - D)^2} \right] + \frac{1}{V_0} \left[ \frac{DV_{T}}{1 - D} + V_D \right]}
\]

The above analyses have all assumed ripple-free inductor current. If this assumption cannot be taken, the analyses become rather complex. In such cases the above analyses only give approximate losses, as a first approximation. Simulation packages like PSIM, Plexim Spice, Saber and Simulink are now-a-days used to obtain better estimates of losses and \(V_o\) for a given \(D\) easily.
3.5 Switching Loss

The converter circuits treated so far have diode clamping. Most converter circuits which use gate turn-off devices are operated with diode clamping. In these circuits, a diode provides a freewheeling path for the switch current to flow through when the switch is turned off. This prevents disastrously high $L \frac{di}{dt}$ voltage from appearing in the circuit at turn-off. Note that if current through an inductive circuit is turned-off by a switch, the rate of fall of current, in the absence of a freewheeling path, is forced by the turn-off time of the switch which are in micro or nano seconds.

$$v_L = L \frac{di}{dt}$$

The high $L \frac{di}{dt}$ voltage can be prevented by having a resistive, resistive-capacitive or diode freewheeling path for the load current to continue to flow and fall at a slower rate when the switch is turned off.
The fall of current through the switch at turn-off may not be along a single straight line as suggested in the previous page.

After the switch turn off, the $V_{ds}$ or $V_{CE}$ across it rises to $V_d$. The rise of $V_T$ and fall of $i_T$ may have some overlap, giving rise to power loss during turn-off across the switch.
Similarly, at turn-on, the voltage and current transition may also have some overlap leading to power loss at turn-on.

![Figure 3.23](image)

Power losses indicated by the shaded areas (in Joules) occur as many times per second as the switching frequency.

For the diode-clamped Buck converter, the turn-on and turn-off $v_t$ and $i_t$ waveforms are given below:

![Figure 3.24](image)
$t_{ri}$: Current rise time.

$t_{fi}$: Current fall time.

$t_{rv}$: Voltage rise time.

$t_{fv}$: Voltage fall time.

$W_{on} = V_{on} I_o t_{on}$

$t_{con} = t_{rt} + t_{fv}$

$t_{coff} = t_{rv} + t_{fi}$

Figure 3.25
If the turn–on and turn-off transients are not short compared to \( T_s \), the average power loss in the switching process, \( P_{SW} \), may become large compared to the loss during the ON time (the on-state power loss, \( P_{on} \)).

\[
P_{sw} = \frac{1}{2} V_d I_0 f_s (t_{con} + t_{coff}) \quad \text{Watts}
\]

The on-state power loss is given by

\[
P_{on} = V_{on} I_{on} f_s \quad \text{Watts}
\]

where \( t_{on} \) is the on-time of the switch in a switching period. Note that \( P_{sw} \) increases proportionately with \( f_s \), while \( P_{ON} \) does not, since \( T_{on} \) and \( f_s \) are inversely proportional to each other.

The energy dissipated (power loss) in the switch during turn-on and turn-off transients can be found by multiplying the voltage \( v_T(t) \) and current \( i_T(t) \) of the switch and integrating the product over the duration to each transient. The calculation is simplified if the origin \( t = 0 \) for each case is shifted to time when the respective transitions begin, and if the on-state voltage of the switch is neglected in comparison with the DC supply voltage \( V_d \).

Thus, for turn-on transient,

\[
W_{sON} = \int_{t_{ri}}^{t_{f_0}} V_d \frac{I_0}{t_{ri}} t dt + \int_{t_0}^{t_{f_0}} I_0 V_d \left(1 - \frac{t}{t_{fy}}\right) dt \quad \text{Joules.}
\]
\[ W_{sON} = \frac{1}{2} V_d I_0 t_{ri} + \frac{1}{2} V_d I_0 t_{fv} \]
\[ W_{sON} = \frac{1}{2} V_d I_0 (t_{ri} + t_{fv}) = \frac{1}{2} V_d I_0 t_{on} \quad (J) \]

Similarly, it can be shown that for turn-off transient,
\[ W_{sOFF} = \int_{t_{rv}}^{t_{fi}} V_d I_0 t_{on} dt + \int_{0}^{t_{fi}} I_0 V_d \left( 1 - \frac{t}{t_{fi}} \right) dt \]
\[ W_{sOFF} = \frac{1}{2} V_d I_0 (t_{rv} + t_{fi}) = \frac{1}{2} V_d I_0 t_{off} \quad (J) \]

The total switching power loss is thus given by
\[ P_{sw} = \frac{1}{2} V_d I_0 (t_{con} + t_{off}) f_s \quad (W) \]

Note that the straight-line transition of current is rather simplified, especially at turn-off. The actual turn-on and off transients are found manufacturer's data sheet and should be used to obtain the switching losses more accurately.

**Other Losses**

The foregoing analyses did not take into account losses of magnetic origin (hysteresis and eddy current), proximity effects and loss in the ESR of the capacitor. These will be treated later.