Forward Converter

The forward converter is another single-transistor isolated converter, and differs from the flyback in that energy is supplied to the secondary side during the "on" period of the transistor.

When Q1 is on, \( V_{in} \) appears across the primary and hence the secondary voltage is

\[
V_S = \frac{N_S}{N_P} V_{in}
\]

This will forward bias D1 so \( V_P \approx V_S \) (ignoring the diode voltage drop). The voltage across the inductor is then \( V_L = V_X - V_{out} = V_S - V_{out} \).

When Q1 is off, the primary and secondary voltages change sign turning D1 off. When \( i_L \) starts to decrease, \( V_P \) changes sign and free-wheeling diode D2 turns on, clamping \( V_P \) at 0 V so \( V_L = -V_{out} \).

\[\begin{align*}
N_o & \quad \text{t} \\
-V_{out} & \quad I_L
\end{align*}\]  
\[\text{(for continuous mode)}\]
At this point we could use voltmeter balance on $V_i$ to determine $N_{in}$ but it's easier just to exploit the close similarity to the buck converter: all we need to do is replace $V_i$ in the buck equation by $V_{in} N_s / N_p$, so the output voltage is

$$V_{out} = V_{in} D \left( \frac{N_s}{N_p} \right)$$

Thus the turns ratio can be exploited to accomplish most of the voltage change, with the control circuit varying $D$ to adjust for smaller variations in $V_{in}$.

There is something important missing from the above discussion, however: when the transistor switches off, any real transformer will have some energy stored in the core. That energy must be discharged before the start of the next switching cycle, otherwise we could encounter a problem called "saturation" where the flux keeps growing with each cycle.

If the stored flux is not removed before the start of the next cycle, each new switching cycle will cause the flux to grow until it "wakes up" the core to saturation.
One common method to "reset" the core is to add a third "reset winding" to the transformer as shown below, along with a catch diode D3.

At the instant Q1 switches off, the primary voltage switches sign. With the winding polarity shown, the voltage across the reset winding will go negative and forward-biases D3, thus:

$$V_r = 0 - V_m = -V_m$$

and hence:

$$V_p = V_r \left(\frac{N_p}{N_r}\right) = -V_m \frac{N_p}{N_r}$$

These voltages will persist until the core energy is discharged, at which point $$V_r$$ and $$V_p$$ will go to zero, D3 will turn off.

Voltage balance:

$$V_m T_m = V_m \frac{N_p}{N_r} T_r$$

To reset the core before the start of a new cycle, $$T_m + T_r < T$$.
\[ 20 \quad ||_{\text{on}} + ||_{\text{on}} \frac{N_r}{N_p} \leq 1 \]
\[ \Rightarrow D \left[1 + \frac{N_r}{N_p}\right] \leq 1 \Rightarrow D \leq \frac{1}{1 + \frac{N_r}{N_p}} \]  \hspace{1cm} (2)

Thus in a forward converter with a reset winding there is always a limit on the maximum duty-cycle.

What determines \(N_r/N_p\)? Consider the voltage across \(Q_1\) in the off-state: this is
\[ V_d = V_m - V_P = V_m \left[1 + \frac{N_p}{N_r}\right] \]  \hspace{1cm} (3)

The maximum allowable stress on the transistor will therefore constrain \(N_r/N_p\) and hence \(D\) in (2)

Typically \(N_r \approx N_p\) so \(D \leq 0.5\) (50% duty cycle)

Note that a reset winding is not the only method that can reset the core. We could accomplish the same thing with a snubber circuit:

\[ \text{in this case the stored energy in the core is dumped into a resistor.} \]
\[ \text{This solution would therefore be less efficient, but it avoids an extra winding on the transformer.} \]
Now let's consider the relationship between the input current and the secondary currents.

\[ \Delta i_L = \left( \frac{V_{in}}{N_p T} \right) \cos \omega t \]

\[ \langle i_L \rangle = \frac{V_{in}}{R} \]

During the on-state, the primary and secondary currents in an ideal transformer are related by

\[ N_p I_p = N_s I_s \]

But in a real transformer, there is an additional primary component of current due to the magnetization current. If the core is properly reset before each new cycle, then the magnetization current will start at zero and

\[ \Delta i_m = \frac{V_{in}}{L_m T} \cos \omega t \]

So we expect the transistor current to look like this:

The peak current in Q1 is then:

\[ I_p = I_{peak} \frac{N_s}{N_p} + \Delta i_m = \left( \langle i_L \rangle \pm \frac{\Delta i_L}{2} \right) \frac{N_s}{N_p} + \Delta i_m \]
The model we developed earlier for a real transformer might be helpful here because it clearly separates the role of the magnetization current.

\[ I_p + I_m \rightarrow I_s \text{ (still assumes } k=1) \]

So when \( Q_1 \) is on, the total primary current is

\[ I_d = I_m + I_p = I_m + I_s \frac{N_p}{N_s} \]

The model also helps visualize what happens during turn-off and core resetting in this case.

When \( Q_1 \) turns off, the magnetizing current \( I_m \) will continue to flow into the no-dot end of \( N_p \), and this will induce a current flow out of the no-dot end of \( N_r \) as shown.

\( I_r \) is the reset current that would flow in \( \delta_3 \) given by

\[ I_r = I_m \frac{N_p}{N_r} \]
If you recall from the buck converter, the output inductor is usually chosen so that $\Delta L$ is about 20-40% of the maximum load current, so,

$$\Delta L = \frac{1}{3} I_{D,\text{max}}$$

So

$$I_D = \frac{N_s}{N_p} \left( 1 + \frac{3}{2} \right) I_{D,\text{max}} + \frac{V_{in}}{L_m} DT$$

If the maximum allowed transistor current is specified, then this equation can be used to set a lower bound on $L_m$:

$$\frac{N_s}{N_p} \left( 1 + \frac{3}{2} \right) \frac{V_{out}}{R_{\text{min}}} + \frac{V_{in}}{N_s} \frac{1}{L_m T_s} < I_{D,\text{max}}$$

so

$$L_m T_s > \frac{\frac{N_s}{N_p} \frac{V_{out}}{R_{\text{min}}} - \frac{V_{in}}{N_s} \frac{1}{L_m T_s}}{I_{D,\text{max}}}$$ \hspace{1cm} (4)

Recall that the turns ratio $N_s/N_p$ is set by (1) and (2)

$$\frac{N_s}{N_p} \geq \left( \frac{V_{out}}{V_{in}, \text{max}} \right) \quad \text{Dmax} = \frac{1}{1 + \frac{N_s}{N_p}}$$

Once $L_m$ is chosen, the transformer can be designed.

Note that the forward converter is not required to store energy, so large $L_m$ is desirable. This favors an ungapped core with large $A_p$. So forward converters typically have smaller transformers than flybacks.