Transformer Design Pitfalls: Stepup Is Not As Easy As Stepdown

by Gregory Mirsky, Design Engineer, Deer Park, Ill.

When designing transformers, engineers often forget that they not only transform one voltage into another but also transform impedance. The apparent input impedance has a component that is the secondary impedance divided by the squared transformation coefficient. This causes certain problems with power transfer at high frequency by means of a stepup transformer.

In particular, these problems relate to the impact of the turns ratio and other factors on the input circuit time constant. In this article, we will analyze the relationship between these parameters and demonstrate this relationship with a design example.

The Analysis

Imagine we have to transfer power from the primary side to the secondary side with a transformation coefficient (turns ratio) of N_t. Next, let's assume that the transformer in question has stray (leakage) inductance. We'll designate these primary and secondary stray inductances as L_{s1} and L_{s2}, as depicted in Fig 1. Additionally, in this transformer model, V_{m1} and V_{m2} are the primary-side and secondary-side voltages across the primary and secondary transformer windings.

We will also want to designate the primary-side impedance as $Z_1(s)$, which represents the impedance that can be measured across the input of the transformer. Through our analysis we can define how its value depends on the secondary-side components. Note that to simplify this analysis, we are applying the Laplace transform.

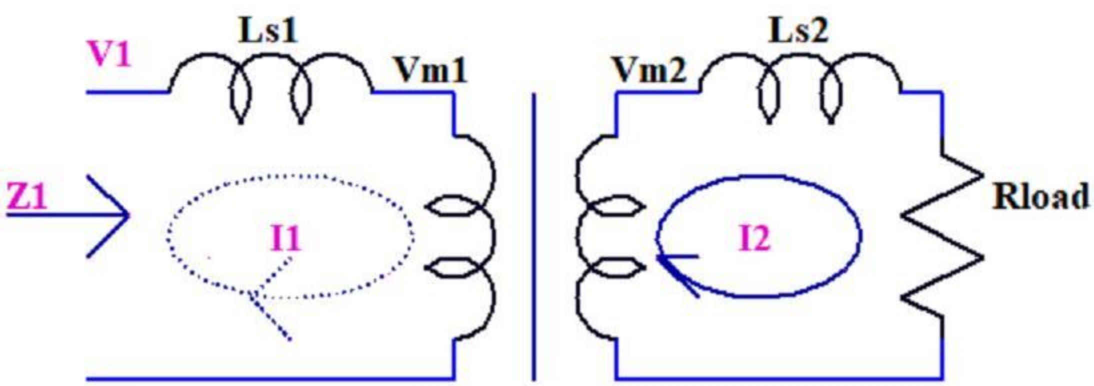

Fig. 1. Transformer model for analyzing impact of turns ratio and secondary-side components on input impedance.

We begin the analysis by noting that the transformation coefficient

$$N_t = \frac{V_{m2}}{V_{m1}} \tag{1}$$

which is also defined by

$$I_1(s) = N_t \cdot I_2(s) \tag{2}$$

From Fig. 1, if we designate the primary-side total resistance as r1, we can further define V_{m1} and V_{m2} in the s domain as

$$V_{m1}(s) = V_1(s) - I_1(s) \cdot (sL_{s1} + r_1) \tag{3}$$

and

$$V_{m2}(s) = V_{m1}(s) \cdot N_t \quad (4)$$

Then

$$I_2(s) = \frac{V_{m2}(s)}{R_{load} + s \cdot L_{s2}} \quad (5)$$

Therefore, substituting (3) and (4) into (5) with the assumption of (2) we get the following expression for $I_1(s)$:

$$I_1(s) = I_2(s) \cdot N_t = \frac{V_{m2}(s)}{R_{load} + s \cdot L_{s2}} \cdot N_t = \frac{V_{m1}(s) \cdot {N_t}^2}{R_{load} + s \cdot L_{s2}} = {N_t}^2 \cdot \frac{V_1(s) - I_1(s) \cdot (s \cdot L_{s1} + r_1)}{R_{load} + s \cdot L_{s2}} \quad (6)$$

which yields

$$I_1(s) = \frac{V_1(s)}{(s \cdot L_{s1} + r_1) + \frac{R_{load} + s \cdot L_{s2}}{{N_t}^2}} \quad (7)$$

Taking into account that

$$Z_1(s) = \frac{V_1(s)}{I_1(s)}$$

and using (7) we obtain an expression for $V_1(s)$:

$$V_1(s) = I_1(s) \cdot \left[(s \cdot L_{s1} + r_1) + \frac{R_{load} + s \cdot L_{s2}}{{N_t}^2}\right]$$

which then yields an expression for $Z_1(s)$:

$$Z_1(s) = \frac{V_1(s)}{I_1(s)} = \frac{I_1(s) \cdot \left[(s \cdot L_{s1} + r_1) + \frac{R_{load} + s \cdot L_{s2}}{{N_t}^2}\right]}{I_1(s)}$$

$$Z_1(s) = s \cdot L_{s1} + r_1 + \frac{R_{load} + s \cdot L_{s2}}{{N_t}^2} \quad (8)$$

Expression (8) means that if you supply the load through a stepdown transformer, you "see" the secondary-side impedance as a high value since $N_t < 1$.

On the other hand, in a stepup transformer $N_t > 1$, and this always causes issues, especially if $N_t >> 1$ because in this case the load shorts the transformer input. This occurs because the load, leakage and stray reactances on the secondary side of stepup transformers are reflected into the primary side as much lower values than they actually have.

This effect comes into play in power supplies where the voltage source being applied to the transformer's primary winding is a pulse train. In this case, the impact of N_t on the transformer's primary-side impedance in turn affects the time constant of the input circuit, as we will now define.

Let the input voltage be a pulse train with a 50% duty-cycle and amplitude V_0, where τ_c is the pulse duration, and consider one full pulse of the input pulse train for simplicity:

$$V_1(t) = \left(\Phi(t) - 2 \cdot \Phi(t - \tau_C)\right) \cdot V_0 \qquad (9)$$

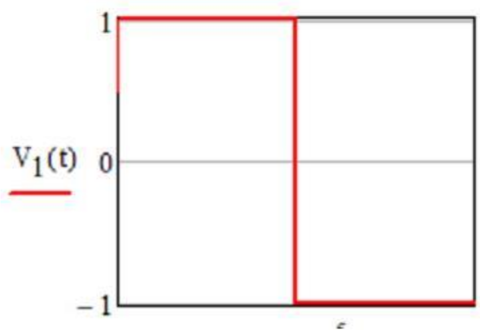

Fig. 2. Applying a pulse train with 50% duty cycle to the input of a power supply transformer will allow us to analyze the impact of the transformation coefficient N_t on the time constant of the input circuit.

Using (8) we can define the input circuit time constant τ_1 now as follows:

$$\tau_1(N_t) = \frac{L_{s1} + \frac{L_{s2}}{N_t^2}}{r_1 + \frac{R_{load}}{N_t^2}} \qquad (10)$$

It is also convenient to normalize the input circuit time constant to the value obtained for the transformer having a 1:1 turns ratio τ_0:

$$\tau_0 = \tau_1(1) \qquad (11)$$

and the normalized time constant Θ is

$$\Theta(N_t) = \frac{\tau_1(N_t)}{\tau_0} \qquad (12)$$

Design Example

To see the impact of these equations, let's consider a design example with the following parameters:

R_{load} = 178 Ω

L_{s1} = 6 μH

L_{s2} = 1 μH

r_1 = 0.8 Ω

Applying equations (8) through (11),

$$\tau_1(N_t) = \frac{L_{s1} + \frac{L_{s2}}{N_t^2}}{r_1 + \frac{R_{load}}{N_t^2}}$$

$$\tau_0 = \tau_1(1)$$

$$\Theta(N_t) = \frac{\tau_1(N_t)}{\tau_0}$$

we can plot $\Theta(N_t)$ as shown in Fig. 3.

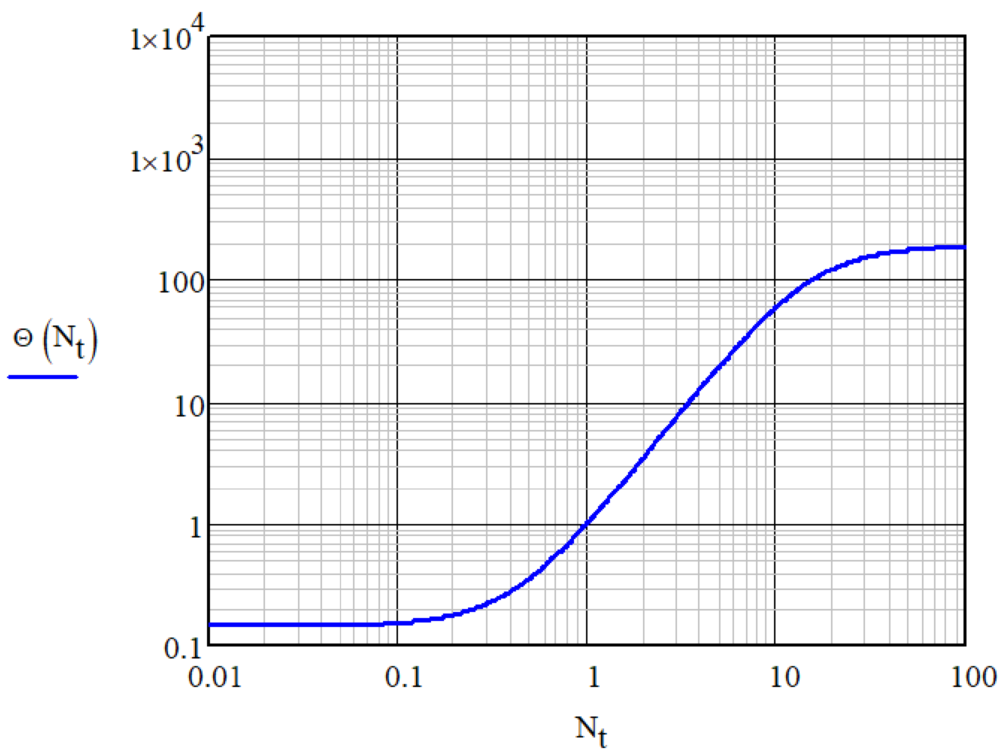

Fig. 3. The normalized time constant of a transformer's input circuit plotted as a function of the transformation coefficient N_t. At $N_t = 1$ we have the dividing line between stepdown ($N_t < 1$) and stepup ($N_t > 1$) transformers. As the graph illustrates, there is a much larger increase in the time constant for high stepup N_t values than for low stepdown N_t values.

It is obvious that a stepup transformer whose $N_t > 1$ increases the apparent input time constant of the input circuit. This increase depends on the transformer secondary-to-primary turns ratio, operating frequency, and secondary stray inductance. It is easy to show that the same relates to the stray capacitance. In the case of a stepdown transformer the apparent input time constant decreases but not as significantly as it increases for the stepup transformer.

In switching power supplies stepup transformers may significantly distort the secondary pulse shape, which may cause in turn, an efficiency drop, driving transistors to overheat and microcontrollers to malfunction due to dV/dt slow down.

Reference

"Step-Up Transformer: All You Need to Know" by Cecelia, EasyBOM blog entry, April 20, 2022.

About The Author

Gregory Mirsky is a design engineer working in Deer Park, Ill. He currently performs design verification on various projects, designs and implements new methods of electronic circuit analysis, and runs workshops on MathCAD 15 usage for circuit design and verification. He obtained a Ph.D. degree in physics and mathematics from the Moscow State Pedagogical University, Russia. During his graduate work, Gregory designed hardware for the high-resolution spectrometer for research of highly compensated semiconductors and high-temperature superconductors. He also holds an MS degree from the Baltic State Technical University, St. Petersburg, Russia where he majored in missile and aircraft electronic systems.

Gregory holds numerous patents and publications in technical and scientific magazines in Great Britain, Russia and the United States. Outside of work, Gregory's hobby is traveling, which is associated with his wife's business as a tour operator, and he publishes movies and pictures about his travels online.

For more on magnetics design, see these How2Power Design Guide search results.