Understanding Transformers

Part 2: Transformer Types & Frequency Response Analysis

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Abstract: This paper is the second part of the "Understanding Transformers" application note series. While the Part 1 per covered the basic parameters of transformers, this paper will briefly highlight how these parameters play an important role in the process of selecting a transformer type for different applications and how the presence of such parameters leads to the non-ideal frequency behavior of the transformers. Frequency behavior (voltage gain and phase shift) and how to measure it using frequency response analysis (FRA) in the lab will be discussed in more detail. Moreover, a simulation will be performed to illustrate the frequency behavior of the transformer using the non-ideal model that includes all the parameters.

Table of Contents

Introduction

A transformer is a passive device that can be used for galvanic isolation in circuitry and used to step up or step down an AC voltage. This is fundamentally useful in the transmission lines where the voltage drop across the line restricts the transmission distances up to few miles. By introducing transformers, it is possible to step up the generator voltages to a few hundreds or even thousands of volts (kV). This allows transmitting the electrical energy across a much longer distance with much less loss.

A transmission line is an example of a common industrial application. However, many different variants of transformers in today's electronics industry have made them popular in relatively low-power applications like DC-DC converter circuitry, isolation in ethernet, impedance matching for audio, and others. Therefore, selecting a transformer is not a trivial process because the end application dictates how much emphasis is put on some of the transformer parameters over the others. The upcoming sections will highlight some of the end applications, the type of transformer used in each one, and the main parameters to consider when choosing a transformer.

Transformer Types and Applications

There are many different types of transformers that span across the industry, from high-power industrial to low-power microelectronics applications. Examples of high-power industrial transformers include power transformers that generate high voltage for long-distance power transmission as well as distribution transformers, which are used to step down the voltage for residential or commercial facilities. These are typically large-sized three-phase transformers (three lines of input with 120-degrees phase shift between the lines).

Another type is the current transformer, which is commonly used to monitor the current traveling through a power line. These can be used for safety devices in high-power circuity to trip a protection mechanism, such as relays or circuit breakers, when the current level exceeds the safe range. Current transformers are also used in metering or instrumentation applications like utility billing devices and clamp-on current sensors.[1]

Transformers are also used for impedance matching of high-speed data signals and low-frequency audio applications. For example, when a loudspeaker's input impedance does not match the power amplifier's output impedance in an audio amplifier, a transformer with the appropriate turn ratio can be introduced to change the impedance that the amplifier sees on the primary windings. By matching the impedance values, the maximum power transfer can be achieved. [2]

Saturable reactors are another category of transformer used as variable inductors. In this type, an adjustable DC voltage source is applied on the primary windings. The DC current saturates the core of the device and decreases the inductance and impedance of the secondary windings, which can be useful in controlling AC signals.[2]

Parameters to Consider when Choosing a Transformer

End-application requirements are critical in determining the essential properties of the transformer to be employed. When it comes to transformers, there is not a "one-size-fits-all" option. They come in various winding configurations with multiple taps, sizes and materials to fit the intended application. The following are the parameters to look at when selecting a transformer:

1) Rated power, current and voltage of the primary and secondary windings;
2) Turn ratio;
3) Magnetizing inductance;
4) Leakage inductance;
5) Winding resistance;
6) Frequency response and self-resonant frequency (SRF).

As shown in previous section, for high-power applications such as transmission lines, rated power, voltage, and current are critical to the design since these systems must deal with up to 1000s of KiloVARs of power. On the other side, switch mode power supply (SMPS) applications require the designer to pay more attention to the frequency characteristics of the transformer since they can operate up to several MHz. Meanwhile, transformers in lighting ballasts are intentionally designed with higher leakage inductance to limit the output current. While many of these parameters are explored in [6], this paper will examine frequency response in more detail.

Frequency Response Analysis (FRA)

It might be necessary to observe the frequency characteristics of a transformer over a wide range of frequencies. This is particularly useful for ensuring the frequency behavior of a proposed transformer suits the frequencies of the targeted application. Additionally, the analysis is useful in verifying that the transformer is mechanically intact and that no damage has occurred due to manufacturing or transportation anomalies.

Ideally, transformers should have constant voltage gain (or attenuation) across the entire operational frequency range. However, this does not happen due to the parasitic elements that are present in the transformer, namely the leakage and magnetizing inductances, the inter-windings capacitance, and the windings' resistance, which has been explored in [6]. These effects are represented in the non-ideal equivalent circuit model of transformers, as shown in Fig.1 in the "Simulation" section. The elements of the circuit model are a function of the transformer's physical construction and the type of materials used. This leads to the unique frequency characteristic of each transformer.

Frequency response analysis (FRA) is done to examine how much the parasitic elements affects the output signal by sweeping the voltage gain and phase shift over a frequency range. These measurements illustrate how the output signal compares to the input signal vertically (difference in amplitude) and horizontally (difference in time) at the tested frequency range. The voltage gain is the ratio of output voltage to input voltage. It is usually expressed in decibels (dB) using the following equation:

$$Votlage\ Gain\ (dB) = 20Log\ (\frac{Vout}{Vin})$$

Eq. 1[3]

Whereas:

V_{out} = Output voltage at the secondary windings;
V_{in} = Input voltage at the primary windings.

Meanwhile, the phase shift is the difference between the phases of the output and input signals; or how much the output lags or leads the input, timewise. This is usually expressed in degrees using the following equation:

$$Phase\ Shift\ (°) = \Phi_{Output} - \Phi_{Input} = \Delta t * f * 360$$

Eq. 2

Whereas:

Φ_{output} = Phase of the output signal in degrees
Φ_{intput} = Phase of the input signal in degrees
Δt = Time difference between the two signals

There are multiple ways to perform this analysis. One way is by using an oscilloscope and function generator, as follows:

1) In FRA, a sinusoidal signal is typically used for the testing. Most, if not all, function generators have the capability to produce sinusoidal signals at different frequencies (usually up to 20MHz).
2) The sinusoidal test signal is applied to the transformer's primary windings. While the output voltage at the secondary windings is measured using the oscilloscope.
3) The amplitude of the test signal must be chosen carefully since the output voltage at the secondary windings may be much higher than the input signal at the primary windings, depending on the turn ratio.
4) For high voltages, it is advised to use x100 or x10 probes to attenuate the amplitude of the output signal [4].
5) Care must be taken such that voltage and current do not exceed the maximum rated values of the probe and the oscilloscope.
6) The voltage amplitude is measured at the secondary windings using the oscilloscope.
7) Most oscilloscopes can calculate the phase shift from Measure menu. The input signal from the generator is fed to the oscilloscopes, and Phase function is used to find the phase shift. If the phase function is not available, then the two signals are adjusted vertically such that the zero crossings of both are on the horizontal x-axis.

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8) The number of divisions (and subdivision) between the points where both signals cross the x-axis are counted and then multiplied by the horizontal axis scale (which is in seconds/division) to calculate time difference.
9) Frequency, input voltage and output voltages, and time difference are recorded.
10) The frequency of the testing signal is increased, and another voltage measurement of both input and output is taken. More data points are acquired until the entire desired frequency range is covered.
11) After collecting input and output voltage pairs across a range of frequencies as well as the time difference, Eq. 1 and 2 can be used to find the voltage gain and phase shift at each single frequency.
12) The frequency response is obtained by plotting the voltage gain and phase shift on the y-axis verses the frequency on the x-axis using any graphing tool.

A faster alternative way to measure the frequency response is using the same testing setup mentioned above but using a sweep signal from the function generator instead, as follows:

1) A sweep signal is set up on the function generator by choosing the starting frequency, the stop frequency and the sweeping time. This signal is fed to the primary windings of the transformer.
2) With the output at the secondary windings connected to one of the oscilloscope's channels, a sweep signal can be seen on the screen.
3) The sync port of the function generator is connected to the second channel of the oscilloscope.
4) By using Trigger menu of the oscilloscope, the sync signal is used as a trigger for the measurement of the transformer output signal that is present on the other channel. A rising edge or falling edge trigger is chosen depending on when the signal starts, which can be seen on the screen. Triggering the oscilloscope using the sync signal allows it to capture a cleaner signal.
5) The time on the horizontal x-axis of the oscilloscope (the time per division multiplied by the number of divisions) must be set equal to the sweeping time that has been set in Step 1. This allows the oscilloscope to capture the different amplitudes throughout the whole swept frequency range.
6) The sweeping time of the function generator can be adjusted as necessary so that it is equal to the sweep time of the oscilloscope.
7) The output signal is moved down on the y-axis such that the zero volts level is at the bottom of the screen. (Only the top half of the signal can be seen.)
8) The envelope of the signal (the trace drawn by the amplitude) at this point represents the frequency response of the transformer. If 1V test signal is used from the function generator, then the envelope represents the voltage gain (Gain=Vout/Vin), and the x-axis represents the frequency.
9) It is important to note that the x-axis (and y-axis) in this case is linear (unlike the typically logarithmic frequency graphs). This can be fixed by changing the sweeping mode to logarithmic on the function generator if it has this capability.
10) The most left point on the x-axis represents the start frequency of the sweep, while the point at the right end represents the stop frequency. [5]

Simulation

Simulating the frequency behavior of a transformer based on the information from the datasheet is a powerful tool to get an idea about suitability of a transformer for a specific application. Below is an example simulation of a non-ideal transformer model. The component's values are the typical values for small-sized transformers. The value of each parameter can be found in Abracon's transformer datasheets but may be labeled differently than what is shown below.

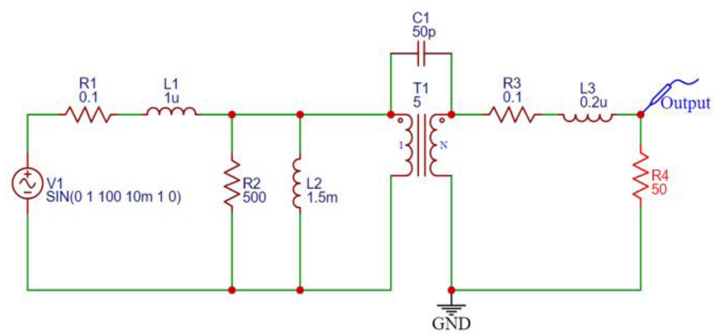

Fig.1: Non-ideal Transformer Model

The parameters in Fig. 1 are as follows:

R1 = Primary resistance (Ω);
R2 = Represents core losses (Ω);
R3 = Secondary resistance(Ω);
L1 = Leakage inductance of the primary (H);
L2 = Magnetizing inductance (H);
L3 = Leakage inductance of the secondary (H);
C1 = Inter-windings capacitance (F).

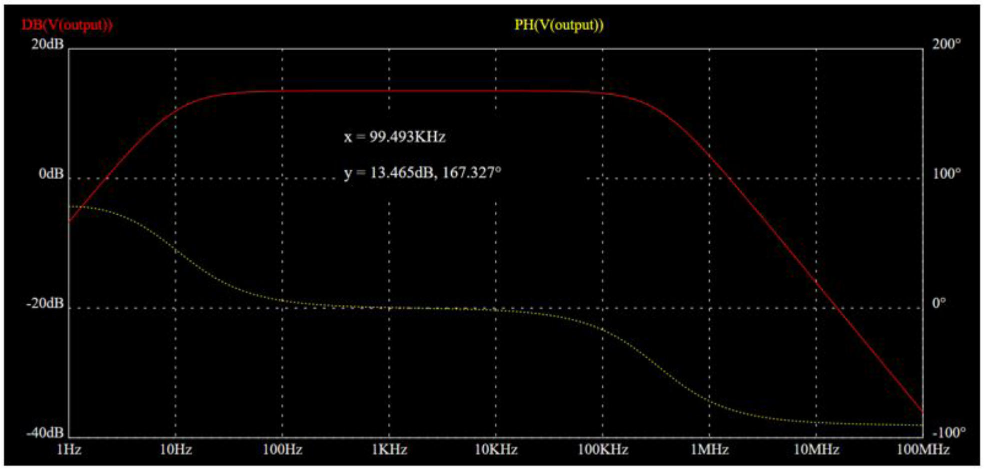

Fig. 2: Frequency Response of the Non-ideal Transformer Model

Shown in red, the trace line corresponds to the voltage gain in decibels plotted against the change in frequency up to 100MHz. It is observed that the output is attenuated until about 10Hz at low frequencies. Then, the response flattens out at ~13.46 dB up to 100kHz. Note that the 13.45 dB corresponds to a gain of about five, which is the turn ratio of the transformer that is shown in Fig. 1.

Additionally, the yellow trace line corresponds to the phase shift between the output and input that is introduced by the transformer at different frequencies. This can be critical for some sensitive applications, like audio processing circuits, because the different phase shifts at the frequencies of interest can lead to distorted audio output.

Conclusion

This paper explored some of the different types of transformers and illustrated how the parasitic parameters lead to a non-ideal frequency behavior that must be accounted for when choosing a transformer. Moreover, the frequency behavior has been characterized using FRA, and the steps to perform it in the lab was explored as well. In addition, by using the non-ideal circuit model of the transformer, it was shown how a simulation of the circuit can be used to observe the frequency behavior of the transformer.

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