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Calibration

Electrical load limitations of transconductance amplifiers

Technical Note

The transconductance amplifier (TA) is a widely used, stable, and accurate source of current. The TA takes a voltage input (and in some cases current) and produces an accurate current that is nearly independent of electrical load impedance. For an ideal TA, the output current is directly proportional to the input signal. Consider a TA that has a 100 A full scale range with a 1 V input. It has a transimpedance ratio of 100 A/1 V—a value of 100 Siemens. If one places 0.5 V into the same amplifier, the expected output will be 50 A. The transconductance amplifier is a nearly perfect device to use when one wants a constant current source for calibration or other testing purposes. However, it must be used with knowledge about its limitations to assure its specifications are met.

The TA is able to maintain a constant current into a varying load within some specified limits. This limit is determined by a parameter known as compliance voltage. The compliance voltage is the maximum voltage at the TA output terminals that is available to produce the desired current into the connected load. Load variation may occur as connection resistances (contact resistances) change with time, conductors heat as current is applied, load heating, and any other causes or changes in connected resistance or inductance.

There are many manufacturers of TA's that cover a wide range of currents and frequencies. All of the amplifiers discussed herein cover bipolar (positive and negative polarity) direct currents (dc) as well as sinusoidal alternating current (ac) over some frequency range. Typical maximum current ranges are 10 A, 20 A and 100 A and recently a 120 A. Maximum frequency limits are typically 1 kHz, 10 kHz and as high as 100 kHz. TA's may also have additional multiple lower current ranges. For example, a 100 A TA may also have ranges of 0.002, 0.02, 0.2, 2, and 20 A as well as the 100 A range. Each range may have the same full scale input voltages or different voltages. The user must read the instruction manual to assure they are supplying proper voltages; otherwise the TA will not perform as expected. Also, not all ranges will have the same compliance voltage as discussed below.

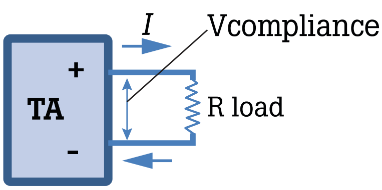
Typical maximum compliance voltages range from approximately 2 volts to as high as 7 volts. Specifications for compliance voltage are typically broken into two categories: dc and ac. Further, the voltages may be different on each range. The reason for the differences is related to the peak vs rms (root-mean-squared) current specification. To produce a sinusoidal current the TA must produce the peak current that corresponds to the rms current value that is desired. The relationship between the peak and rms values is given by: **Ipeak= Irms*sqrt(2)**.

Therefore, when we need 100 A rms the amplifier must produce a peak current of 141 A into the electrical load. We will see later how this impacts the specifications and use of the TA.

Direct current

Let's look at the simple case of producing a 100 A dc into a load with a resistance of 0.04 Ω. Using simple Ohm's law, the voltage required to accomplish this is:

V=IR=100*0.04 = 4 Volts



For the amplifier to be able to produce the desired current into the 0.04 Ω load, it must have a compliance voltage of at least 4 V. If the TA only has a compliance voltage of 3 V on the 100 A range, then significant error in the current produced will result. In many but not all TA's, the compliance voltage limit error is indicated by an LED being illuminated on the front panel. Many TAs will also detect the over compliance condition, stop producing current, and go into standby mode. What the user must do in this case is either reduce the load or accept a lower current for the existing load. The remainder of this application note will investigate the tradeoffs of current, frequency, and connected load in more detail.

The dc load that the TA sees is the sum of any loads being driven, such as a shunt or resistor, the cable resistances and contact resistances; in other words, the sum of all resistances connected to the TA output terminals. The nominal value of a shunt or resistor is usually known. We can easily calculate the cable resistances as in the following and the contact resistances usually must be estimated.

Let's consider a typical circuit for testing a 0.01 Ω current shunt at 100 A. To estimate the cable resistance:

1. Identify the conductor AWG or cross sectional area,
2. Find the resistance per unit length and
3. Multiply the value obtained in step 2 times the total length of conductor.

For example, a typical cable supplied by one TA manufacturer has a cross sectional area of 25 mm^2. The resistance is 0.7 mΩ/m. The cables are approximately 1 m each. Therefore, the cable resistance is calculated as:

2 m * 0.7 mΩ/m = 0.0014 Ω for both cables

We might estimate the contact resistance at 0.002 Ω. Our total load will be:

R_{total}= 0.01+0.0014+0.002= 0.0134 Ω

The amplifier will need a compliance voltage of:

V=IR=100 A*0.0134 Ω= 1.34 V

A compliance voltage of 1.34 V is well within the range of most TA's. However, what happens if we try to drive a 0.1 Ω load with 100 A?

V=IR=100 A*(0.1+0.0014+0.002)=10.34 V

There are no known TA's from any manufacturer that can produce 100 A into the 0.1 Ω load because of the compliance voltage limitations. We must either reduce the load or the current to be within the compliance voltage range of the present TA's. However, the same amplifiers could easily generate 100 A into a different lower resistance load. Just as with all test equipment, we must understand the specifications, proper use, and any limitations.

Alternating current

We now consider the TA driving an alternating current. When we want to produce an alternating current, we have to consider the ac characteristics of the load and cabling. This involves looking at the inductance of the load, as well as the resistance connected to the TA output terminals. Load capacitance is neglected because of the low voltages involved and the dominance of the resistive and inductive values in the overall connected load.

Inductance opposes the rate of change of current. It is comprised of two components—the self and mutual inductance. For our purposes we will consider the total inductance. For a more detailed treatment, the reader is referred to [1]. The following information is based on the work by Grover [2] which is the most detailed reference on inductance that is known. The inductance equations presented below can be found in [3].

In the simplest case, the TA sees a load that it must drive current through which is the series sum of R_t and X_L. To produce the current in the load will require a compliance voltage given by

$$V_{comp} = \text{IZ} = I\sqrt{R_t^2 + X_L^2}$$

where

$X_L=2\pi fL_t$, the inductive reactance,
f = frequency in Hz,
L_t = the total of all inductances connected to the TA,
Z= the impedance magnitude,
I = the current rms value,
R_t = the total of all resistances

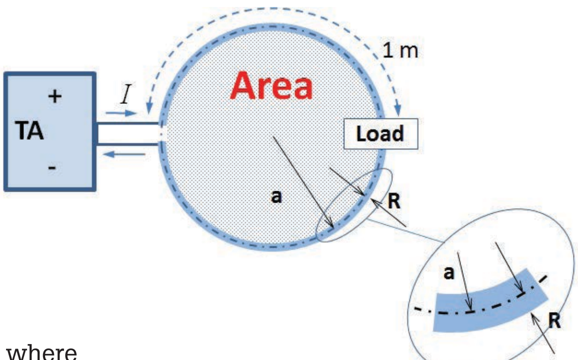
We neglect the difference between the dc and ac resistance and resistance proximity effects in the following analyses.

In high current circuits, the dominant source of inductance is created by either the load or the cabling. The load inductance must be provided by a device manufacturer, estimated, or possibly measured. In the case of shunts, Hall Effect current sensors, and Rogowski-type sensors, the inductive component is negligible compared to the cabling.

The interconnection length and conductor size are the main contributors to the inductance especially for resistive loads.

We can categorize the most common interconnection geometries as either circular path or a rectangular path, aka *structures*. We consider the circular structure first as it is the simplest to calculate. The circular path inductance is given by:

$$L = \mu_o a\left[\ln\left(\frac{8a}{R}\right) - 1.75\right]$$



where
R = conductor radius in meters
a = radius of conductor loop in meters

Let's consider testing a 0.001 Ω shunt driven by a TA at a current of 100 A at 50 Hz. We assume the connections are such that a nearly circular path is created with a total cable length of 2 m. Well known circumference and area formulas yield the following:
a: 0.32 m
R = 0.0028 m ($\mu_0 = 4\pi x10^{-7}$ H/m)
L = 2.04 µH

R_t is the sum of the load resistance, cable resistance and an estimate for connection contact resistances.
R_t= 0.001+0.0014+0.002 = 0.0044 Ω

Now use the above to determine the required compliance voltage required.
V_{comp}=I*Z=100*sqrt(0.0044^2+(2π*50* 2.04 x 10 $^{-6}$) ^{2}) = 0.44 V

If the calculation is repeated, at 500 Hz we see that X_L and R_t are nearly equal. Above 500 Hz, X_L is larger than R_t and dominates the value of Z in the above equation.

This calculation is repeated for multiple frequencies and currents and plotted. If we assume we have a maximum compliance voltage of 6 V up to a frequency of 10 kHz, we can plot this with the above data. We can see how current and frequency interact to stay below the maximum compliance voltage. Our selection of test setup is very important to whether we can use the TA to test the shunt at 100 A and 10 kHz. Only when keeping the frequency below approximately 4 kHz could we produce 100 A into our circuit.

Next let's look at the effect of current path loop size. The rectangular path is something that is closer to many practical configurations. The inductance of a rectangular current path is given by:

$$L = \frac{\mu_o}{\pi}\left[x\ln\left(\frac{2x}{R}\right) + y\ln\left(\frac{2y}{R}\right) + 2\sqrt{x^2+y^2} - x\sinh^{-1}\left(\frac{x}{y}\right) - y\sinh^{-1}\left(\frac{y}{x}\right) - 1.75(x+y)\right]$$

Using the same 25 mm^2 cable, let's investigate the effect of loop size as a function of current and frequency on compliance voltage. Keeping a 1 m width (W) for one side, we will change the height of the loop, H, starting at 1 m and reduce it to 11 mm where the cables are nearly touching. This would not be possible for manufacturer-provided cables unless they were modified. However, many users make their own cables for a specific measurement application. The following figures show the method.

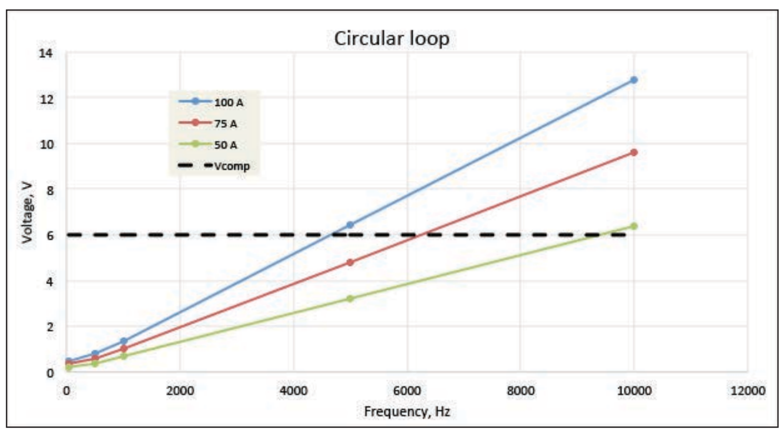


Figure 1. Determining the required compliance voltage. Selection of test setup is important.

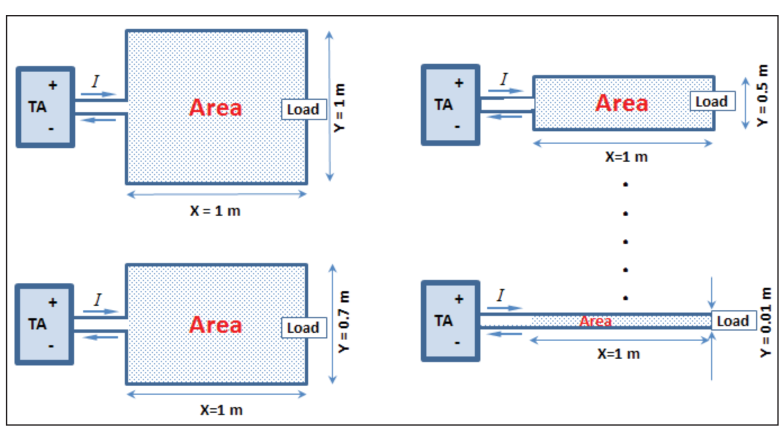


Figure 2. The process of changing loop width and keeping a constant 1 m height.

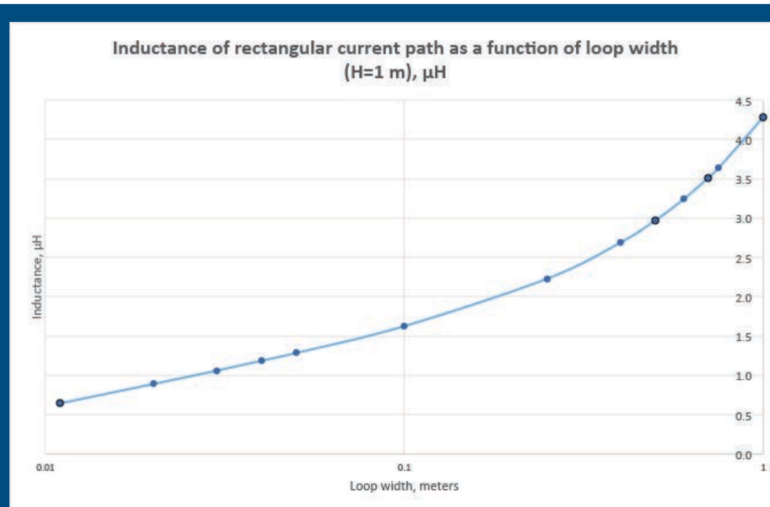


Figure 3. The inductances that result for various loop widths with a constant 1 meter height.

The above plot shows us the inductance as a function of width, but the real question is, *how does this impact our need for TA compliance voltage at various frequencies?* We take the inductance and determine the compliance voltage at a range of frequencies similar to the circular example. On top of the family of curves, we plot the TA maximum compliance voltage for a typical TA. In the previous example, we simply assumed a fixed compliance voltage. For some TA's, the maximum compliance voltage is slightly reduced as the maximum frequency is approached. For one amplifier, the compliance voltage remains constant at 4.5 V up to 1 kHz. Above 1 kHz to the maximum frequency of 10 kHz, the maximum compliance voltage decreases to 3 V.

We make numerous calculations and plot the results to get a better appreciation for the impact of the size of the current path. Figure 4 shows the required compliance vs. frequency for multiple loop widths.

We can see that the impact of loop size at low frequencies is minimal, and the TA can easily generate 100 A into most loop sizes up to about 1 kHz. Above 1 kHz the decreasing compliance voltage combined with the large increase in inductance with loop size greatly limits the generation of 100 A at higher frequencies.

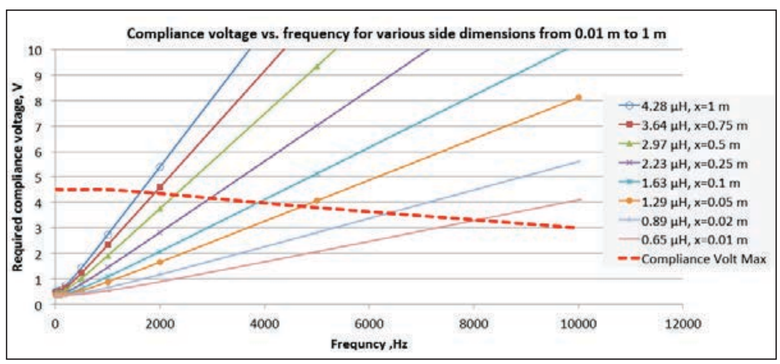


Figure 4. Required comliance vs. frequency for multiple loop widths.

What have we learned?

Generating direct currents at the maximum currents for TA's is easily done without much consideration to the total resistance for the cables, but the load resistance should still be considered. When we try to generate higher alternating currents, the size (total length and separation of the positive and negative leads) of the current path is very important, especially for the highest currents and frequencies. Generating the maximum current at the maximum frequencies requires minimizing the inductance – keeping the current leads as short as possible and as close together as a test configuration allows. Finally, another method commonly used to further reduce the inductance is to spiral twist the cables between the TA and the load.

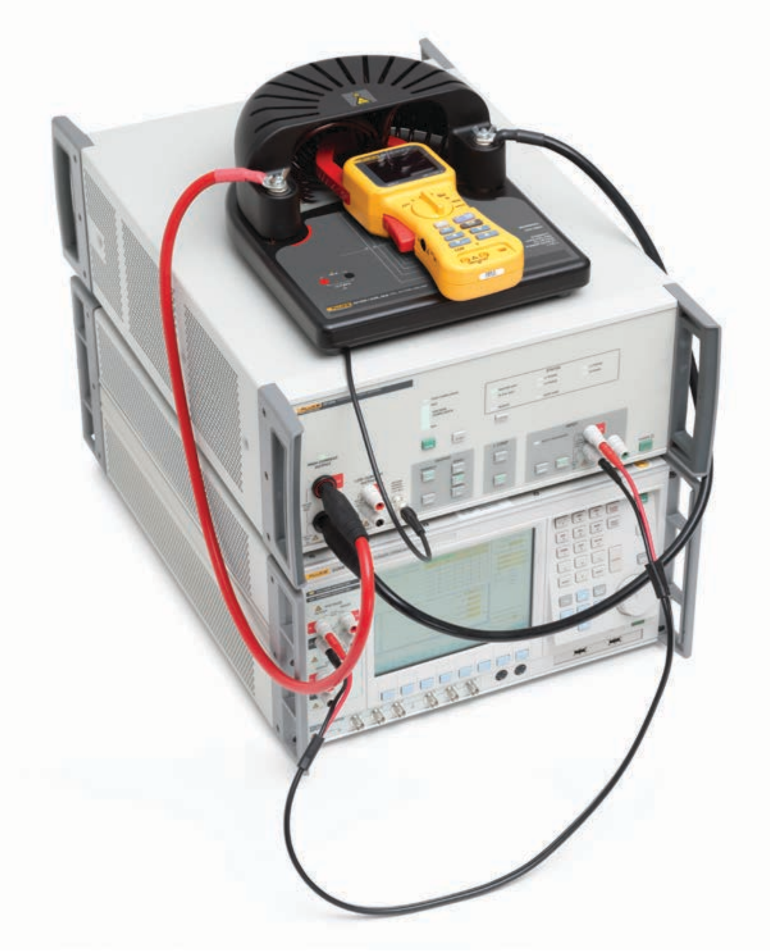
Now that you have taken the time to read this app note you can look at the beginning and ending product photos and see a significant difference in the setups. There will be no difference in required compliance voltage for either setup for direct currents. For higher frequency currents the set up in the last photo will be more likely to cause the TA compliance voltage limit to be reached. The set up in the first photo shows a reduced separation of cables resulting in lower inductive reactance and reduces compliance voltage requirements for the TA.

References

[1] Carl T. A. Johnk, Engineering Electromagnetic Fields and Waves, pg527, John Wiley and Sons, 1975.

[2] F.W. Grover, Inductance Calculations –Working Formulas and Tables, D. Van Nostrand and Co. , May 1947.

[3] Thompson, Marc T., Inductance Calculations Techniques – Part II: Approximations and Handbook Methods, Power Control and Intelligent Motion, Dec 1999.



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