AN001: Introduction to ABC's CT3613xxxxSA CT Products (Jan. 2021)

(1). Introduction to Current measurement:

The basic issues regarding the measurement of electric current:

(i). No matter in traditional or modern electronic/electrical engineering, for the safety, reliability and functionality of the whole system, voltage and current at critical points are always to be measured and/or controlled all the time.

(ii). Voltage measurement, excluding the extra high voltage, is not difficult. It can be achieved by a few basic electronic components in the circuitry, with very low cost, little loss and little troubles.

However, current measurement is usually not very convenient to carry out. It could easily cause interference with the circuit it measures, cause significant power loss plus safety concerns in some circumstances.

(iii). If the accuracy of current measurement with a wide range of magnitude is also demanded, it will significantly increase the complexity and difficulty of this task.

(2). How to carry out the proper current measurement in electronic/electrical systems:

(i). The most simple and popular way: To place a current sensing resistor (R_{SENSE} in Fig. 1) on the path of that current flow.

Acquire the voltage across R_{SENSE}, and get the value of the current flown by using the equation: $I_{LOAD} = V_{OUT} / (R_{SENSE} * Gain)$. (as Fig. 1)

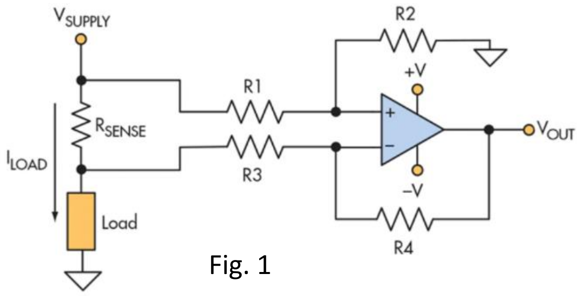

Fig. 1

(ii). The basic precautions of R_{SENSE} in Fig.1 are:

* The resistance needs to be as small as possible when compare to load impedance, so that it won't affect the original circuit's performance.

* To reduce the unwanted power loss, the resistance also needs to be as small as possible.

* The resistance needs to be reliable and stable enough, so that there is always a reliable reading of the voltage drop on it.

(iii). Other precautions in current measurement:

* Voltage rating: If the VSUPPLY is too high (below Fig. 2), one may not find appropriate amplifier circuit to suit this application.

* Safety Isolation: If the VSUPPLY is hazardous voltage to human (e.g. mains electricity, grid power), then the next-stage circuit needs to be isolated from the grid power if the next-stage is accessible by men.

* High frequency noise & surge spike on the current sensed need to be expelled from next-stage circuitry for a precise and stable measurement: certain type of isolation devices needs to be placed in between them.

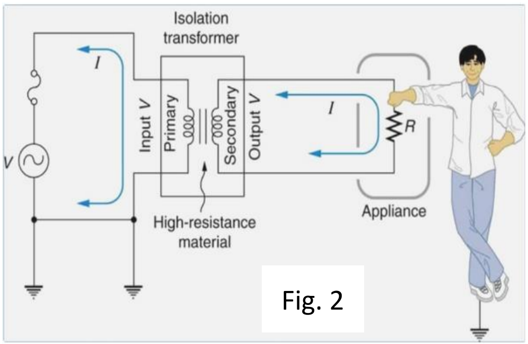

Fig. 2

(3). CT (abbreviated as CT) **is the best measure to all above issues:**

(i). Theory of operation of CT: All principles (e.g. Faraday's & Ampere's Law) related to a voltage transformer are to be obeyed in CT as well.

(ii). Allow the "large" current flow thru the primary side and acquire a scaled clone of that current on the secondary side. (scaling ratio = reciprocal of turn ratio)

Equivalent circuit of a typical transformer:

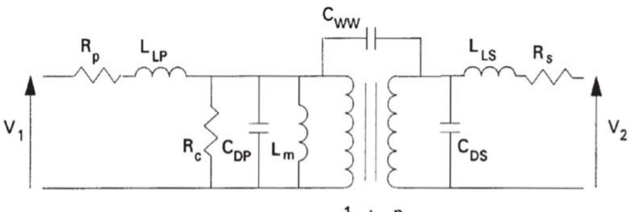

Fig. 3

(iii). Bring everything from secondary side to primary side: For a CT with a turn ratio of 1:1000. If we have a load resistor (Z2 in Fig. 4) of 100 Ω, then it appears only as 0.1mΩ on the primary side, which is very good for a current measurement device and the whole system operation.

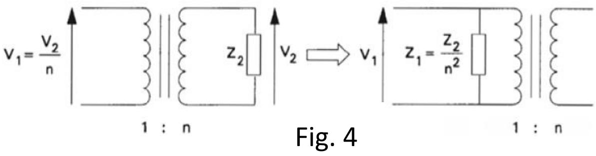

Fig. 4

(4). Basic requirements of a CT:

* Magnetic cores with high permeability & good saturation capability to achieve very high magnetizing inductance and allow large flux density (volt-second product).

* B-H curve of magnetic cores with good linearity.

* Low dissipation loss: Low copper loss (low DCR/ACR), low magnetic core loss.

* Acceptable accuracy under wide operating frequency range: to achieve this, it must have low leakage inductance, low parasitic capacitance and low dissipation loss.

* All characteristics with low temperature drift.

*Appropriate turn ratio to best suit the desired applications.

Basic problems of a CT:

* Simple CT can only work on AC current but not DC current.

* It is not practical, if not impossible, to demand high accuracy of measurement of AC current with a very wide operating frequency range. Accuracy is a big problem due to the reactive loss at high frequency.

* Waveform of primary current (current to be sensed) and accuracy of measurement may get a bit distortion at secondary side due to the nature of nonlinearity of magnetic cores, especially when it is at two extreme sides of flux density level (very large and very small ones). (Fig. 5)

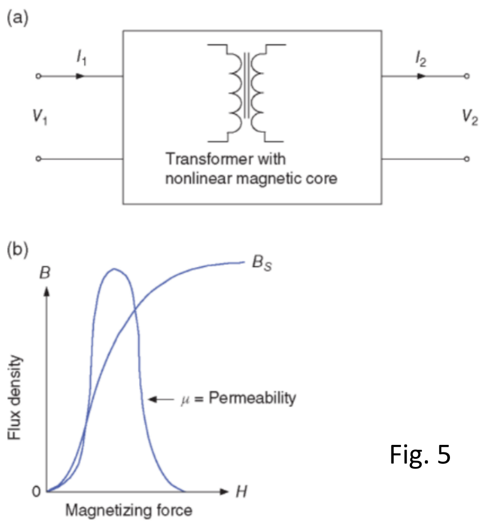

Fig. 5

* Higher cost of CTs compared to using electronic circuit for AC current measurement (in the case of non-isolated application).

(5). Applications: In regard to the magnitude of the current measured:

(i). For very small magnitude of current (roughly 1uA ~ 100mA), there are special techniques (circuit) to do a precise measurement, which is out of the scope of this application note.

(ii). For extra-large magnitude of current (200A ~ up to tens of kiloamperes), there are large current measurement device (such as the one shown in

Fig. 6) with hall effect sensors and/or fluxgate controllers built in. Those are also beyond our topic of this note.

Fig. 6

(iii). For medium magnitude of AC current measurement (0.1A ~ 200A) : the simplest way is to use a single CT with appropriate turn ratio and features such as our TL-8450-2500-N & CT3613xxxxSA series of products. Measurement devices for this range of current magnitude are what ABC-Atec's focus now.

(6). Applications: In regard to the frequency of the current measured:

(i). **DC current (frequency=0Hz)**: Regular transformers do not work on DC current. For large DC current, Hall effect sensors plus electronic circuit are employed. With circuit and Hall sensors built in, they are called current transducer instead of CT. Also, with the functions of Hall sensor, they usually can measure current from DC up to very high frequency AC (1MHz as shown in Fig. 6). These are very high-end products with extremely high cost in some special market.

(ii). **For low frequency (20Hz~1KHz)** measurement, a single CT with appropriate core material, usually iron silicon (silicon steel) or nickel permalloy (such as our newly developed TL-8450-2500-N) is used.

(iii). **For medium-low frequency (50Hz~50KHz)**, again, a single transformer with appropriate material of core such as Nickel-iron, amorphous or nanocrystalline core is used (such as our CT3613xxxxSA series product, Fig. 7, Fig. 8).

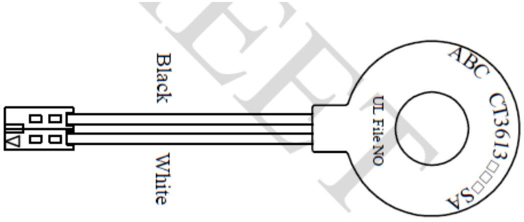

Fig. 7


Fig. 8

(iv). **For medium-high frequency (1KHz~200KHz)**, amorphous, nanocrystalline or some ferrite materials can be used to make the appropriate CTs for such frequency range. When using amorphous or nanocrystalline cores, the major difference between this type and the aforesaid medium-low frequency type is the design in winding & construction. With better and more complex winding method & construction, the same core material can be made into CT running higher frequency (upgrade from 50KHz to 200KHz).

(v). **For very high frequency (50KHz~5MHz)** applications, ferrite Mn-Zn core is the material of the choice. With appropriate cores and bobbins, we can make versatile CTs suitable for all kinds of switching converters. However, it is uncommon to have very large AC current (>50A) for very high frequency (>200KHz). Besides, many switching converters do not have balanced AC waveform on their main current paths, in which our CT can't be used. (volt-second products have to be balanced for the positive and negative cycles in an AC current waveform).

* Summary of applications regarding to the frequency of AC current (**Table 1**)

Frequency Band	Frequency Range	Main applications	Auxiliary applications	Used by electronic/electric equipment
Low	20Hz ~ 1KHz	(i). Mains electricity (Worldwide grid power) (50Hz~60Hz) (ii). Current from VFD to motors (10Hz~120Hz) (iii). Current from (PV) inverter to AC output (20Hz ~ 1KHz)	Electricity used in aircrafts and ships (360Hz~800Hz)	(i). All domestic appliance used in **land, air or sea**. (ii). All sorts of VFD output current. (iii). Large capacity (PV) inverter output.
Medium-Low	50Hz ~ 50KHz	(i). Hi-power switching converter using **IGBT**. (5K~20KHz) (ii). All applications that use grid power (50~60Hz) (iii). Analog audio power amplifier (20Hz~20KHz)	Legacy switching power converter using **MOSFET** (30K~50KHz)	(i). Hi-power (>3KW) switching power converter. (ii). All equipment use grid power (50~60Hz) (iii). **Class A, AB & C** power amplifier
Medium-High	1KHz ~200KHz	Modern switching power converter using **MOSFET** (65K~250KHz)	Audio power amplifier using **MOSFET** (50K~200KHz)	(i). All modern switching power converter. (ii) **Class D** Audio power amplifier.
Very High	50KHz ~5MHz	Modern switching power converter using **Sic or GaN** (200K~2MHz)	**RF power amplifier** (Analog or switching type) (100K~120MHz)	**(i). Modern switching DC/DC converter.** (ii). **Class A~C & class E, F** RF amplifier.

* One major interest in very low frequency applications is the output current measurement from VFD (Variable Frequency Drive) to AC motors. The operating frequency for such AC current ranges from **10Hz ~ 120Hz** normally. The magnitude of such current ranges from several amperes to several hundred amperes. Picture below (Fig. 9) shows the block diagram of an operating VFD with indication of where the current of interest (to be measured).

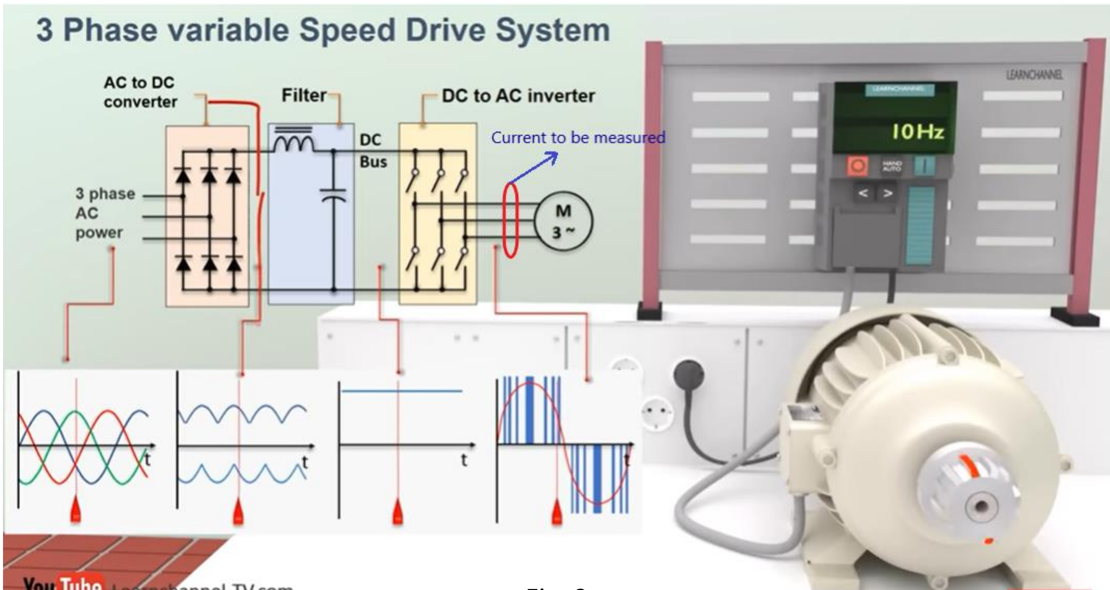

Fig. 9

(7). Introduction of ABC-Atec's lately developed CTs:

(i). TL8450-2500-N: Epoxy encapsulated with nickel permalloy magnetic core, suitable for low frequency (**20Hz~1KHz**) AC current measurement, up to **75A**. Suitable for all sorts of appliance or equipment that supplied by grid power. This is also the best one for VFD (or PV inverter) output current measurement among all ABC-Atec's CT products.

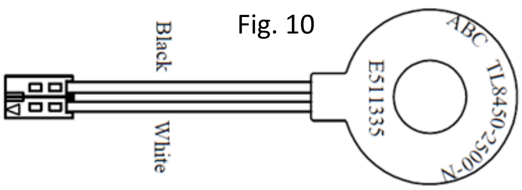

Fig. 10


Fig. 11

I_r	Vmax	Te(typ.)	DCR(Ω)	Frequency
75	12	2512 Ts	160 max.	20Hz-1kHz

(ii) TL-8450-2500-N is complied with all necessary safety regulations(i.e IEEE-C57.13 &CSA-C61869-1) and has been certified by UL **with a designated file no. "E51335".** This product can be used to sense and measure hazardous AC current of any sorts of mains electricity worldwide with no safety concerns at all.

(iii). CR3613xxxxSA is the latest CT product series from ABC-Atec. With nanocrystalline magnetic cores, this series focuses at low to medium frequency (**50Hz ~ 100KHz**). We currently have 3 individual products with different turn ratio in this series. All 3 products can measure AC current up to 100A. Please refer to Fig. 7 and Fig. 8 for their outline appearance. Following table (Table 2) is the major electrical characteristics for these products:

(iv). Explanations of all the figures in Table 2 :

Part Number	I_r (A)	Vmax(V) RMS	Te(typ.)	DCR(Ω)	Frequency
CT36131000SA-□□□	100	15	1005 Ts	26.5 max.	50Hz-50kHz
CT36132000SA-□□□	100	26	2003 Ts	76.0 max.	
CT36132500SA-□□□	100	28	2504 Ts	150.0 max.	

1).I_r = Maximum AC input current to be linearly sensed

2).Vmax. = Maximum VAC saturation voltage,tested at 100Hz

3).Te = Effective turn ration including losses , Load Resister =100 Ω

Table 2

(iv-1). Vmax (RMS) is the maximum secondary voltage (in rms value for sinusoidal waveform), see below Fig. 12 for illustration:

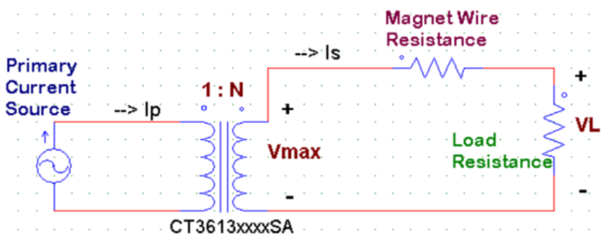

Fig. 12

In the circuit above, "Magnet wire resistance" represent purely the secondary wire resistance, which is about the DCR at low frequency (<10KHz), and gradually increases as the frequency increases, but for the frequency in concern now (<100KHz), the value of DCR is still a good approximation of the real magnet wire resistance even at 100KHz since the wires we use in secondary winding are small enough that the skin effect and proximity effect do not have impact at this frequency range (up to 100KHz). Thus, a simple calculation is as follows:

$$\mathrm{Vmax} = \left(\frac{\mathrm{Ip}}{\mathrm{Te}}\right) * \mathrm{DCR} + \mathrm{VL}$$

Where "Ip" is the primary AC current to be sensed, "Te" is the effective turn ratio of this transformer. VL is the voltage drop on the load resistor.

The user must take precautions that load resistance must be carefully chosen so that the following condition is met at all time.

$$\mathrm{VL} < \mathrm{Vmax} - \left(\frac{\mathrm{Ip}}{\mathrm{Te}}\right) * \mathrm{DCR}$$

Vmax represents the saturation voltage of our CT and is derived from Faraday's Law as follows:

$$\mathrm{B} = \left[\frac{1}{(\mathrm{N} * \mathrm{Ae})}\right] * \int_0^{T/2} V(t) * dt$$

Where B is the flux density in the magnetic core,
N is the number of turn in secondary winding,
Ae is the effective cross section area of the core.
V(t) is the voltage function vs time.
T is the period of V(t). (reciprocal of frequency).
Figure of this property (Vmax) in the datasheet is acquired based on a sinusoidal V(t). In actual applications, if V(t) is not sinusoidal, the user should do the integration calculation (above equation) by oneself instead of using the figure specified in our datasheet as the saturation limit.
Furthermore, saturation limit in the core of our CT (Fig. 13) is not a precise number. It's only a number telling the user that saturation phenomenon is appearing beyond this limit, and it would have a significantly negative impact on the accuracy of the measurement.

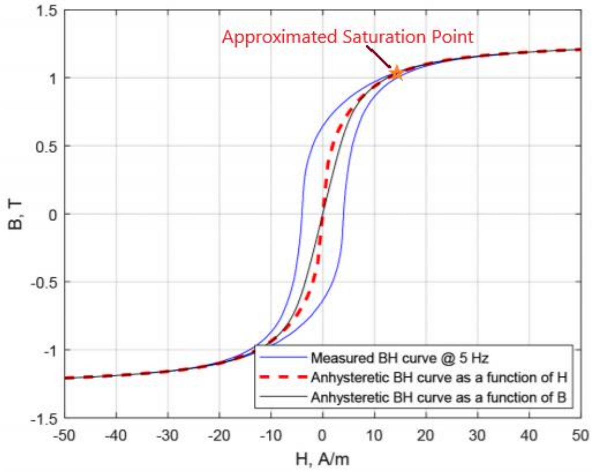

Fig. 13

To have good accuracy of measurement, the user needs to use the linear region on the BH curve as much as possible. Thus, the maximum voltage drop (VL) on the load resistor should be kept away from the saturation limit, i.e. [Vmax-(Ip/Te)*DCR] in this case. To have even better accuracy, **we recommend that the user get 15% margin away from the above saturation limit**.

(iv-2). "Ir" in Table 2 means the rated primary current of this device, that is 100A (RMS value) for this series of products. In another word, it is the maximum primary current allowed to flow under the worst (hottest) ambient temperature. As to the worst ambient temperature, our datasheet does not define it. Instead, we specify the maximum allowable operating temperature (including self temperature rise) as 105℃ in all situations.
If the following two rules are strictly followed, then Ir can be much higher than the specified value:
* The maximum voltage drop (VL, under maximum primary current) is still somewhat away from the saturation limit (this is easily done, just use a very small load resistance, yet there is trade-off of it).
* The temperature of the CT (in operation) is under well controlled. For example, keep the surface temperature of the CT under 45℃ all the time by forced convection.
For example, use small load resistance of 100Ω to work with our CT36132000SA and keep its surface temperature under 60℃ all the time, then it is OK to measure primary current up to 2*Ir (200A).

Extreme cautions need to be taken when operating the CT beyond its rated current:
* The temperature must be tightly controlled; thus, forced and strong convection is usually needed. Once the temperature is out of control and goes beyond a certain level, thermal runaway can happen quickly or eventually. Accuracy will be ruined and the whole CT can also be destroyed under such thermal runaway.
* Wattage rating of the load resistor must be chosen carefully. Wattage rating of the load

resistor is recommended to be 4 times as large as the real power consumption.

To put it in a nutshell, as long as the temperature is strictly controlled under certain level and the maximum voltage drop (VL) is still away from the saturation point, then primary current higher than spec value can still be measured up to two folds of Ir.

However, **the maximum continuous primary current allowed is set as 4*Ir (400A in this case)**. Beyond this level of primary current, the internal enameled wires (inside the CT body) can be burned out in a short time, no matter how strong the forced convection is used.

II . Description：

a . Nanocrystalline T core construction
b . Enamelled copper wire：class H
c . Product weight：55.0 g（ref.）
d . Products comply with RoHS' requirements
e . Halogen free
f . Max Primary continuous current :400A
g . Insulation Voltage :3500VAC,60sec.

(iv-3). The effective turn ratio (Te): Instead of the actual turn ratio, using effective turn ratio (Te) in calculation of primary current can improve the overall measurement accuracy significantly. Current measurement by plain CT is inevitably influenced by its leakage inductance, parasitic capacitance and dissipation loss. At two extreme sides; the low frequency range (<100Hz) and the high frequency range (>50KHz), the influence is outstanding and cause non-negligible errors. However, as long as the linearity in characteristics of CT remains good, different values of Te can be assigned for different frequency, with which the best overall measurement accuracy is achieved.

To give an illustrative example, our CT36131000SA has a Te of 1005 (evaluated at 60Hz), this figure is good for primary current calculation from 50Hz to 10KHz. With such Te, the measurement accuracy in that frequency range is usually around = +/-0.5% (typical but not guaranteed value, excluding very small primary current, Ip < 2A). The measurement errors increase to +/-1%~1.5% when operating frequency increases to 50KHz and above. However, with a Te of 999, the overall accuracy at 50KHz ~100KHz is improved back to +/-0.5% again.

Te is found by lab experiments. Large number of experiments need to be carried out and many data need to be collected before we can make an official list of Te vs frequency for CT3613 series.

(7). Conclusion of characteristics of ABC's CT3613xxxxSA :

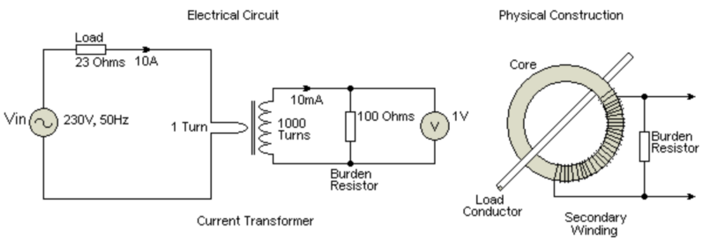

Fig. 14

Besides completely understanding all the electrical characteristics, perhaps the most important thing when using such a CT is how to choose the appropriate load resistor, some people call it "Burden resistor" (Fig. 14). How to manage the saturation issue of a CT? how to reduce power consumption and hence boost the efficiency? how to increase the linearity of the measurement system? how to achieve the best measurement accuracy? All the answers to above questions are around the load (burden) resistor. We can't emphasize enough how important it is.

Next application note (Choosing the load resistor for a CT) from ABC-Atec would give you a full picture and explanations of them.

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