Explore new paths with the CT Analyzer – Extended testing benefits for your applications

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1. Introduction

This paper describes on the one hand side the principal test procedure of the CT Analyzer and points out the advantages of this test method in regards to a conventional high current injection measurement method. On the other hand side it elucidates special current transformer testing applications and reveals attempts at solutions. Furthermore, the CT Analyzer PC Tools are introduced and their advantages and possibilities for the individual user are presented.

2. Principal Test Procedure of the CT Analyzer

The CT Analyzer measures the losses of a current transformer according to the equivalent circuit diagram of the current transformer, in terms of the copper losses and the iron losses. The copper losses are described as the winding resistance R_{CT} of the current transformer. The iron losses are described as the eddy losses as eddy resistance R_{eddy} and the hysteresis losses as hysteresis resistance R_H of the core.
With this knowledge about the total losses of the core, the CT Analyzer is able to calculate the current ratio error and the phase displacement for any primary current and for any secondary burden. Therefore all operating points which are described in the standards for current transformers can be ascertained.
Additionally, important parameters such as the residual remanence, the saturated inductance, the unsaturated inductance, the symmetrical short-current factor, resp. the over-current factor and also the transient dimensioning factor according to the IEC 60044-6 standard for transient fault current calculations.
Figure 1 shows the equivalent circuit diagram of a current transformer at rated frequency and figure 2 shows the correlating vector diagram.

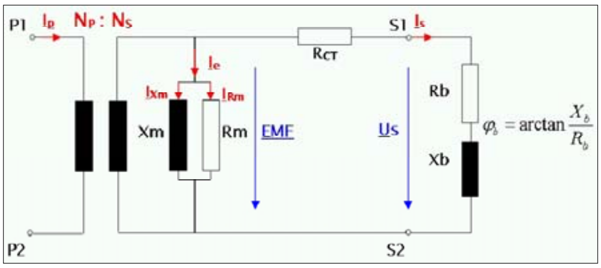

Figure 1: Equivalent circuit diagram of a real current transformer

I_e	excitation current
I_S	secondary current
I_P	primary current
X_m	main inductivity of the core
R_m	magnetic losses of the core
N_P,N_S	amount of turns of the ideal core
R_{CT}	ohmic resistance of secondary turns
EMF	Electro-Motive Force – secondary core voltage
U_S	secondary terminal voltage
R_B	ohmic part of complex burden
X_B	inductive part of complex burden
φ_B	phase angle of burden

Figure 2 shows the vector diagram of current and voltages for a linear main inductivity.

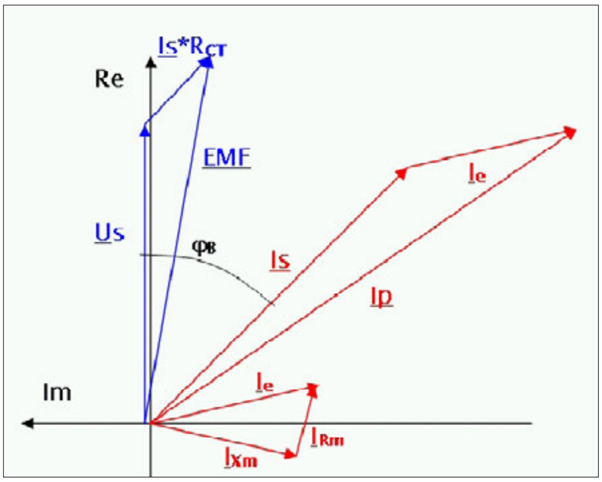

Figure 2: Vector diagram for a linear main inductivity

The CT Analyzer performs following measurements in a row:

- Measurement of residual remanence (obligatory)
- Measurement of secondary winding resistance
- Measurement of excitation curve
- Measurement of eddy losses and hysteresis losses
- Measurement of turns ratio N (core ratio)
- Calculation of current ratio error and phase displacement at desired burden and primary current values

All measurements mentioned above are done automatically and without the need of rewiring the device under test.

2.1 Measurement of Residual Magnetism

The residual magnetism measurement is done before the current transformer test, as for instance a winding resistance test or an excitation test would influence the residual magnetism in the core.
The residual magnetism expressed in percentage (M_r) is related to the magnetic flux at the knee-point (Ψ_S).

$$M_r = \frac{\Psi_{res}}{\Psi_s} * 100\%$$

Basically, residual magnetism effects in the core occur after the current transformer was confronted with very high transient fault currents (DC offset from transient behavior of the network) or after a DC winding resistance measurement.
During normal operation of the current transformer the residual magnetism in the core won't be decreased. In order to decrease the residual magnetism demagnetization process, pretty much as the CT Analyzer is using for the demagnetization process (Figure 3), has to be conducted.
Therefore, the core is driven into positive and negative saturation, but with decreasing the total flux in order to get the working point of the current transformer back to the origin, which means no residual magnetism in the core.

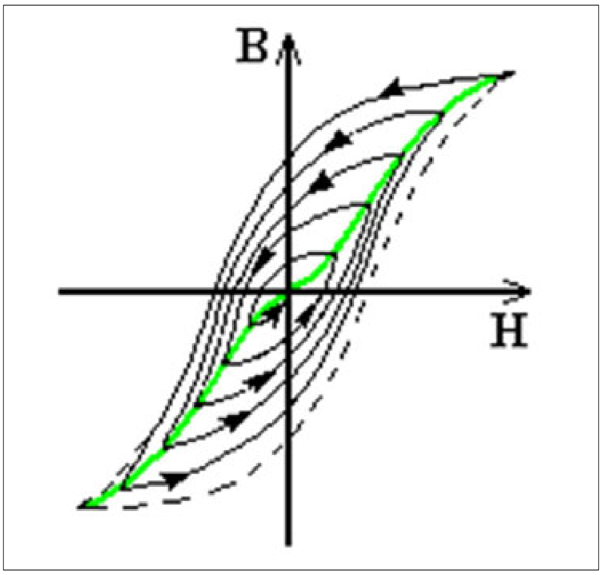

Figure 3: Demagnetization process

In case the current transformer core is affected by residual magnetism, the rated accuracy limiting factor cannot be guaranteed. Due to the effect of residual magnetism, the accuracy limiting factor will decrease.
This is the reason why, e.g. differential protection relay or distance protection relays cannot operate properly as the core starts to saturate when a fault in the power grid occurs.
A distance protection relay, for instance, measures a smaller current than the total fault current due to saturation effects and thus calculates the fault impedance wrongly. So the relay won't trip within the defined tripping time.

2.2 Measurement of Secondary Winding Resistance

For the current transformer measurement with the CT Analyzer a secondary winding resistance measurement is needful, as the winding resistance is necessary for the calculation of most of the current transformer parameters.
The measurement is done with a DC current signal. As soon as the core saturates, the current and drop off voltage measurement is conducted. Upon completion of the secondary winding resistance measurement the core will be completely demagnetized by the CT Analyzer.

2.3 Measurement of Excitation Curve

For the measurement of the excitation losses a voltage signal is applied at the secondary side of the current transformer, whose voltage-time area (integral) is equal to the induced magnetic flux in the core.
The voltage – and current amplitude and as well as the phase angle between the voltage and the current are measured at different resulting magnetic fluxes in the core. Hence, the excitation curve can be drawn.
In case the core won't saturate at a voltage level of 120V, the CT Analyzer reduces the measurement frequency in order to increase the resulting magnetic flux in the core. The measured voltage amplitude will be transferred back to rated frequency under consideration of the eddy losses. Using this method, knee-point voltages up to 30kV can be measured, although the maximum output voltage is limited to 120V. Upon completion of this measurement, the core will be completely demagnetized again.

2.4 Measurement of Eddy Losses and Hysteresis Losses

Due to the physical property of the eddy losses which are proportional to the square of the frequency and the hysteresis losses which are proportional to the frequency, the CT Analyzer can distinguish in between both losses. Therefore, the CT Analyzer measures the total core losses at two different frequencies with the same resulting flux in the core.

The total iron losses are calculated as follows;

$$P_{IRON} = P_{HYSTERESIS} + P_{EDDY}$$

The hysteresis losses are proportional to the frequency.

$$P_{HYSTERESIS} = a * f$$

The eddy losses are proportional to the square of the frequency.

$$P_{EDDY} = b * f^2$$

The measurement of the total iron losses at two different frequencies at the same resulting magnetic flux delivers both constants, *a* and *b*.

$$P_{f1} = a * f_1 + b * f_1^2$$
$$P_{f2} = a * f_2 + b * f_2^2$$

$$=> a = \frac{P_{f1} * f_2^2 - P_{f2} * f_1^2}{f_1 * f_2 * (f_2 - f_1)}$$

$$=> b = \frac{P_{f2} * f_1 - P_{f1} * f_2}{f_1 * f_2 * (f_2 - f_1)}$$

2.5 Measurement of Turns Ratio

For the measurement of the turns ratio of the ideal core a sinusoidal voltage is applied at secondary side of the current transformer which is approximately at the operating point of the current transformer. The voltage amplitude at the secondary terminals (U_{SEC}) and the resulting exciting current (Ie) are measured. In order to calculate the core voltage (EMF) the drop off voltage at the secondary winding resistance (U_{Rct}) needs to be considered.

$$EMF = U_{SEC} - U_{Rct} = U_{SEC} - Ie * R_{CT}$$

In parallel, the induced voltage at the primary side (U_{PRIM}) of the current transformer is measured as well. Out of these measured values, the turns ratio *N* can be calculated as follows;

$$N_{CORE} = \frac{EMF}{U_{PRIM}}$$

2.6 Calculation of Current Ratio Error and Phase Displacement at desired Burden and Primary Current Values

In order to force a secondary current (I_B) throw a desired secondary burden, a specific core voltage ($V_{Core} = EMF = I_B * \sqrt{(R_{CT} + R_B)^2 + X_B^2}$) is needed.
As the excitation losses and as well as the phase angle between excitation voltage and exciting current are known for every desired core voltage, the current ratio error and phase displacement can be calculated for every desired primary current and secondary burden. Figure 4 indicates how the current ratio error and phase displacement can be evaluated out of the excitation data. In this way all operating points defined in the IEC 60044-1 standard and the IEEE C57.13 standard can be ascertained.

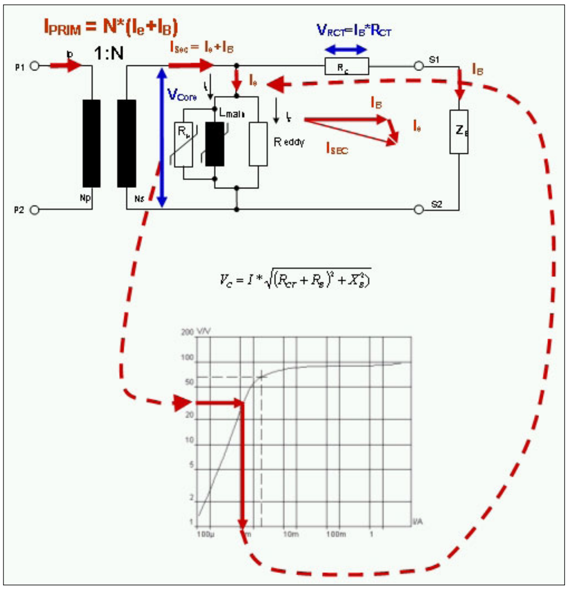

Figure 4: Calculation of current ratio error and phase displacement out of the excitation data

3. Application Examples

Basically, a four-wire measurement technique should be used for the secondary connection to the current transformer as shown in figure 5.
Otherwise, the possibly existing contact resistance of the clamp could affect the measurement results, i.e. the CT Analyzer possibly delivers incorrect measurement results.

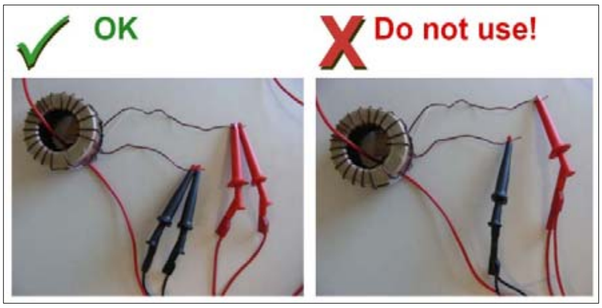

Figure 5: Proper four-wire connection technique vs. two-wire connection technique

When using the two-wire connection technique as shown in the figure above, considerable measurement errors for the turns ratio error, current ratio error and other parameters can occur, if the connection of the clamp to the current transformer is not ideal and has a considerably high contact resistance. Since this contact resistance will change with each connection, resp. disconnection of the clamp at the current transformer, it is furthermore not possible to reproduce such measurements.
The total contact resistance caused by the two-wire connection technique, as shown in figure 7, can be up to several 100mΩ and thus can cause an additional burden. Due to this, the influence of the contact resistance is higher the smaller the winding resistance

of the current transformer under test. When testing a 5A current transformer, such a contact resistance can lead to completely incorrect measurement results while it is practically negligible when measuring a current transformer with a relatively high winding resistance.

The following connection diagrams make this clear.

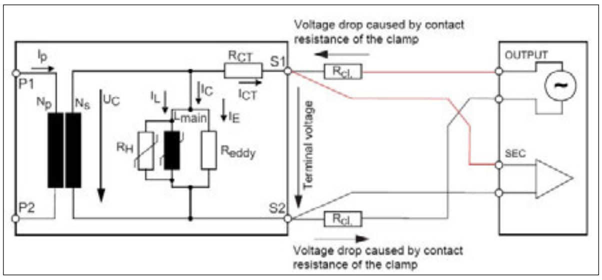

Figure 6: Four-wire connection technique

$$R_{TOTAL} = R_{CT}$$

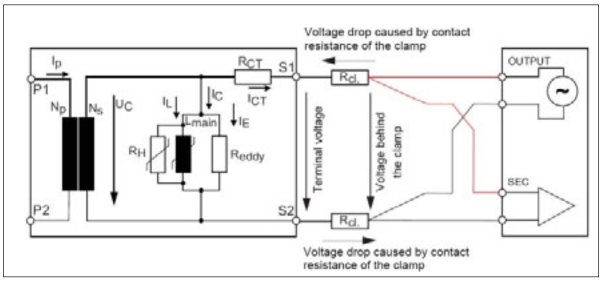

Figure 7: Two-wire connection technique

$$R_{TOTAL} = R_{CT} + R_{CONTACT}$$

3.1 Measurement at Bushing-Type Current Transformers

In past the measurement of current transformers in power transformers was not possible as the main impedance of the power transformer is connected in series to the primary side of the current transformer and thus a high power current source is needed for testing current transformers in such a constellation, especially when testing the accuracy limiting factor, respectively the instrument security factor.
This is why the secondary voltage injection method as it is used by the CT Analyzer is the only suitable method to perform such measurements.

3.2 Measurement at Y-Winding Transformers

For the measurement of current transformers in Y-connected transformer windings it has to be guaranteed that the main impedance of the transformer does not influence the test results.
The CT Analyzer has an input impedance of approx. 500kΩ. However, this measurement impedance can be low enough to influence the test results. In order to prevent any influence of the CT Analyzer's input impedance, the transformer winding at the same leg should be short-circuited. Short-circuiting the windings on all legs of the transformer is even better.
Furthermore, all bushing terminals which are not connected to the CT Analyzer should be connected to protective earth in order to prevent the influence of external disturbances.

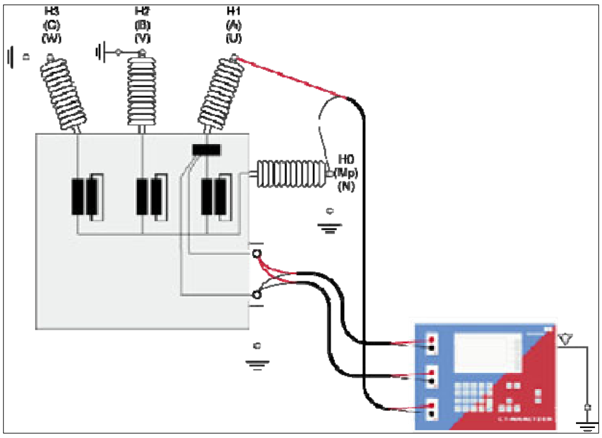
Figure 8: Bushing-type current transformer in a Y-winding transformer

3.3 Measurement at Delta-Winding Transformers

As the delta connected windings act as a voltage divider, it is not possible to read the current transformer winding ratio directly. In order to obtain the correct current transformer ratio, the ratio value determined by the CT Analyzer has to be corrected.
For this purpose, the CT Analyzer allows to set a so-called Delta Compensation on the CT-Object card. The appropriate delta compensation factor should be selected, depending on the bushing terminals which are used for the induced primary signal measurement.
In case there is the possibility to short-circuit the transformer winding at the same leg as the primary measurement is done, the measurement should be conducted with a short-circuited winding. In this case no delta compensation is needed as the induced voltage at the transformer secondary winding will become zero and thus also the induced voltage at the primary side of the transformer will become zero.
For the measurement setup shown in Figure 9, the delta compensation factor on the CT-Object card has to be set to "Ratio 2/3".

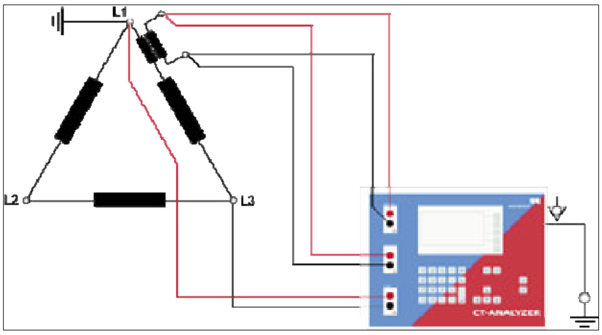

Figure 9: Delta winding transformer – delta compensation 2/3

For the measurement setup shown in Figure 10, no delta compensation is necessary thus the delta compensation can stay at "Ratio 1" which is the default value.

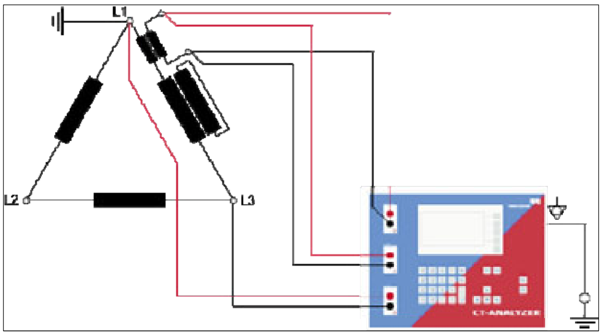

Figure 10: Delta winding transformer – delta compensation 1

3.4 Use Case: Measurement at an Autotransformer

In order to measure the current transformers shown in figure 11 with the highest possible accuracy, following points should be considered for the test setup;

- The tap changer position should be at tap position 14. Otherwise, the regulation winding built-up an inductive voltage divider with main winding and thus it will influence the accuracy of the test results. Generally it can be said that the tap position should be at the minimum or maximum tap position so that the regulation winding is completely bridged.
- The winding on the same leg should be short-circuited so that there will be no influence of the induced voltage at the main winding
- All bushing terminals which are not connected to the CT Analyzer should be connected to protective earth in order to prevent the influence of external disturbances
- In case there is the possibility to short-circuit all unused current transformer cores, it can be ensured that they won't have any additional influence in the test results.
- The primary connection of the CT Analyzer which collects more superimposed disturbances from the test environment should be connected to protective earth as well. It does not matter whether the red or the black terminal of the input PRIM is connected to protective earth.

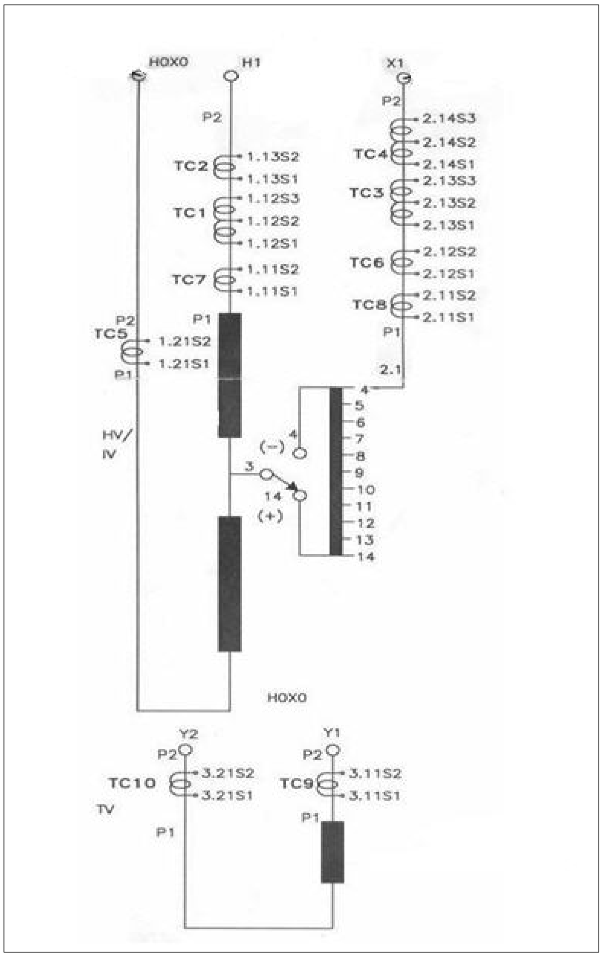

Figure 11: Nameplate of the autotransformer

TC	TERMINALES	TRANSFORMADORES DE CORRIENTE		
		RELACIÓN	CLASE	APLICACIÓN
1	(1.12S1–1.12S2)/(1.12S1–.12S3)	500/1000/1 AMP	5 VA, CL 0.2 FS 10	MEDIDA
2	(1.13S1/1.13S2)	1000/1 AMP	10 VA, CL 5P20	PROTECCION
3	(2.13S1–2.13S2)/(2.13S1–2.13S3)	1250/2500/1 AMP	5 VA, CL 0.2 FS 10	MEDIDA
4	(2.14S1–2.14S2)/(2.14S1–2.14S3)	1250/2500/1 AMP	20 VA, CL 5P20	PROTECCION
5	(1.21S1–1.21S2)	600/1 AMP	10 VA, CL 5P20	PROTECCION
6	(1.12S1–2.12S2)	1574.6/1 AMP	10 VA, CL 5	LDC
7	(1.11S1–1,11S2)	692.8/5 AMP	10 VA, CL 5	MONITOR DE TEMPERAT
8	(2.11S1–2.11S2)	1574.6/5 AMP	10 VA, CL 5	MONITOR DE TEMPERAT
9,10	(3.11S1–3.11S2) & (3.21S1–3.21S2)	2500/1 AMP	10 VA, CL 5P20	PROTECTION

Figure 12: Current transformer specifications

3.5 Measurement on Multi-Ratio Current Transformers

When testing a multi-ratio current transformer, all windings on the same core that are not in use must be open.

If one winding is not open, it is not possible to test the current transformer using the CT Analyzer, as parts of the core are short-circuited.

The maximum output voltage of the CT Analyzer is 120V. Therefore, only the corresponding transformed voltage can occur at other taps.

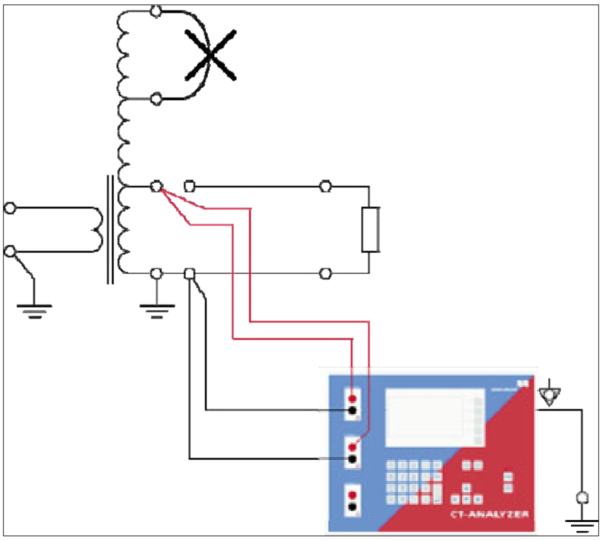

Figure 13: Testing tapped current transformers

With the newly available accessory, called CT SB2 (Switch Box) for the CT Analyzer, all possible tap ratios of a multi-ratio current transformer can be measured fully automatically without the need of rewiring the test setup.

The CT SB2 is intended for the following applications;

- Multi-ratio current transformer testing
  The CT SB2 enables automatic testing of multi-ratio current transformers with up to six tap connections
- Burden and primary winding resistance measurement
  Using the CT SB2 it is also possible to include burden and primary winding resistance measurement to the automatic current transformer test procedure without rewiring.
- Single-ratio current transformer testing
  Due to the possibility to include burden and primary winding resistance measurement, the CT SB2 is not only useful for testing multi-ratio current transformers but also for testing single-ratio current transformers

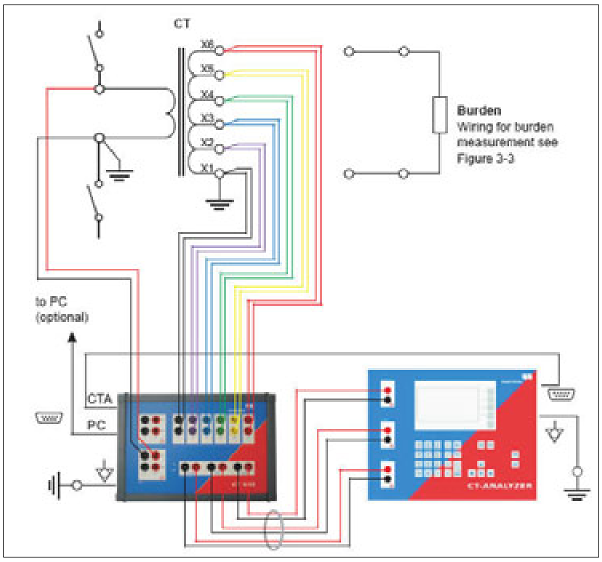

Figure 14: Basic measurement setup for multi-ratio CT testing (6 tap CT, no burden measurement, no primary winding resistance measurement)

4. CTA PC Toolset – Possible Applications

The CTA PC Toolsets provide, besides controlling the CT Analyzer remotely, a lot of other useful possibilities which are presented in this paper.

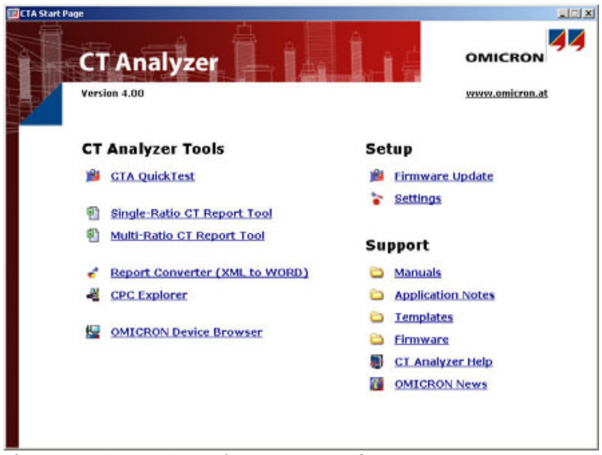

Figure 15: CTA PC Toolset User Interface

4.1 CTA Quick Test

The CTA Quick Test is an optional feature for the CT Analyzer. The CTA Quick Test software is part of the CTA PC Toolset and therefore always available after installation of the CTA PC Toolset software. For operating the CTA Quick Test mode on the CT Analyzer as stand-alone unit, an additional license is needed.
Using CTA Quick Test it is possible to use the connected CT Analyzer as a remote-controlled versatile multi-meter with included power source.

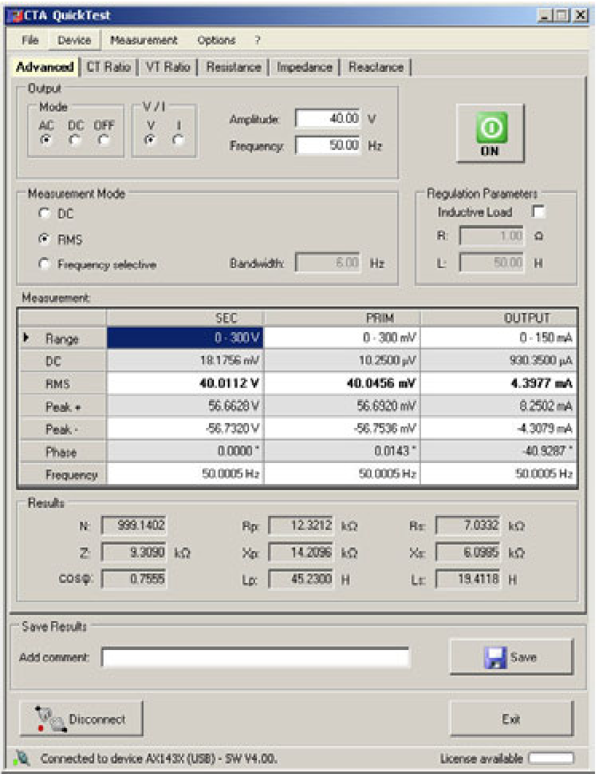

Figure 16: CTA Quick Test PC User Interface

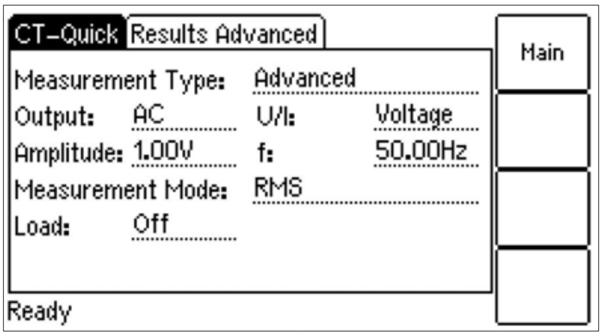

Figure 17: CTA Quick Test – CT Analyzer User Interface

Possible fields of application for the CTA Quick Test are:

- Quick and easy resistance measurement
- Quick voltage ratio checks for voltage transformers as shown in Figure 18
- Measurement of burden values, e.g. to determine the new burden value after changes of the relay equipment. This allows the recalculation of the current transformer test results, obtained with the CT Analyzer, for the new burden value and thus makes it unnecessary to run an additional current transformer test in order to determine the behavior of the current transformer with the new applied burden
- Measurement of impedance and reactance, for instance of winding impedances
- Measurement of low-current current transformers with rated primary currents smaller than 5A, resp. with knee-point voltages smaller than 1V

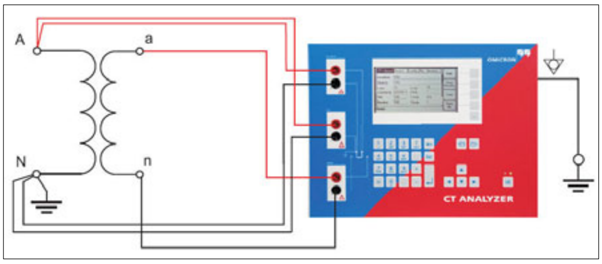

Figure 18: Voltage transformer ratio test with CTA Quick Test

4.2 CTA Remote Excel File Loader

The CTA Remote Excel File Loader is an Excel based tool for remote-controlling the CT Analyzer. The test results obtained with the CT Analyzer are transferred automatically into the Excel program for further assessment and reporting possibilities. When using the ready-made Excel templates, a test report is generated automatically as illustrated in figure 19.

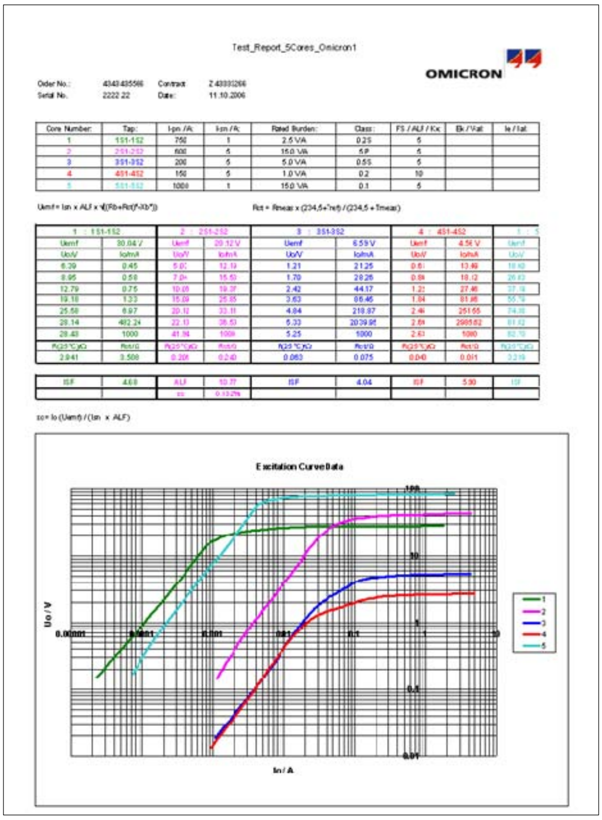

Figure 19: Example test report generated with CTA Remote Excel File Loader

5. CTA Support for NetSim

The network simulation software NetSim, which is a part of the Test Universe software package, tests relays under close to realistic conditions. NetSim uses a numerical network model to simulate processes in an electric power network composed of voltage sources, lines, circuit breakers, fault instances and switching events.

For realistic current transformer simulations, NetSim provides the possibility to retrieve the current transformer data from a CT Analyzer measurement result file (Figure 20). So, transient fault current simulations can be performed under consideration of current transformer saturation effects.

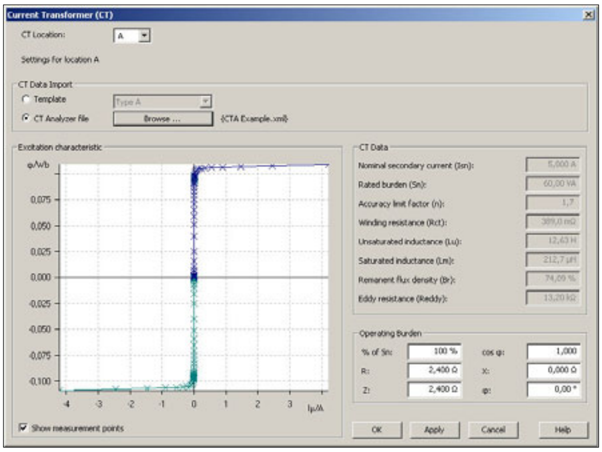

Figure 20: CT Analyzer data import in NetSim

The simulated currents represent the expected secondary currents in case of a transient fault in the network. The transient line-to-earth fault case elucidated in figure 21 shows the saturation of a current transformer with extremely low accuracy limiting factor.
An application for this purpose would be for instance testing of saturation recognition in transformer differential protection relays.

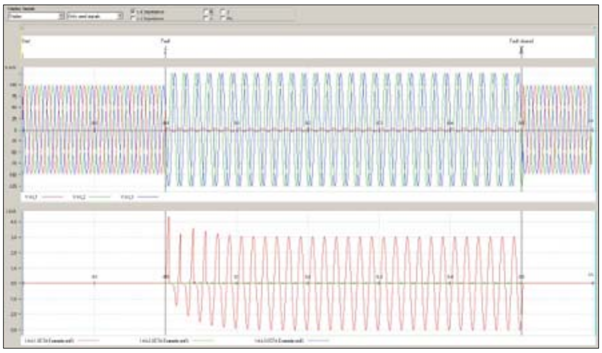

Figure 21: Transient fault case simulated in NetSim

Figure 22 illustrates a 100% DC offset fault current which is applied to a current transformer which is burdened with 25% of rated load. The top curve indicates the simulated current transformer secondary current and the bottom curve indicates the ideal secondary current in case of no saturation effects. The current transformer transfers the primary current properly to the secondary side. In case the same current transformer is burdened with 100% of rated load (Figure 23) the core will start to saturate at 100% DC offset fault current. As indicated in the top curve, the transferred secondary current is heavily distorted due to saturation effects.

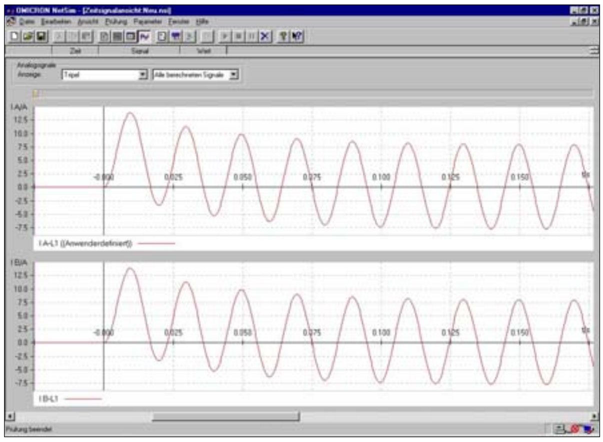

Figure 22: Transient fault – 25% of rated load applied to the current transformer

This example elucidates the influence of the burden value applied to the current transformer and its behavior at transient fault currents. By way of example, such a configuration with two current transformers of the same type, but with different burden values applied to the secondary side can cause faulty activation of differential protection relays.
The calculated current propagation and voltage propagation can be physically injected into a protection relay with e.g. the secondary test device CMC256plus, whereby realistic protection tests can be performed even under extreme fault conditions.

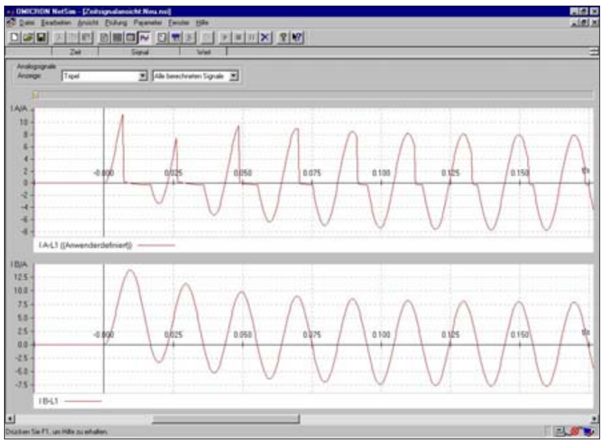

Figure 23: Transient fault – 100% of rated load applied to the current transformer

6. References

[1] CT Analyzer Theoretical Background Manual, OMICRON electronics

[2] CT Analyzer User Manual, OMICRON electronics

[3] NetSim User Manual, OMICRON electronics

[4] IEC 60044-1 consolidated with amendments 1:2000 "Instrument Transformers, Part 1: Current Transformers", International Electrotechnical Commission, Geneva, Switzerland

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