Accuracy Considerations while performing Loss Measurements on Shunt Reactors

R.M. Schomper and S. Widmer
Haefely Test AG, Lehenmattstrasse 353 – Basel, Switzerland
Email: <Schomper.richard@haefely.com>

Abstract: Shunt Reactors are widely used as reactive components for regulating purposes in long distance transmission lines. They limit the over-voltage surges associated with long transmission lines and compensate the capacitive generation on power lines and avoid uncontrolled voltage rise, especially on lightly loaded lines. Shunt Reactors compensate for power losses in the lines and therefore must have low inherent losses. A high precision measurement system will be shown to measure the dissipation factor (tanδ) respectively the power factor (PF) on such loads with accuracy down to $1x10^{-5}$. In the past frequency instability of the used power supply to perform the loss measurement had a major impact on the stability and accuracy of the measurement. The new integrated measuring technology and a simplified test setup will be described to make the setup independent of a fluctuating test frequency as seen in the real test application. With different shunt reactor configurations, power- and voltage ratings, choosing the correct measuring setup, current comparator and standard capacitor are still critical issues. This paper describes the problems and different solutions in order to perform highly accurate measurements. Furthermore it compares the latest technological improvements in modern bridges with the traditional measurement setups.

1 INTRODUCTION

Wherever long power transmission lines are used, shunt reactors are needed. A transmission line can be represented by a Resistance in series with an inductance (due to the magnetic field around the conductor) and a shunt capacitance and admittance to earth (due to the electrostatic field to earth). If the transmission line is energized but lightly loaded with a small current, it causes the line-to-earth capacitance to draw a current through the line, which maybe capacitive. This capacitive current flowing through the line inductance causes a voltage rise along the line (Ferranti-effect).

In order to stabilize the line voltage, series capacitors can be used to compensate for the line's inductance and shunt reactors can be used to compensate for the line to earth capacitance. In high voltage cables the capacitance to ground is much higher than with overhead lines and therefore shunt reactors are also used with long distance cables and especially with submarine cables above 100kV. Shunt reactors are also needed for large urban networks in order to prevent excessive voltage rise when a high load in the network is suddenly disconnected due to a failure.

All these shunt reactors are needful accessories inside an efficient transmission network and they need to realize certain economic parameters too. The Shunt reactors should have low inherent losses indicating a very low tanδ for each winding. A highly accurate instrument is needed to measure these low tanδ values, typically in the range of 0.001 to 0.004 with an accuracy equal to or better than 1% (10~40ppm).

For a 3-phase Shunt-reactor in the range of 250MVA, a tanδ value of 0.002 relates to a continuous loss of approximately 0.5MVA. Therefore it is of the utmost importance for both manufacturer and buyer that the tanδ of the winding of the shunt reactor is measured with the highest possible accuracy. Ideally to measure at such high accuracy, "Capacitance & Tanδ" instruments in conjunction with highly accurate current comparators (compensated instrument current transformer), wherein the shunt reactor is compared versus a standard capacitor (with negligible tanδ), are needed.

Depending on the test facility the frequency of the test voltage might change slowly during the test, resulting in fluctuations in the readings caused by the opposite-frequency behaviour in the reference C_n-arm (Capacitance) and the Shunt Reactor-arm (Inductance) of the Ratio Bridge. To overcome this problem, in the past, various kinds of circuits with integrating functions were used to obtain the same-frequency dependency in both arms of the measuring bridge. A recently developed Capacitance & Tanδ instrument has this external correction circuit replaced by an innovative algorithm implemented in the hardware and software.

Although state of the art instruments, when used, simplify the loss measurement on shunt reactors, great care has to be taken in choosing the optimal test configuration in order to get the most accurate test results. This paper explains the measurement, describes the problems and introduces different solutions by using the latest technological improvements in modern Capacitance & Tanδ instruments, which help in increasing the overall accuracy of the measurement. Various test configurations will be presented and their merits and demerits will be explained.

2 MEASURING PRINCIPLES

Over the years different measuring principles have been used to measure the loss of the shunt reactors. The calorimetric method offers a satisfactory precision however has been found to be too time consuming and expensive to perform. Conventional Watt-meters and instrument transformers did not have the accuracy which was acceptable for the measurement on large shunt reactors. Although the accuracy of more modern Watt-meters integrated in complete transformer measuring systems (TMS-systems) has increased, higher accuracy of the tanδ instruments is often preferred. In the following part the most common measuring principles, which make use of tanδ instruments are explained.

a. Schering bridge (manual balancing bridge with R/C adjusting elements)

In earlier times Schering bridges were used for loss measurements on Shunt Reactors. In the test set up a mutual inductance was used, a Schering bridge, a Standard capacitor, a Guard Potential Regulator and a (passive) Current Transformer (CT). For the final determination of the Loss, the residual error of the mutual inductance and the CT declared in their calibrating report had to be taken into account together with their uncertainty.

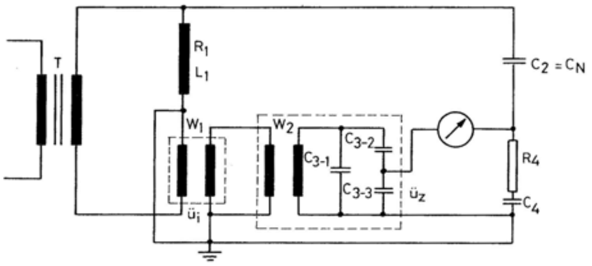

Figure 1: Typical Schering bridge setup

b. Automatic balancing bridge with differential transformer

Later-on automatic balancing bridges were used for the loss measurements. In this test set up, together with the Measuring Bridge, a Standard Capacitor and an active Current Comparator (CC) were used. This simplified the application and increased the accuracy because of the eliminated mutual inductance and smaller error of the (active) Current Comparator (CC). However the capacitor and the shunt reactor have an converse behaviour related to the test-frequency and often produced unstable measurement values for unstable test-frequencies (often seen when a motor-generator group is used). For these applications an additional integrating unit had to be used in order to get stable readings.

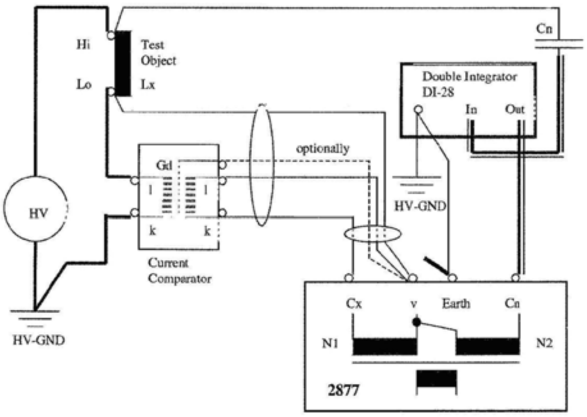

Figure 2: Automatic Balancing bridge with differential transformer and separate Integrator unit

c. Actual State of the Art instrument

The latest tanδ instrument 2840 [1] also compares the Shunt reactor to a Current Comparator against a Standard Capacitor C_n. However it does not perform bridge balancing and therefore the reading stability is no longer frequency dependant. The Loss is determined by sampling both signals from the C_n and the Shunt Reactor and calculated accordingly. With the use of this method an accuracy down to $1*10^{-5}$ is reached for tanδ measurements. Apart from this sinusoidal wave shape and higher harmonics can be shown, giving the instrument the advantages of both a power wattmeter (visualizing higher harmonics) and a tanδ bridge (higher accuracy).

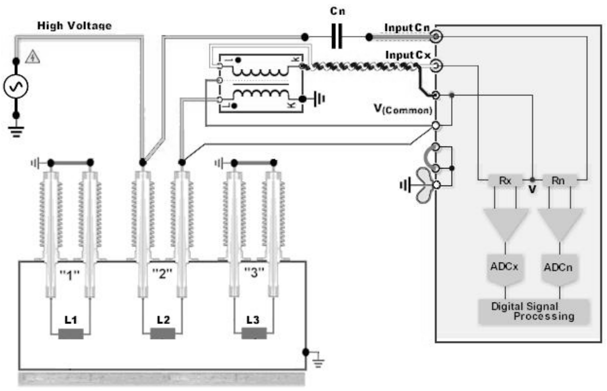

Figure 3: Actual State of the Art tanδ instrument 2840 with inherent test setup

The higher harmonics can also be processed and taken into account for Loss determination by choosing the designated measuring mode, showing the real power factor:

$$\lambda = \frac{|P|}{S} \qquad (1)$$

Where: P = Real Power
S = Apparent Power

Often λ [2] is mistakenly interchanged with the ‘cos(φ)’, both have the same definition; ‘power factor'. However the 'cos(φ)' can only be used when current and voltage are 100% sinusoidal.

3 GENERAL TEST CIRCUITS

During measurement on a shunt reactor large currents will flow and the use of a current comparator (CC) in the test circuit becomes necessary. To connect the current comparator (CC) together with an Automatic balancing bridge with differential transformer or a state of the art instrument mentioned under measuring principal *c* to the shunt reactor, several test circuits can be selected. Each of these test circuits has its own merits and demerits.

a. Test Circuit A

This circuit is only useful in the rare cases that the test object (C_x) is immovably connected to ground and the available HV power supply is ungrounded and shielded. Disadvantages of this setup are;
The stray capacitance to ground of the connection between the test object (C_x) and the reference capacitor has a big influence on the measurement.

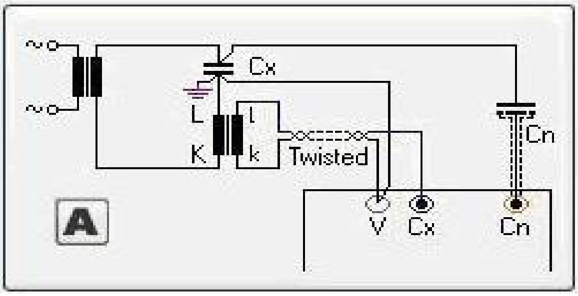

Figure 4: Test Circuit A

b. Test Circuit B

This circuit can be used when a grounded HV source is available and the test object (C_x) itself is ungrounded, the latter being the case for most shunt reactors. In this circuit, the voltage drop V_LO from LO-DUT via CC to HVGND is eliminated by the separate sense line from V to the LO of the DUT, with the open link from V to HVGND.

Therefore this circuit is the preferred circuit for shunt reactor testing.

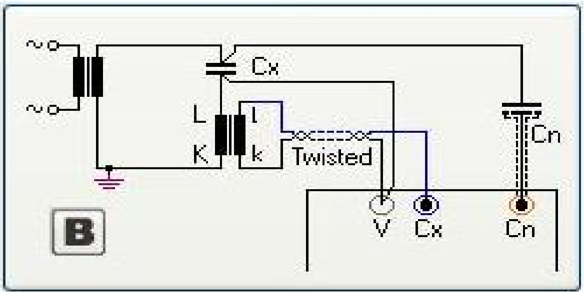

Figure 5: Test Circuit B

c. Test Circuit C

This circuit can also be used when a grounded HV source is available and the test object (C_x) itself is ungrounded. The voltage drop between the low-side of the test object via the CC to ground generates an additional tanδ, which is added to the real tanδ. Finally this results in a higher Loss reading than actuality. For a DUT with a small tanδ, this circuit should be avoided.

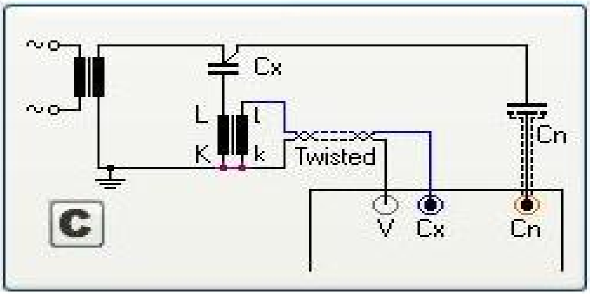

Figure 6: Test Circuit C

Unfortunately the use of the preferred circuit is not always possible due to the type of shunt reactor which needs to be tested and the available HV power source. To summarise the above mentioned test circuits;
- Circuit A is used in the rare case when an ungrounded HV power supply is available and the test object is grounded.
- Circuit B is the most suitable for measuring shunt reactors en Circuit C should only be used if Circuit B is difficult or not possible to construct.

4 APPLICATION

With so many different shunt reactor configurations, power- and voltage ratings, choosing the correct measuring setup, current comparator and standard capacitor are still critical issues. Some examples of shunt reactors with different types of winding configurations and the optimum test setup for these types of reactors will be presented in this part of the paper.

a. Power supply

Around the world different types of HV power supplies are used for testing; single phase-, three phase star/delta, grounded-, ungrounded-, shielded-, double shielded-, open neutral-, closed neutral, etc.

The type of HV power supply available together with the type of shunt reactor greatly decides which type of test circuit can be used to perform the measurement.

As a rule a voltage between phase and ground is supplied to test the shunt reactor. However some times a Phase to Phase voltage is supplied to reach the required voltage level. In this case one Phase has to be earthed because the CC is not isolated for HV. Care has then to be taken that the supplying transformer can withstand the corresponding voltage.

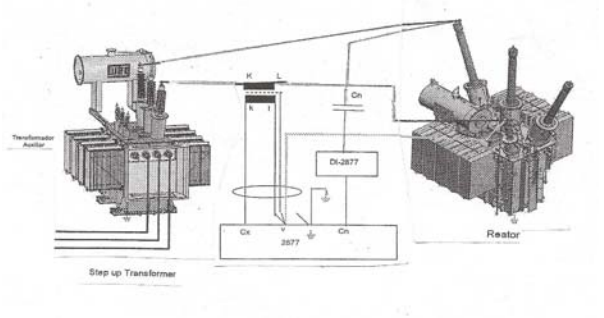

Figure 8: Step-up transformer supplies phase to phase voltage to reach the required voltage level to test the shunt reactor.

b. Types of Shunt Reactors

Different types of Shunt Reactors are built and have to be measured, the most common types are;

A. Single phase reactors

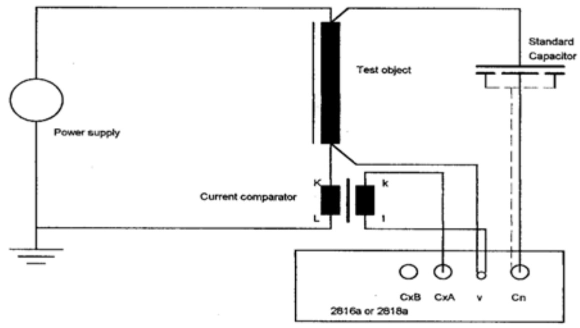

Figure 8: Single phase shunt reactor connected via test circuit B

B. Three phase star reactors with separated neutral terminals

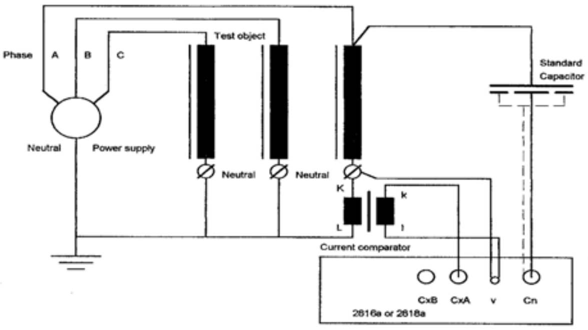

Figure 9: Three phase star reactor with separated neutral terminals connected via test circuit B

C_1. Three phase star reactors with grounded Neutral, HV power source with open star point

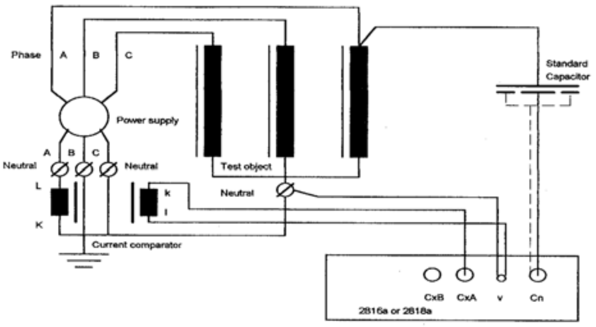

Figure 10: Three phase star reactor with grounded Neutral, HV power source with open star point

C_2. Three phase star reactors with closed star point

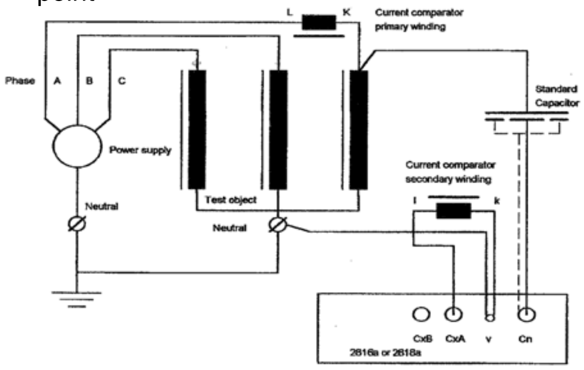

Figure 11: Three phase star reactor with grounded neutral, HV power source with closed star point.

D. Three Phase star reactors with tap changer and closed Neutral

E. Three Phase Delta reactors

To measure the loss of shunt reactor types A. and B.; Test Circuit B can best be used. For shunt reactor type $C_{1.}$; the CC has to be inserted in the low side of test object to ground path of the supplying transformer of the phase to be measured. For shunt reactor type $C_{2.}$; the CC has to be connected to the HV side of the phase to be tested. For shunt reactor types D. and E.; the corresponding circuit has to be found depending on the user's possibilities.

5 ACCURACY VERIFICATION/CALIBRATION

Of great interest is the question about the absolute accuracy of the whole system, consisting of a Standard Capacitor, Measuring instrument and Current Comparator. The IEC 289 Standard [3] mentioned that the overall tolerance of the loss measured shall not exceed the guaranteed loss by more than 15%. The newer IEC 60076-6 Standard [4] mentions that the loss measured shall not exceed the guaranteed loss by more than 10%. A common way to verify the overall accuracy or tolerance is to calibrate the system against a well known, certified traceable standard.

But in this case no such standard is available. As alternatives the following solutions can be used:

a. Partial Calibration

Partial calibration of the Standard Capacitor, Measuring Bridge as well as the Current Comparator is one alternative. With the obtained values the system accuracy can be calculated, according to the recommendation NIST 1204 [5] for the calibration of Loss Measuring Systems for Power Transformers.

b. Power Calibrator

Standard Power Calibrator, like e.g. FLUKE 6100 (limited in voltage and current capability)

c. DUT Simulator

Application specific calibration system, which is in principle a power calibrator that almost simulates real measuring conditions.

Because of the limited capacity of alternative **b.** and the absence of a suitable DUT Simulator as mentioned under alternative **c.**, the option **a.**; ‘Partial Calibration’ is mostly used. It has the advantage that well known specification of the standard units in the system accuracy can easily be calculated for working frequencies 50 and 60Hz. For signals with a significant harmonic content, similar calculations can be made for each harmonic and the total error calculated from the partial errors of all the harmonics.

Using calculations according to NIST 1204 the whole system error specification can be given by;

- Combining linearly the random error at a certain accepted confidence level and all systematic errors (Maximum error).
- Combining the systematic errors in quadrature and adding linearly the result to the random error (RSS error).

The total accuracy for a test system like the 2840 will comprise:

- Voltage measurement accuracy
- Current Measurement accuracy
- Tanδ Measurement accuracy
- Sum of errors of entire test system (Voltage, Current, Tanδ) at various tanδ
- System error at various tanδ/PF
- Reference system errors at various tanδ/PF
- Sum of combined system errors at various tanδ/PF
- Combined system errors at various tanδ/PF (Test system including uncertainties of the reference system)

Applying the before mentioned on our 2840; the following system accuracy is found:
a. System error at: tanδ/PF=0.002: 1.29%
b. Combined system errors at: tanδ/PF =0.002: 2.83% (might become smaller if other, more accurate, calibration instruments are used)

Table 2: Combined system error at various tanδ/PF

No.	Power Factor	RSS Error		
		a	b/cosphi	Total
	cos phi	%	%	%
1	0.01	0.36	1.384	1.43
2	0.005	0.36	1.706	1.74
3	0.002	0.36	2.807	2.83
4	0.001	0.36	4.772	4.79

Test system including uncertainties of the reference system can be seen in Table 2 and Figure 11.

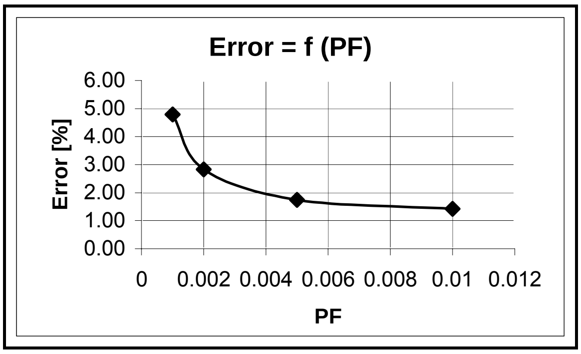

Figure 11: Combined system error at various tanδ/PF

The System Accuracy (including uncertainties) to be declared by the user to his customer, not only depends on the measuring system itself, but also on the accuracy of the used calibration instruments. Therefore it is in the interest of both manufacturer and the user to have the system calibrated with the most precise instruments available.

For a relevant comparison measurement between different Loss measurement systems and an accurate determination of the Loss related to a certain reference temperature, the test object’s temperature also has to be measured as accurately as possible during the measurement on the shunt reactor.

6 CONCLUSION

In order to perform accurate measurements on shunt reactors, not only the type of shunt reactor, the HV power source available, the (HV) connections/cables, the standard capacitor, and the current comparator, but also the type of tanδ instrument should be taken into account.

With the actual state of the art tanδ instrument 2840, the disadvantages of the Schering Bridge and the Automatic balancing bridge with differential transformer have been eliminated. An improved accuracy is reached and the friendly user interface offers suitable comfort to perform accurate Loss measurements on shunt reactors.

7 REFERENCES

[1] Operating Instructions 2840 V1.2, 10-2010, Haefely Test AG.

[2] Applikationsbericht 105, Rev 1.0, ZES Zimmer Electronic Systems

[3] IEC 289 Reactors, clause 8.7 Measurement of loss (1988)

[4] IEC 60076-6 Reactors edition 1.0, 2007-12

[5] NIST 1204, Calibration of Loss Measuring Systems for Power Transformers.