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Title: Analysis of metrological requirements for electrical measurement of HVDC station losses
Author(s): Bergman, A.
Journal: IEEE Transactions on Instrumentation and Measurement
Year: 2012, Volume: 61, Issue: 10
DOI: 10.1109/TIM.2012.2196395

Funding programme: EMRP A169: Call 2009 Energy
Project title: ENG07: HVDC: Metrology for High Voltage Direct Current

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Analysis of metrological requirements for electrical measurement of HVDC station losses

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Abstract—Losses of HVDC converter stations need to be accurately measured and/or estimated in order to support evaluation of bids for such systems and to underpin efforts to reduce greenhouse gas emissions. The challenge of measurement has risen with modern converters where Insulated Gate Bipolar Transistors – IGBT – are used at high switching frequency. The theoretical basis for measurement errors are studied, both for measurement on the IGBT as a component, and on complete converter stations. The study shows that electrical measurements are difficult to augment to an accuracy level sufficient for the needs, and that supplemental method such as calorimetric measurement may be needed.

In certain cases, there will be a possibility to make temporary connections to permit two converters to operate in back-to-back mode, permitting a direct measurement of losses. The achievable accuracy is studied and estimated.

Index Terms—Error analysis, HVDC converters, HVDC transmission, Loss measurement, Measurement uncertainty.

I. INTRODUCTION

The energy losses of an HVDC transmission system have to be generated in power plants supplying the system. The losses therefore represent both a direct cost for the owners of the transmission system, and an emission of greenhouse gases into the environment. Transmission system investment requires an accurate knowledge of the expected losses; this plays an important part in the evaluation of options.

One of the dominant contributors to losses in HVDC transmission is the converter valve itself. The latest generation of d.c. converter valves utilise a technology which increases the demand on accurate measurement of fast changing voltage and current signals in order to determine losses.

As converter stations are used for transmission of bulk energy, even relatively small loss reductions can translate in large energy savings. The detection and improvement of these small efficiency changes requires a step change improvement in precision of loss measurement, going from present percentage-level precision to a small fraction of a percent.

This paper investigates requirements on loss measurement systems used for measurements on converter components as well as on those used for complete converter stations.

Although many researchers discuss the importance of loss evaluation for converters, especially voltage source converters equipped with IGBT’s, [1-4] their primary interest is on the relative advantages of different switching patterns or different components and not on the achievable accuracy of loss measurement. Traceable calibration of such measurements on IGBT circuits has however recently come under discussion [5] and is expected to be of increasing importance in the future.

Calorimetric methods to assess losses from IGBT switches have been discussed in [2] where an uncertainty of 7.1% was attained. This uncertainty is higher than desirable, but refinements of the method should permit lower uncertainties to be reached.

Full-scale measurements of losses on complete converter stations would provide reliable data on actual losses. Two major schemes suggest themselves, direct measurement from a.c. side to d.c. side, or a back-to-back configuration where the a.c. grid would only need to supply the losses. So-far no such measurements are known.

Similar challenges have been addressed in other areas of high voltage engineering. E.g. for power transformers, where two identical transformers can be connected back-to-back and driven so that power is circulating between them with only loss power supplied from the energizing circuit [6] p 358 ff. Similarly, two electrical machines can be connected to the same drive shaft and controlled so that one is in generating mode and the other in motor mode with the energizing circuit once again providing only the loss power [7]. While these examples are parallel, little can be learned from them in terms of uncertainty of measurement for HVDC.

II. CONVERTER TECHNOLOGIES

A. Current source converters

For thyristor-based current source converter stations a standardized method for estimation of losses based on evaluation of components is available from IEC since 1999 (it was revised in 2011) [8]. The standard provides both requirements on the set of operating parameters that the estimation shall cover, the calculation methods and indications of which measurements are required to support the calculations. The metrological difficulties are of moderate severity since switching frequency is the same as the grid
frequency. The standard has been in use for more than a decade and can be regarded as reasonably mature: this paper will not discuss it further.

B. Voltage source converters

Many components in a voltage source converter station are sufficiently similar to the ones used for current source converters so that the procedures of [8] can be used. The exception is estimation of losses in the valves [9].

Valves in voltage source converter (VSC) schemes rely on fast switching, utilizing the turn-off capability of, for example, Insulated Gate Bipolar Transistors (IGBTs) to realise fully controllable converters. Switching frequency is higher than grid frequency and often in the kHz range. Losses are predominantly incurred during the conduction mode and the switching mode.

Measurement of these losses requires measuring systems that can cope both with a large dynamic range for the conduction loss and fast and accurate response for measurement of the loss during switching events.

Global measurement of converter station loss can provide a much needed verification of measurements and estimations performed on converter valve components and other station equipment.

III. ACCURACY TARGET

The losses of a converter station are often reasonably small. For example in IEC standardization [8] for current source converters is mentioned that “The losses of an HVDC converter station at full load are generally less than 1 % of the transmitted power.” Losses in voltage source converter stations are generally thought to be larger, but not more than 2 % of transmitted power [9].

For voltage source converters there is at present no standardization available for loss estimations, although work has been initiated in 2011 in IEC Technical Committee 22F to produce standards for “Determination of power losses in voltage sourced converters (VSC) for HVDC systems - Part 1: General requirements” and “Part 2: Valves for Modular Multi-Level Converters”. The work is planned to finish in 2014 and the present work is one of its possible inputs.

The accuracy needed for determination of losses is usually not defined in standards, but is instead handled in the commercial evaluation of bids on converter stations. A hint is however found in IEEE standardisation for power transformers, where it is defined that the uncertainty of loss measurement shall be 3 % or less [10]. IEC standardisation does not have requirements on uncertainty, see e.g. [11]. It is however a reasonable assumption that uncertainty of loss measurement should be lower than 3 % of the loss power. This estimate represents a compromise between the economic significance of losses vis-à-vis the achievable uncertainty of the estimation of losses.

The requirement on uncertainty of loss estimation should be applied at least for major components such as converter transformer and converter valve. For other converter station components, larger uncertainties could be accepted since their contribution to overall loss is minor.

IV. MEASUREMENT ON CONVERTER VALVE COMPONENTS

The converter valve represents a major fraction of total losses in a converter station. Losses originate from ohmic conduction losses, together with switching losses in the semiconductor switches and their anti-parallel diodes.

Measurement of ohmic conduction loss requires both voltage and current sensors to have high dynamic ranges due to the large difference between on-state and off-state magnitudes. However, requirements for dynamic performance are moderate.

Switching losses, on the other hand, entail measurement of fast current and voltage transients for the purpose of determining the energy consumed during the switching process. Proper handling of phase errors / time delays in the measurement circuit presents a true challenge, and other methods such as calorimetric measurement may need to be used as validation of the electrical measurements. Calorimetric measurement uses coolant flow rate and temperature rise measurements to determine losses.

The analysis in this Section centres on the effect of timing and rise-time errors on the final uncertainty of loss measurement on IGBT’s and IGBT modules. The analysis is theoretical and is intended to support future experimental work.

In a final analysis of experimental measurement uncertainty, many other sources of uncertainty will also need to be evaluated, e.g. calibration of probes, linearity, temperature dependence, accuracy of instruments etc.

A. Conduction loss

In conduction mode, the voltage drop across the IGBT is on the order of a few volts while the current may be 1000 A or more. The measuring system for ohmic loss must therefore be able to handle the high voltage during the blocking mode – on the order of 1 kV - while still retaining sufficient resolution to measure the conduction mode voltage. Modern digitizers are available with sampling speeds up to several 100 kSamples/second at a resolution of 24 bit [12]. This is adequate for accurate measurement of ohmic loss.

B. Simplified model of switching

The switching between on- and off-states of an IGBT is fast and occurs in the approximate time frame from a few 100 ns up to approximately 1 µs [13] with the latter being typical for high power applications. The actual switching process is complex and may exhibit plateaus and fast ramps. The basic requirements on measurement of IGBT losses due to switching can however be studied in a simplified model, where the current and voltage of the switching process are modelled as linear ramps between fully on- and fully off-states, see Fig. 1 and equations (1) and (2). The loss energy is the time integral of the product of voltage and current, and this necessitates that distortion of those signals is small and that they are closely
simultaneous, as will be shown.

In this model, there is no essential difference between switch-on and switch-off processes.

![Fig. 1. Simplified model of IGBT switch-off process, ideal case with 1 µs switching time, off-state voltage 1000 V and on-state current 500 A.](image)

The true voltage $U_{\text{true}}$ and true current $I_{\text{true}}$ in the IGBT circuit are in this model defined as

$$
U_{\text{true}}(t) = \begin{cases} 
0 & t < 0 \\
U_0 \cdot \frac{t}{t_1} & 0 < t < t_1 \\
U_0 & t_1 < t 
\end{cases}
$$

$$
I_{\text{true}}(t) = \begin{cases} 
I_0 & t < 0 \\
I_0 \cdot \left(1 - \frac{t}{t_1}\right) & 0 < t < t_1 \\
0 & t_1 < t 
\end{cases}
$$

(1)

(2)

where $1/t_1$ is the slope of the linear function for the voltage and $-1/t_1$ is the slope for the current.

C. Effect of time delay

Small differences in the lengths of signal cables or in transmission delays in instrumentation can lead to errors in the measurement of energy lost in the switching process. This is modelled by introduction of a fixed delay in one circuit. Modelling the delay in the current or in the voltage channel, will lead only a difference of the sign of the calculated error.

Choosing the current channel as delayed with a fixed time $\Delta t$ in relation to the voltage channel, we can write the current $I_{\text{ind}}$ indicated by the measuring system as

$$
I_{\text{ind}}(t) = \begin{cases} 
I_0 & t < \Delta t \\
I_0 \cdot \left(1 - \frac{t - \Delta t}{t_1}\right) & \Delta t < t < t_1 + \Delta t \\
0 & t_1 + \Delta t < t 
\end{cases}
$$

(3)

From this is seen that the true energy $W_{\text{true}}$ and the indicated energy $W_{\text{ind}}$ will be

$$
W_{\text{true}} = \int_0^{t_1} U_{\text{true}}(t) \cdot I_{\text{true}}(t) \, dt 
$$

(4)

$$
W_{\text{ind}} = \int_0^{t_1} U_{\text{true}}(t) \, dt + \int_0^{t_1} U_{\text{true}}(t) \cdot I_{\text{ind}}(t) + 
U_0 \int_{t_1}^{t_1+\Delta t} I_{\text{ind}}(t) \, dt
$$

(5)

The case is illustrated in Fig. 2 using the same switching parameters as in Fig. 1. The error in the indicated loss energy is calculated using equations (4) and (5).

![Fig. 2. Simplified model of IGBT switch-off process, 1 µs switching time, off-state voltage 1000 V and on-state current 500 A, and current channel delayed by 100 ns. Indicated loss energy is overestimated by 31 %.](image)

The case shown has been chosen to illustrate the impact of a time delay that is 10 % of the switching time, resulting in 31 % error in loss energy $W_{\text{ind}}$. This example is exaggerated compared to that which is expected to occur in practice. However, even for a time delay of 1 % of the switching time (i.e. 10 ns for 1 µs switching time) an error of 3 % will ensue. The relation is close to linear and a time delay of 0.1 % (i.e. 1 ns) will lead to 0.3 % error. As discussed in section III, the overall target of uncertainty should be 3 % or better, which means that the time delay $\Delta t$ should be substantially less than 1 % of switching time.

A delay of 1 ns may seem innocuous, but with a travel speed on the signal cable of 0.7 times the speed of light, this corresponds to a difference of 0.2 m in the signal paths. Careful attention to signal path lengths is indispensable.

D. Effect of rise-time

In practice all measuring systems will have limitations in rise-time, and for measurement of losses in IGBT’s, especially the sensors used to capture voltage and current are liable to exhibit limited rise-time. This can be studied using the same model as for the effect of delay. Let the true voltage and current be given by equations (1) and (2) and assume that one sensor is significantly faster than the switching time. Modelling the other sensor as a first order filter circuit, its output is deduced by convolving its impulse response with the wave-shape of the quantity to be measured. Procedure for convolving is given for example in Annex D in [14]. The step
response \( g(t) \) of the sensor is assumed to be described by the function

\[
g(t) = 1 - e^{-\frac{t}{\tau_s}}
\]  

(6)

where \( \tau_s \) is the time constant of the sensor step response. The corresponding rise-time from 10 to 90 % is \( 2.2\tau_s \). The first derivative of this function is the impulse response of the sensor. For a voltage sensor used to capture an IGBT switch-off process the output will then be described by

\[
U_{\text{ind}}(t) = U_0 \int_0^t g'(\tau) d\tau = U_0 \int_0^{t_1} \frac{1}{\tau_c} \cdot e^{-\frac{t-\tau}{\tau_c}} d\tau
\]  

(7)

The energy developed during the switching process is given by equation (4) above. The energy indicated by a measuring system with a finite rise-time in the voltage channel, and perfect current channel is

\[
W_{\text{ind}} = \int_0^{t_1} U_{\text{ind}}(\tau) \cdot I_{\text{true}}(\tau) d\tau.
\]  

(8)

The integral has been truncated after time \( t_1 \) because the current has become zero and there is no further contribution to energy.

![Fig. 3. Simplified model of IGBT switch-off process, 1 \( \mu \)s switching time, off-state voltage 1000 V and on-state current 500 A, and effect of rise-time limitation of voltage sensor on captured wave-form for a sensor with a 10-90% rise-time of 100 ns. Loss energy is underestimated by 12 %.](image)

As can be seen from Fig. 3, the case of rise-time limitation resembles the time delay shown in Fig. 2. For the case illustrated, the parameters have once again been exaggerated by assuming \( 1 \mu \)s switching time and a voltage sensor with 100 ns rise-time, resulting in an error of -12 % in loss energy \( W_{\text{ind}} \). Looking at a rise-time 20 ns, an error of -2.7 % is achieved, and similarly 2 ns rise-time will lead to an error of -0.27 %. Careful attention to effect of rise-time on measurement of loss energy is needed.

E. Interaction between test object and instrumentation

Attaching probes to the test object may cause loading of the circuit that will change the voltage or the current signals that are to be measured. For high power circuits, this effect is in general small, although a final analysis of a test will need to address the question. For example a high voltage probe will typically present a load of a few pF and some 100 Mohm, which is negligible in comparison to circuit capacitance and resistance. Likewise the effect of current probes may have an effect that needs to be evaluated, even though most such probes have a negligible voltage drop compared to the voltage in the circuit.

V. MEASUREMENT ON CONVERTER STATIONS

A. Direct measurement

A measurement of the difference between input power and output power would provide the desired measurement of the actual losses. Due to the small magnitude of the losses, the accuracy of measurement will have to be very good. Making a reasonable estimate of the losses being 1 % of the transferred power, and assuming that the uncertainty of the measured losses must be 3 % of the measured losses leads to a requirement of 0.03 %. In order to reach this, the uncertainty of measurement of input and output power respectively has to be better than 0.02 %.

The measurement is in principle possible to carry out, but the requirements cannot be met with standardized energy measuring equipment: instead sophisticated current and voltage transducers are required, together with laboratory grade measuring instruments. For the a.c. side, both current and voltage transducers with sufficient accuracy are available. For the d.c. side, suitable current transducers are available, whereas voltage transducers (in general a voltage divider) with sufficient stability and accuracy are difficult to find. Furthermore, there are few, if any, calibration institutes that can provide traceable high voltage calibration with the required precision.

It can be concluded that at present, there are severe difficulties precluding a direct measurement of losses by a measurement of power on a.c. and d.c. sides.

B. Measurement in back-to-back configuration

An intriguing possibility is to operate two VSC converters in a station such that their d.c. sides are connected in series and their a.c. sides in parallel. Operating one of the converters in rectifier mode and the other in inverter mode, active power can be arbitrarily transmitted on the d.c. connection between the two and only the loss power needs to be supplied by the a.c. connection.

A disadvantage of this method is that losses attributable to rectifier mode cannot be distinguished from those attributable to inverter mode. On the other hand, this may be acceptable since HVDC transmission always will include both modes, one mode at each end of the transmission, as well as having both modes in use at different times in accordance with power flow.

The scheme is shown in Fig. 4 where the a.c. power is fed via the link with meter DM1. The circulating power can be monitored on a.c. meters DM2 and DM3. It is also possible to monitor the circulating power using the meters KM1 and KM2 on the d.c. side.
1) Current circuit

The current drawn from the AC grid during the back-to-back test will be a small fraction of the current in normal operation, probably in the range of 0.1 to 1 % of the rated current of the two converters depending on operating point and type of converter. This current is small compared to the normal operating current of the converters, and current transformers intended for normal operation cannot be used. Measuring the a.c. bus current instead with a three-phase set of current transformers rated for e.g. at 5 % of rated current of the two converters, would enable traceable measurement, if IEC class 0.2S is used. These would have to be installed specifically for this test and need to be removed after the test.

The choice of rated current for the CT is limited by achievable designs, where a rated current of appreciably less than 100 A (at 1 A secondary) is difficult to obtain for 400 kV system voltage where insulation requirements and short-circuit stresses severely limit the number of primary turns that can be used.

A transformer conforming to class 0.2 S is required to have a ratio error less than 0.75 % between 1 % and 5 % of its rated current. At higher current, errors are lower. In this case, the conservative assumption of 0.75/% standard uncertainty can be therefore be used for all current magnitudes. The factor 1/% relates to the standard uncertainty estimated for a rectangular error distribution. The contribution to uncertainty of a three-phase group of current transformers is estimated to be 1/% of the standard uncertainty, i.e. the sensitivity coefficient is 1/%. The power factor of the loss power is further assumed to be larger than 0.8, which means that the phase displacement of the instrument transformer has moderate effect on the accuracy of the power measurement. The phase displacement difference between current and voltage transformers is assumed to be limited to 0.9 crad leading to a standard uncertainty contribution of 0.9/% crad. The effect on the power measurement is then expressed by tan (ϕ) = 0.75 at cos (ϕ) = 0.8.

2) Voltage circuit

The line voltage during the back-to-back test will be in the normal range, i.e. within 80 to 120 % of rated voltage. The voltage transformers intended for normal operation will be suitable, if class 0.2 is chosen. The errors of an instrument transformer are known at power frequency, but can be quite different at other frequencies, especially for voltage transformers. However, for VSC converters the lower order harmonics typical for current source converters are largely absent and are not expected to contribute to uncertainty in measurement of loss power.

3) Voltage circuit from voltage transformer to energy meter

The voltage drop on the wiring from the voltage transformer terminal to the energy meter terminal is a measurement error that must be controlled. By suitable choice of connected burden and wiring cross-section, this error can be kept small. It is here assumed that the voltage drop is less than 0.05 % of the voltage on the voltage transformer secondary circuit.

4) Energy meter

The voltage input to the energy meter will be in the normal range of 80 to 120 % of rated voltage. The current range will be in the range 1 to 120 % defined for energy meters of class 0.2 S. The uncertainty of energy measurement will therefore be within the limits defined for this class and the contribution to standard uncertainty is estimated to 0.2/%.

5) Combined uncertainty

The following analysis is based on certain simplifications, but adheres to the principles of the GUM [15]. These simplifications will in general be conservative and lead to slightly over-estimated uncertainty. A final analysis of actual measurements should be done “a posteriori” when corrections can be applied for all known errors and is therefore expected to be at least as good as the results given here.

<table>
<thead>
<tr>
<th>Table 1. Relative uncertainty estimate of loss measurement in back-to-back operation of two equal converters</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity</td>
<td>Standard uncertainty</td>
<td>Sensitivity coefficient</td>
<td>Uncertainty contribution</td>
</tr>
<tr>
<td>CT ratio error</td>
<td>0.75/%</td>
<td>0.577</td>
<td>0.250</td>
</tr>
<tr>
<td>VT ratio error</td>
<td>0.2/%</td>
<td>0.577</td>
<td>0.066</td>
</tr>
<tr>
<td>VT wiring</td>
<td>0.05</td>
<td>0.577</td>
<td>0.029</td>
</tr>
<tr>
<td>Energy meter</td>
<td>0.2/%</td>
<td>1</td>
<td>0.115</td>
</tr>
<tr>
<td>Phase displacement</td>
<td>0.9/%</td>
<td>0.75*0.577</td>
<td>0.225</td>
</tr>
<tr>
<td>Variation in readings</td>
<td>0.5</td>
<td>1.000</td>
<td>0.500</td>
</tr>
<tr>
<td>Standard uncertainty U_P2</td>
<td></td>
<td></td>
<td>0.620</td>
</tr>
<tr>
<td>Expanded uncertainty U_P2</td>
<td></td>
<td></td>
<td>1.2 %</td>
</tr>
</tbody>
</table>

This measurement can thus be used to obtain verification of other estimations of total losses of a converter station, but this is obtained at the expense of the need to configure the station for local back-to-back operation – which is seldom possible.
A unique possibility has however opened where the author has been asked by Svenska Kraftnät (Swedish National Grid) to evaluate the achievable uncertainties in measurement of total loss of an HVDC converter station where a provisional back-to-back configuration of two converters will be utilized to measure the loss power supplied from the grid under various power transfer between the two converters. The measurement is planned to be performed in 2014.

VI. CONCLUSIONS

It has been shown that even small differences in the delay between current and voltage channel, or differences in the respective rise-times, can have a profound effect on the error of measurement of losses of the switching elements of an HVDC converter. It may in fact prove difficult to demonstrate by calibration that the measuring systems for losses are sufficiently accurate, even if best available equipment and calibration services are employed. Other means of determining the losses of the switching elements and/or switching modules are available, e.g. calorimetric methods where the heat loss is directly measured. Such additional methods may be needed to underpin the results of electrical measurements.

It has been shown that simultaneity between voltage and current signals must be significantly better than 1 % of the switching time. It has also been shown that the rise-time of current and voltage measurement systems should be significantly shorter than 2 % of the switching time. Further experimental work is needed, and is also planned within the scope of the EMRP ENG07 research project.

A method to measure the losses of two converters connected back-to-back has been discussed and the uncertainty estimated for a typical application, which is also planned to be realized.

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Anders Bergman (M’010-SM’11) was born in Överluleå, Sweden in 1948. He received his B.Sc. in physics at Uppsala University, Sweden in 1971. He received his Ph.D. at Uppsala University in 1994 with the thesis "In situ calibration of voltage transformers on the Swedish national grid", which is based on the results of a project to calibrate the total complement of voltage transformers on the Swedish 220 and 400 kV grids.

After being involved in the design and construction of a 100 MeV cyclotron at a Scanditronix in Uppsala, he moved to the high voltage laboratory at ASEAA in 1977 to be engaged in the metrological aspects of high voltage testing, with the main emphasis on impulse voltages and partial discharges. He has since 1988 been with SP Technical Research Institute of Sweden in Borås where he is responsible for calibration activities for high voltage and high current. Dr. Bergman is primarily engaged in calibration activities in fields of high voltage engineering which are needed by industry and he has developed several major reference systems that are used for on-site calibration of high voltage measurement systems. As of September 2010, he coordinates a 3 year research project for metrology for HVDC, with participation from 8 other European bodies. The project is funded by the European Commission.

Dr. Bergman is involved in international standardization, mainly within IEC TC42, High voltage test techniques, where he is convenor of WG20, Instruments and software used for measurements in high-voltage and high-current tests. Dr. Bergman has received the 1906 award from IEC.