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Reference Setup for On-Site Calibration of High-Voltage Revenue Metering Systems

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Abstract — A reference setup for on-site calibration and validation of revenue metering systems is realized. The system consists of a three-phase power meter and high-accuracy current and voltage transformers (CTs and VTs). Measurements can be made up to 150 kV (system voltage) and line currents up to 5000 A. The power meter, the CTs, and the VTs were all calibrated. Based on the excellent results of the calibration of these components it is possible to predict the full system performance with an accuracy of 35 $\mu\text{W}/\text{VA}$. This estimation was verified with a full system validation, showing that the system is much more accurate than required and that detrimental effects to the accuracy are well understood.

Index Terms — power, revenue metering, billing, traceability, substation, high voltage (HV), high current, current transformer, voltage transformer, power meter, precision measurements.

I. INTRODUCTION

Revenue metering of the electrical energy transported in high-voltage (HV) grids is the basis for fair trade between commercial parties exploiting the grids. In the Netherlands, liberalization of the electricity market has led to new billing points in the HV grids [1]. According to the Dutch metering code [2], revenue metering systems need to be present at the new billing points in the HV substations. Several studies were performed in order to prove that the existing, inadequate, equipment of the substations can still be used for HV revenue metering provided that the errors of the current transformers (CTs) are corrected for and that voltage transformers (VTs) from elsewhere in the substation are used for the voltage measurement [3].

However, this approach requires an overall system validation of the revenue metering setup. To this aim, a reference setup has been developed that will be placed in the grid in parallel with the system to be calibrated.

II. REQUIREMENTS AND APPROACH

HV revenue metering systems, as used in HV grids, consist of a three-phase power/energy meter and a set of CTs and VTs to reduce the high currents and voltages, respectively, to the appropriate signal levels of the power / energy meter. In the Netherlands, the Electricity Metering Code [1] requires that new HV revenue metering system for contracted powers of 5 MW and higher, a total system accuracy of 0.4 % should be achieved. A reference setup for calibration of such a metering

system should be at least three to five times more accurate [1], [4], and preferably even better. So the VSL reference setup should have at least an overall accuracy of 0.08 %, and preferably 0.05 % or better.

III. MEASUREMENT SETUP

The VSL reference setup is based on a power/energy meter, three CTs and three VTs [1]. In order to achieve an overall uncertainty in power measurement of 0.08 % or better, the accuracy of the CTs and VTs should be at least 0.05 % and that of the power meter at least 0.03 %.

A commercial power meter was acquired with a basic accuracy of better than 0.01 % and a small temperature dependence. The input range of the meter is 30 – 525 V and 0.02 – 120 A. The selected CTs and VTs were custom made, with specified accuracies of better than 0.02 % in ratio and 290 μrad in phase displacement. The CTs have two ratios, 2000:1 and 600:1, both with 250 % over-current capability so that currents up to 5000 A can be measured. A 220 kV VT was selected since it has a better performance at 150 kV and 110 kV than the available 150 kV models. The VTs have three ratios, 2200:1, 1500:1, and 1100:1, for grid voltages of 220 kV, 150 kV, and 110 kV respectively. The nominal output of the VTs is $100/\sqrt{3} \approx 57.7$ V line to ground.

The CTs and VTs were thoroughly tested and calibrated to improve their accuracy by correcting for their errors.

IV. CALIBRATION OF COMPONENTS

The power meter has been calibrated for all ranges it will be operated in. In addition, extensive tests have been performed to determine how its sensitivity is affected by harmonic content and temperature fluctuations. For the tests and calibrations the VSL sampling wattmeter was used as the reference system [5]. The results of the tests show a deviation from nominal value for all three input channels of less than 50 $\mu\text{A}/\text{A}$ and 30 $\mu\text{V}/\text{V}$ for current and voltage respectively. The power meter was calibrated for power at 57.7 V. The measurements for currents ranging from 1 mA to 120 A, and phase angles from -90° to 90° are summarized in fig. 1. The top plane is defined by the maximum values and the bottom plane is defined by the minimum values. The resulting envelope encloses all measurement points of the three

channels. In the nominal operating range (10 mA to 2.5 A) the accuracy is better than $50 \mu\text{W/VA}$. For a current ranging from 35 mA to 65 mA channel 1 suffers from a larger error of $80 \mu\text{W/VA}$. Over a time range of one year the drift of the power meter was less than $10 \mu\text{W/VA}$.

The error due to harmonic content, such as it appears on the power grid, was verified to be less than $10 \mu\text{W/VA}$. The largest temperature effect that was measured is $2 \mu\text{W/VA}$ per $^{\circ}\text{C}$. To further limit possible effects of temperature on the accuracy, the power meter will be operated in a temperature controlled casing.

Fig. 1. Error of the power meter for all channels over its full current range, for phase angles between -90° and $+90^{\circ}$ at 57.7 V

The CTs were calibrated using the current comparator test set at NRC [6] with 20 parts in 10^6 uncertainty ($k = 2$). The ratio error of the 'worst' performing CT is shown in Fig. 2. Similar results are achieved for the phase displacement of the CT, showing a maximum deviation of $132 \mu\text{rad}$ at 6 A for the 600 : 1 ratio with a burden of 1 VA. The CTs can best be used at the 2000 : 1 ratio, even for the smallest currents, since this ratio has a maximum ratio error of only $5 \mu\text{A/A}$ and maximum phase displacement of $40 \mu\text{rad}$.

The calibration of the VTs showed that for no burden the error always is less than $80 \mu\text{V/V}$ and $125 \mu\text{rad}$ for ratio error and phase displacement respectively.

Fig. 2. Ratio error of a reference CT, at 0 VA and 1 VA burden, as a function of the primary current.

III. REFERENCE SYSTEM PERFORMANCE

Based on the calibration results of the single components the error of the complete system was estimated to be less than $50 \mu\text{W/W}$ at power factor 1 and less than $155 \mu\text{rad}$ in phase. A full system validation was performed at NRC using their load loss standard [7] which proved that the expectations were correct within $35 \mu\text{W/W}$ and $35 \mu\text{rad}$. This indicates that the total setup behavior is very predictable and stable.

VI. CONCLUSION

A reference system has been established at VSL for on-site calibration of high voltage revenue metering systems in substations. Each component proves to be much more accurate than specified by the manufacturer and be even much more accurate than required. The accuracy of the power meter is better than $50 \mu\text{W/VA}$. The CTs have errors of less than $5 \mu\text{A/A}$ in ratio and less than $40 \mu\text{rad}$ in phase displacement. The VTs have errors of less than $80 \mu\text{V/V}$ in ratio and less than $125 \mu\text{rad}$ in phase displacement. The performance of the complete system can be calculated accurately based on the calibration of the individual components. This calculation was verified in a validation of the setup using the NRC load loss standard.

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