ACCURATE REVENUE METERING WITH LOW POWER CURRENT AND VOLTAGE SENSORS ACCORDING TO RECENT IEC 61869-10 AND IEC 61869-11 STANDARDS

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ABSTRACT

In 2017 new IEC standards for low-power passive current transformers (LPCT) and low-power passive voltage transformers (LPVT) were established, the IEC 61869-10 and IEC 61869-11 respectively. The standard accuracy classes vary from 0.1 to 3.0. An accuracy class 0.2 or better in combination with a matching reading unit would make these new transformers suitable for revenue metering of commercial MV customers. Until recently, however, such an accurate LPVT was not available. This paper presents the latest development with the new QX sensor of 3M as an accurate LPVT, and an RTU of Netcontrol with modified I/O cards for reading out the LPVTs and LPCTs. Both low-power transformers comply to the new IEC 61869-10 and -11 standards. This paper shows that 3M's LPVT is able to measure with an accuracy class of 0.2 during type testing. While the goal of this paper was to demonstrate class 0.2 accuracy in the field comparing the LPVT and LPCT combination with conventional metering using VT, CT and an industrial revenue meter, the measurement set-up made it difficult to proof and requires more in depth study.

The implementation of this sensor technology will bring important benefits to network operators in that, the new LPVTs are significantly smaller than conventional VTs with much easier installation that does not require on-site calibration and which is suitable for retrofitting in any existing station. When this is coupled with the expected higher reliability and operational safety, the LPVT brings a new impetus to accurate revenue metering.

INTRODUCTION

This paper describes the application of accurate low power current and voltage sensors (LPCT and LPVT respectively) which are in accordance to the recent standards IEC 61869-10 [1] and IEC 61869-11 [2] respectively. These standards replace the earlier standards IEC 60044-7 for voltage measurement and IEC 60044-8 for current measurement. An overview of applications with these instrument transformers in accordance to the former standard is found in [3].

The second and following paragraph of this paper describes the ultimate goal, namely to demonstrate the application of LPVT and LPCT with matching electronic measurement equipment for accurate revenue metering, at least from a technical perspective. The application of LPVTs and LPCTs for revenue metering would be a revolutionary step forward, with a number of advantages over conventional transformers. The low power sensors are smaller concerning size and weight and for this reason handling is easier and less space is required in the switchgear. As a result, it fits well in existing and future designs of substations. Furthermore, both current and voltage sensors have a low voltage signal output (mV to some Volts). Thereby the safety of the connected equipment and of the field service staff increases. Their electrical and physical properties reduce the risk of damages caused by aging or by human errors is reduced as well.

The remainder of this paper focuses on the demonstration of highly accurate voltage measurements with the newly developed QX sensored MV termination by 3M in conjunction with a slightly modified I/O card, built in a Netcon 100 controller from Netcontrol as measurement equipment. The third paragraph depicts the successful approval testing of the LPVT, including the high accuracy that has been achieved. In the fourth paragraph, accurate measurements of the QX sensor with the Netcon 100 in a lab measurement is demonstrated. The fifth paragraph concerns a field trial where this LPVT, LPCT and controller setup is compared to conventional revenue metering. The required accuracy class 0.2 is analysed in the sixth paragraph, using a statistical method to compare two instruments with comparable accuracies. The paper concludes on the feasibility of accurate revenue metering with LPVTs and LPCTs, summarizing the results of the various experiments and tests.

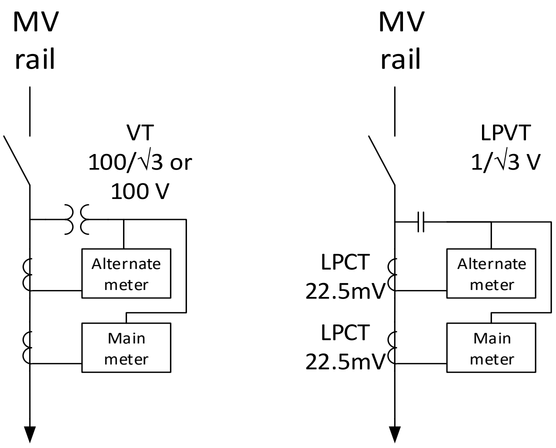
CASE STUDY REVENUE METERING

A common practice for high power MV connections, e.g. above 1 MW, is to apply indirect revenue measurements, using conventional voltage and current transformers. A typical revenue measurement setup is provided in Figure 1a, using the main meter for actual billing and the alternate meter to verify the revenue measurement. The VT with 3x60V nominal phase voltage output is shared between the two meters and could also power the meters. Each meter has his own set of CTs – one per phase – with 1A output at nominal power in our case.

VTs are particularly infamous for their heavy and bulky form factor and typically they need a dedicated metering panel in the switchgear equipment.

The usage of low power voltage and current transformers

would improve the many disadvantages of the conventional VTs and CTs. Typically the LPVT can be integrated in the termination of a MV connection, not taking additional space in a MV panel. Even when the integrated electronic parts of the LPVT fails, the operation of the primary installation is not affected. The LPCT is similar in form factor to a conventional CT, but inherently safe.
A typical revenue measurement setup with LPVTs and LPCTs is shown in Figure 1b. The setup looks very similar although in detail the changes are significant. Besides the usage of the LPVTs and LPCTs, the meters as shown, should be suitable for the low signal levels of the low power transformers and have the correct input impedance as specified in the IEC standards [1][2] to not affect the measurement accuracy.



a) b)

Figure 1a: A single line diagram of a typical revenue metering setup for connections with contracted power larger than 1 MW. Figure 1b: MV revenue metering with low power sensors.

TYPE TESTING OF THE LPVT

Low power voltage transformers are based on the voltage divider principle. The QX sensored termination is primarily a capacitive voltage divider incorporated in a rubber medium voltage cable termination Figure 2a. The rated primary voltage is 20kV/√3 with a rated transformation ratio of 10.000/1. The rated insulation level is 24kV U_{max}. The designed accuracy is 0.5% to accommodate the use of different MV cable types and constructions. The voltage divider is more accurate however and greater accuracy of the LPVT could be achieved by calibrating it for the specific cable type.
Due to the design of the QX two different type tests are required. First type testing according to Cenelec HD 629.1 (test requirements on accessories for use on power cables) [4] and second according to IEC 61869-11 (low-power passive voltage transformers) [2].
The QX sensored termination was type tested at Karlsruhe Institute of Technology, where in addition many in-house qualifications were verified as well.

The type testing sequence according to HD629.1 contains dielectric tests (AC, BIL, PD) and a 1000h heating cycle voltage test. In addition to the required test sequence the basic accuracy of the voltage sensors was measured before and after the whole test sequence. The deviation of the transformation ratio was less than 0.02%. This result would demonstrate the long-term stability of the voltage divider.
The type testing according to IEC 61869-11 confirmed a accuracy class of 0.2 based on the individual corrected transformation ratio in a temperature range from -20 to 60°C. The QX sensored termination would also fulfil the requirements for 0.2P class.

a) b)

Figure 2a: The QX sensored termination; Voltage sensor (left) and installed termination (right).
Figure 2b: The low-power instrument transformers mounted in the MV panel of the switchgear.

LAB MEASUREMENT SET-UP AND RESULTS

Prior to the first field tests were done, several laboratory measurement sessions were performed to ensure correct operation of the QX sensored termination together with Netcon 100. Between the sessions different changes and improvements were done to the Netcon 100 unit to meet the specifications of an accurate measurement over a wide range and to make the configuration of the Netcon 100 with a QX sensored termination as user-friendly as possible.
In the laboratory testing the prime focus was on the voltage measurements, where the 0.2% accuracy requirement was seen to be most challenging.
In high voltage laboratory tests the test equipment was based on a power transformer for voltages up to 12 kV with a voltage divider and a Tettex 4861 for Voltage reference.
In laboratory tests in May 2018 the deviation measured for voltages over the range from 1.5 kV to 12.1 kV showed a

deviation between 0.01% to 0.12 %, with a mean value of 0.06 %.

In new laboratory tests in November 2018 measured over the range from 3 kV to 12 kV, the deviation was between 0.01 % and 0.16 %, with a mean value of 0.07 %.

In both measurement the highest deviation, was measured at the lowest voltages, which, in practice, are outside the range covered by the standard (80%...120 % of rated).

FIELD MEASUREMENT SET-UP AND RESULTS

In June 2018 Alliander started a field trial at an operational substation. The measurement setup was created in one of the MV panels of the Xiria switchgear at the substation in Alliander's service area. The goal of the field trial was to determine the capability of the LPVTs and LPCTs as sensors for revenue metering.

The measurements are therefore compared to a conventional industrial meter, located at the same substation and the same MV cable. The conventional metering equipment consists of an L+G industrial meter, a set of conventional class 0.2 VTs and a set of conventional class 0.2 CTs.

The setup for the field trial exists of the QX sensored termination and class 1 LPCTs coupled to a Netcon 100 controller with a modified I/O card for the LPVTs. The I/O card (FDM112 type) also contains the inputs for the LPCTs. In order to cover the dynamic range of the current with sufficient accuracy, two parallel inputs are used per LPCT which are combined in software to a single measurement. Figure 2b shows the installed low-power instrument transformers in the MV panel of the switchgear.

One of the advantages of the used LPVTs is that on-site calibration is not needed since the calibration data is provided with each LPVT.

The setup for both the L+G conventional metering and the Netcontrol low-power instrument transformer metering needed tweaking regarding the settings and time. The time was manually set within ten seconds accuracy. The recorded and measured quantities at the Netcon 100 are:

- Primary phase voltage, per phase, 3 min RMS
- Primary current, per phase, 3 min RMS
- Active power, total and per phase, 3 min RMS
- Reactive power, total and per phase, 3 min RMS
- Apparent power, total and per phase, 3 min RMS

A representative sample of the primary voltage measurement data of one day is shown in Figure 3 and for current in Figure 4; this sample data is used in this paper for evaluation.

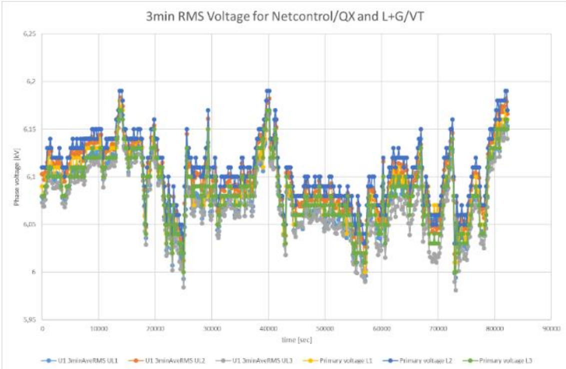


Figure 3: Voltage measurements (3 minutes RMS average) during one day period.

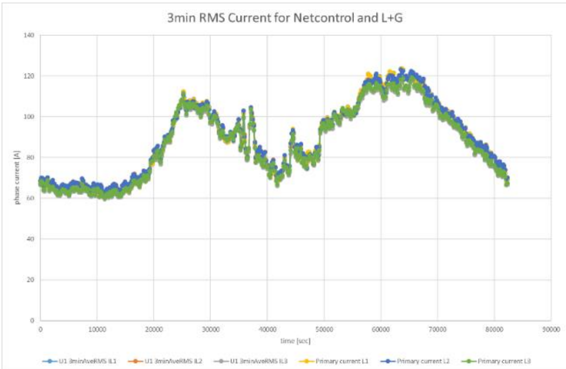


Figure 4: Current measurements (3 minutes RMS average) during one day period.

ANALYSIS

Method

Determining the accuracy of one instrument by comparing it with other instruments of a similar accuracy class is not straight forward. Bland and Altman [5] described a statistical method for assessing the agreement between two clinical instruments. The paper lacks a hard criterion for a decision on agreement, but its quantitative method is valuable for the assessment.

In summary, the method determines the mean difference $\bar{d}$ and the standard deviation s of a set of measurement data, with simultaneous samples of both instruments (one reference and one to be tested). The expected difference for 95% of the samples lies within $\bar{d} \pm 2s$. This range is called the limits of agreement. If these limits of agreement are small enough, one could state that the two measurement instruments are interchangeable.

The limits are only estimates of the whole population. Bland and Altman [5] also provide confidence intervals for the estimated limits above. The 95% confidence intervals can be determined as follows. First the t value for the 95% confidence level is calculated by taking the two-sided inverse of the Student's t-distribution with n-1 degrees of freedom and probability 0.05, where n is sample size Second, the t standard error is found as the multiplication of the t value and the standard error. The standard error of $\bar{d}$ (called bias) is $s/\sqrt{n}$. The standard error of $\bar{d} \pm 2s$ is

about $s\sqrt{3/n}$. Finally the confidence interval will be the observed value plus and minus the t standard error.
In the analysis in this paper, a hard criterion is set for the limits of agreement. If the precision of the test measurement is expected to be 0.2% accurate and the reference for comparison is also 0.2% accurate, and the errors are assumed to be normal distributed, the expected accuracy of the difference of the two quantities is 0.28%. The criterion for the limits of agreement are therefore set to ±0.28%.

Results

The primary focus in this paper is on the voltage sensors. Figure 5 shows the mean versus difference of the recorded 3 minutes RMS average voltage measurement data of one day, one set being the QX/Netcon combination and the other being the VT/L+G combination. With alignment of data, the total set contains 458 pairs.
It is observed that all the plots contain lanes of dots. This is explained by the fact that the L+G voltage data was provided with two digits precision, for instance 6.11 kV. A step of 0.01 kV is already 0.17% of the observed value, which is large compared to the target accuracy of 0.2%. The Netcon 100 data has one digit more. Hence, even if both systems would have had exactly the same accuracy, these lanes would be observed by the way the data is presented. These lanes should have been centred around the x-axis (difference of 0 kV) in that case. This is not the case for all the three plots in Figure 5. This observation will be reviewed later in the discussion of the results.

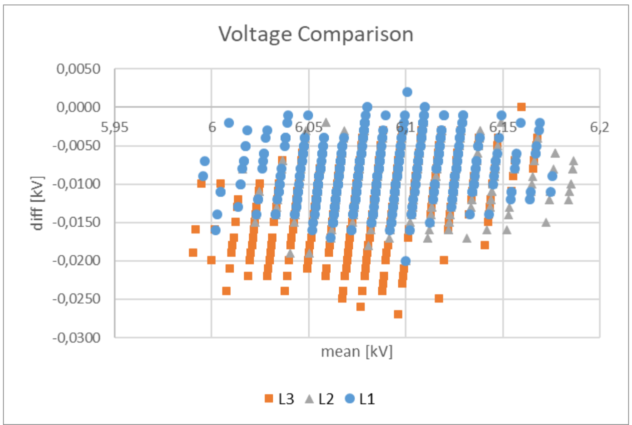


Figure 5: Mean versus difference plot for the voltage measurements of phase L1, L2 and L3, during one day.

The statistics according to the method described above for the voltage measurement data, are provided in Table 1. For phase L1 to L3 the mean differences are respectively -0.13%, -0.15% and -0.22%. So the QX/Netcon combination has a negative bias, measuring lower voltage levels, compared to the VT/L+G combination. This is determined from a limited set of data only (n = 458, about one day of 3 minutes RMS average values). Using a t value of 1.9652, a 95% confidence interval (CI) is achieved for the whole population. The table shows that the mean differences for the three phases have a small CI of ±0.01 percentage point maximum. The limits of agreement for L1 are -0.01% and -0.26%, for L2 -0.04% and -0.27%, and for L3 -0.05% and -0.38%. Also the limits of agreement have a CI of about ±0.01 percentage point.
Similar processing is done for the current measurement, using the pairs of measurement values of the LPCT/Netcon and the CT/L+G. The measurement values are 3 minutes RMS averages in amperes. The mean differences are 0.00%, -0.02% and -0.97% respectively for L1, L2 and L3, with a CI of ±0.03 percentage point. The limits of agreement for L1 and L2 fall within ±0.60%. For L3 however the limits of agreements are -1.66% and -0.28% (CI for both about ±0.05 percentage point).
For the comparison of the energy measurement, some further calculation was needed, comparing cumulative values of energy consumption for the L+G data with the Netcon 100 data that was presented as average power during the last 3 minutes. The mean differences for active energy is 0.43%. For reactive energy larger differences appear with a mean of 3.4%. The measured apparent energy has a mean difference of -0.49%.

Discussion

The results for the 3 minutes RMS average voltage measurements show that the mean difference deviates less than our criterion of ±0.28% for all three phases. It is very likely that for phase L1 and L2 all measurements will deviate less than or equal to ±0.27%, taking into account the worst case of the confidence intervals on the limits. However, for phase L3 we are not so certain. The difference of measurements between the two instruments might exceed the ±0.28% criterion with more than 20% probability.
So, while we may safely say that for L1 and L2 we met our goal showing that the QX/Netcon and VT/L+G measurement setups are interchangeable, we have to be reluctant making this a general statement. There is reason for doubt on the validity of the measurement at phase L3. The point is that for current measurements the LPCT/Netcon and the CT/L+G show the same exception for phase L3 in the comparison, even though the overall error for current is larger. The voltage and current measurements should have been fairly uncorrelated, but again L3 has significant larger error (about -1%, worst case -1.7%) than the others (around 0%, worst case ±0.5%).
The exact cause of the larger deviation for phase L3 has to be analysed in more detail. A quick scan of other measurement data did not reveal the perpetrator. All components are suspected and could induce this error, eg. a common earthing problem for the LPVT and LPCT or the VT and CT at phase L3. Or the phase L3 inputs of the Netcon 100 controller or the L+G equipment.
Next to that, we have a systematic error (larger spread of the differences) by the low resolution of the L+G data for all the three phases. Without the spread, the boundaries will be tighter and phase L3 might have met the criterion,

even with the suspected problem described above. The L+G equipment has higher internal resolution, so this can be resolved by changing settings.

The current measurements are compared with each other while the CT/L+G reference is assumed to be 0.2% accurate and the LPCT/Netcon uses a calibrated class 1 LPCT. The measurements show that our criterion of 0.28% is not met for all phases, with a large offset for phase L3. This issue with phase L3 has already been discussed and will be investigated. But also the fact that accuracy for all phases is not meeting the 0.28% criterion will be studied in more depth.

The energy measurements are a complex summation of all three phases. Therefore, the fact that phase L3 deviates significantly will directly affect the energy measurements. For reference, the mean difference for active energy is 0.43%. The reactive energy measurement with both instruments agrees less, due to the low values (around 2% $I_{nominal}$) and the method of assessment where only increments are evaluated. Higher accuracy is expected by taking the cumulative reactive energy as is commonly used for revenue purposes. The agreement of the apparent energy is slightly worse than the active energy, which is consistent with the discussion above.

CONCLUSIONS

The feasibility of using LPVTs and LPCTs for accurate revenue metering is demonstrated in the various experiments above. The LPVT according to the IEC 61869-11 is quite new and the LPVT of 3M was subjected to type testing, meeting class 0.2 performance.

In lab conditions this LPVT in combination with Netcon 100 achieved better than 0.2% accuracy. Once applied in the field and making a statistical comparison with conventional industrial metering, the LPVTs show good alignment for two phases but was off for the third phase. Therefore, at this moment, a final verdict cannot be given. The calibrated class 1 LPCTs do not match with the class 0.2s CTs in the field measurement to meet the goal of accurate revenue metering. The cause of this needs further investigation and is not *a priori* assigned to the LPCTs.

Overall, the LPVTs for the first two phases aligned so-well without on-site calibration, that we have great confidence that class 0.2 or class 0.2S revenue metering with low-power instrument transformers is within reach. In any case, the LPVT offer great advantages over the usage of the conventional VTs.

REFERENCES

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Phase	mean difference $\bar{d}$	Confidence Interval		standard deviation s	Limits of Agreement 95%		Confidence Interval	
		Min	Max				Min	Max
L1 [kV]	-0.0080	-0.0083	-0.0077	0.0038	Max	-0.0004	-0.0010	0.0002
					Min	-0.0156	-0.0162	-0.0150
relative	-0.13%	-0.14%	-0.13%	0.06%	Max	-0.01%	-0.02%	0.00%
					Min	-0.26%	-0.27%	-0.25%
L2 [kV]	-0.0094	-0.0097	-0.0091	0.0035	Max	-0.0024	-0.0030	-0.0018
					Min	-0.0164	-0.017	-0.0158
relative	-0.15%	-0.16%	-0.15%	0.06%	Max	-0.04%	-0.05%	-0.03%
					Min	-0.27%	-0.28%	-0.26%
L3 [kV]	-0.0132	-0.0137	-0.0127	0.0051	Max	-0.0030	-0.0038	-0.0022
					Min	-0.0234	-0.0242	-0.0226
relative	-0.22%	-0.23%	-0.21%	0.08%	Max	-0.05%	-0.06%	-0.04%
					Min	-0.38%	-0.40%	-0.37%

Table 1: Statistical properties of the 3 min RMS average voltage measurement data. n = 458; t value 1.9652, CI 95%.