Traceability of loss measurements of extra high voltage (EHV) three-phase shunt reactors

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Traceability of loss measurements of Extra High Voltage (EHV) three-phase shunt reactors

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***Abstract*—An overview of traceability issues of loss measurements of EHV 3-phase shunt reactors is presented. Loss measurements of a 345 kV - 55 MVAr three-phase shunt reactor at SMIT Transformers, including their uncertainties, are presented and discussed. The measurement results are confirmed with those obtained using a special HV inductance bridge.**

***Index Terms*—Extra high voltage, measurement uncertainty, shunt reactor, three phase, traceability.**

I. INTRODUCTION

For economic reasons, large high-voltage (HV) shunt reactors are designed to operate at very low power factors, typically 0.001 to 0.004. Accurate loss measurement at such low power factors is difficult because of the presence of the large quadrature component of current. The acceptable accuracy limits when measuring loss in HV shunt reactors are important to manufacturers and utilities since there is a penalty (at least $5 000/kilowatt} for every kilowatt of loss exceeding the guaranteed value. The excess penalty because of measurement error with 5 percent and 1 percent uncertainty, could amount to at least $50 000 and $100 000 respectively for a 0.001 power factor, 200 MVA shunt reactor. For a power measurement that is accurate to 1 percent of 0.001 power factor, a technique with an overall accuracy of (0.001 x 1} or 0.001 percent is required. It is therefore very important that the loss measurement system be properly calibrated to ensure that it meets its proper accuracy specifications and traceability to higher echelon standards requirements.

II. MEASUREMENT METHODS

High voltage power measurements at very low power factors can be done with either the wattmeter method or the bridge method.

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In the wattmeter method, it requires accurate settings of the test voltage or current, including their accurate measurements which determine the overall uncertainty of the power loss measurements. This can be seen from the following equation:

$$W = VI\cos\varphi = V^2(\sin\delta)/Z \approx V^2(\tan\delta)/Z \qquad (1)$$

where W, V, I, cosφ, and tanδ, are the power loss, test voltage, current, power factor, and loss tangent, respectively, and $\varphi = (90^0 - \delta)$. For small loss angles $\sin\delta \approx \tan\delta$. Alternatively (1) can also be written as

$$W = I^2Z\sin\delta \approx I^2Z\tan\delta \qquad (2)$$

Therefore, from (1) and (2) the power loss measurement accuracy is determined by the accurate setting of the test voltage V or current I, including accurate measurements of the corresponding test voltage V or current I, and of course the wattmeter accuracy. For an EHV shunt reactor with a power factor of 0.001, depending on the accuracy of the voltage/current/power measurements, the wattmeter method could possibly achieve an uncertainty/accuracy of about 10% to 20% for its power loss measurements. However, the wattmeter loss measurement system could be calibrated by calibrating the main components or by calibrating the overall system using a "portable" load loss standard of the National Research Council of Canada [1]. The system errors could then be accounted for, improving the overall accuracy of the loss measurements to about 5%, or better, at a power factor of 0.001.

In the bridge method, a high voltage current-comparator-based capacitance bridge with a two-stage current transformer can be used to measure the inductance and loss angle of shunt reactors [2]. The features of the bridge that make this possible are the ability to reverse the phase of the reactor current and to measure what is essentially a negative phase angle. With the current-comparator-based high voltage capacitance bridge having ratio errors of less than 10×10^{-6} in both magnitude and phase, an uncertainty of less than 1% could be achieved for power loss measurements of a shunt reactor at a power factor of 0.001 [2].

Although the current-comparator-based high-voltage capacitance bridge is a highly accurate bridge, under certain test conditions its measurement results could be erroneous. The essentially loss-less compressed-gas-dielectric capacitor offers the best available standard for comparison, the comparison of an inductive current with a capacitive reference however results in a bridge, which is frequency sensitive. Depending on how low the load power factor is, this could present a problem if the test-voltage frequency fluctuates.

Another problem is that the harmonic content of the inductive current is not the same as that of the capacitive reference. This will result in residual harmonic voltages at the detector, which in turn could result in differences in the balance point depending on whether tuned or gated detectors are used. If the residual harmonic voltages are of significant magnitudes, due to a large harmonic content in either the inductive or reference capacitive current, the detector may no longer operate properly due to overload conditions or it may even be damaged.

A special current-comparator-based high-voltage inductance bridge was developed at the National Research Council of Canada to address this issue [3]. An inductive instead of a capacitive reference is used as described in [2]. Such a bridge would be a true inductance bridge and both problems of frequency variations and harmonics of the test voltage would be alleviated. This can be achieved by using a current proportional to the integral of a reduced replica of the applied high voltage as reference. The frequency characteristics of such a current are similar to those of an inductive current.

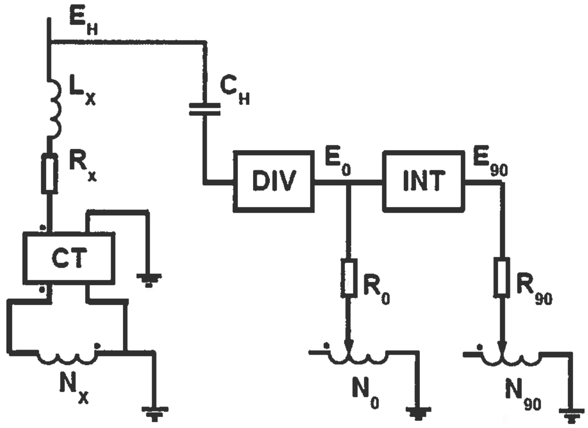

Fig. 1

Fig. 1 shows a simplified circuit of the current-comparator-based high-voltage inductance bridge with a current range extender two-stage current transformer connected in series with the shunt reactor. The reduced replica of the applied high voltage E_0 to be integrated is obtained from the current-comparator-based high-voltage divider DIV. The output E_{90} of the unity-gain current-comparator-based integrator INT drives a reference resistor R_{90} which is used as a voltage-to-current converter to provide the inductive reference current to the bridge. This inductive reference current in turn drives the N_{90} winding to provide an ampere-turn balance of the inductive current L_X of the reactor in the current comparator. The reference current derived from the output voltage E_0 through the reference resistor R_0 drives the N_0 winding to provide an ampere-turn balance of the loss current R_X of the shunt reactor in the current comparator. A current comparator is used in DIV and INT in a feedback loop to correct the magnitude and phase of their corresponding outputs to an uncertainty of less than 10 x 10^{-6} and 10 μrad, respectively [4].

From the bridge ampere-turn balance equation, it can be shown that

$$\tan\delta = (C_H/C_f)(\text{Div.Gain} \times N_{CT}/R_0)(N_0\ \text{Reading}) \quad (4)$$

$$\omega L_X = (C_f/C_H)(R_{90}/N_{CT})\,(1/(\text{Div.Gain})(1/N_{90}\ \text{Reading}) \quad (5)$$

where C_f is the equivalent low voltage feedback capacitor of the current comparator active voltage divider DIV, which is equal to 265200 pF, N_{CT} is the current ratio of the current range extender two-stage current transformer CT, and N_0 and N_{90} are the bridge balance readings of the in-phase and quarature components, respectively. Since $R_X = \omega L_X \tan\delta$, the inductance L_X or the impedance of the shunt reactor $Z_X = \sqrt{(R_X^2 + (\omega L_X)^2)}$ can be calculated. Therefore, the power loss of the shunt reactor P_{Lx} can be obtained from either (1) or (2). Since E_H can be accurately obtained from the measurements of the output voltage of the current-comparator-based active voltage divider DIV using a known/calibrated voltmeter, equation (1) is used to obtain P_{Lx}.

Thus the power loss of the shunt reactor is calculated from

$$P_{Lx} = E_H^2\,(\tan\delta)/Z_X \quad (6)$$

The current-comparator-based inductance bridge is used to provide verifications and traceability of loss measurements of an EHV three-phase shunt reactor rated 55 MVAr - 345 kV, as explained in the following sections.

III. Three-Phase Shunt Reactors

The measurement of loss in EHV three-phase shunt reactors, depending on their construction design, could pose additional problems because of the inaccessibility of phase currents at the neutral or low voltage end of the windings. Special input current transformers, insulated to withstand the circuit impedance voltage at the high-voltage end of the windings, must be provided. In certain countries, EHV three-phase shunt reactors are designed to have the low voltage end of the windings outside the oil tank. This means that the input current transformers could be connected at the low voltage end of the windings, allowing the use of the more accurate HV current-comparator-based bridge measurement method for the loss measurements. This is the case for the three-phase shunt reactor-under-test that is discussed in the next paragraph.

In a three-phase loss measurement system that is used for loss measurements of power transformers, when properly calibrated to ensure that it could provide an appropriate accurate loss measurements at very low power factors, could also be used for loss measurements of high voltage three-phase shunt reactors. At the SMIT Transformers high voltage test laboratory, its loss measurement system is an advanced measurement system, a computer-controlled system designed to measure three-phase voltage (line-to-ground) from 100 V up 100 kV and current from 2 A up to 4000 A. Its current measurement in each phase is made using oil-filled electronically-aided current transformers of 125 kV insulation class. Thus, in order to be able to do loss measurements of EHV three-phase shunt reactors with rated system voltages of 345 kV (200 kV line-to-ground) and higher, a step-up power transformer rated 500 MVA 400/150/50 kV is used for a loss measurements of a 55 MVAr - 345 kV three-phase shunt reactors, as shown in Fig. 2. In Fig. 2, the step-up power transformer SUT provides the means to have the losses of the 345 kV 3-phase shunt reactor to be measured at the proper rated voltage of 345 kV line-to-line voltage.

The process of loss measurements of the 345 kV three-phase shunt reactor is as follows. Before connecting the EHV three-phase shunt reactor HVSR to the step-up transformer SUT, the load and no-load losses of SUT have to be measured first. They are measured using the 3-phase transformer loss measuring system, which has already been calibrated system-wise [4], by short circuiting and open circuiting the output terminals of SUT, respectively. Taking into account the errors of the 3-phase transformer loss measurement system, the overall errors of the 3-phase SUT would be known and could be accounted for, when measuring the losses of the three-phase shunt reactor. Also, the loss measurements results are compared to those obtained using the special current-comparator-based high-voltage inductance bridge [3], as previously explained in Section II.

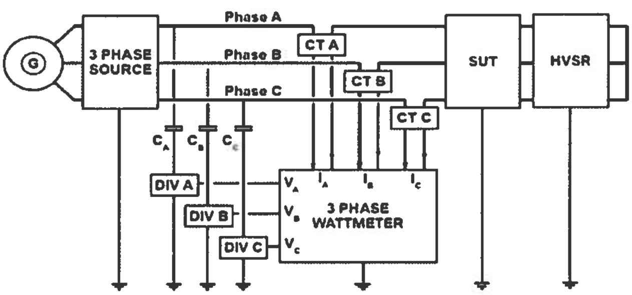

Figure 1. SMIT Loss Measurement System

IV. LOSS MEASUREMENTS ON 55 MVAR – 345 KV 3-PHASE SHUNT REACTOR

As shown in Fig. 1, the EHV three-phase shunt reactor HVSR is measured with all three phases energized from a three-phase source through the step-up transformer SUT. Each phase however is measured individually to allow measurements using the current-comparator-based high voltage inductance bridge with brief shut-downs to permit transfer of the equipment. Three two-stage current transformers, one for each phase, are used since their changeover involves heavy conductors and is rather cumbersome. With three high voltage reference capacitors and suitable switching the shut-downs could of course be eliminated.

The current range extenders two-stage current transformers are connected at the low voltage end of the windings of three-phase shunt reactor. The high-voltage reference capacitor is connected directly to the high voltage bushing of the shunt reactor.

The parameters of the shunt reactor per phase, as measured by the current-comparator-based inductance bridge, can be obtained from the balance equations of the bridge using (4) and (5). The power loss of the shunt reactor per phase can then be calculated for a test voltage E_H as per (6). Operation of the bridge consists of balancing the inductive and the loss tangent components of the shunt reactor impedance by adjusting the N_{90} winding and the N_0 winding, respectively.

Although the performance of the inductance bridge has been verified at high voltage up to 380 kV to have an uncertainty in magnitude and phase of less than 10×10^{-6} and 10 μrad, respectively [2,3], the performance of the inductance bridge has been verified again at a low voltage of 600 V prior to being used to measure the losses of the 345 kV three-phase shunt reactor by comparing/calibrating it with an improved power standard derived from a current comparator power bridge for calibrating active/reactive power and energy meters under sinusoidal conditions at any power factor from zero lag through unity to zero lead, at positive or negative power, at current and voltage ranges up to 200 A and 1200 V, respectively, and 50 or 60 Hz. The improved power standard has an estimated uncertainty of not more than 2.5 μW/VA at $k = 1$ [5]. The comparison/calibration was done at zero and unity power factor to verify again that the bridge magnitude and phase uncertainty is less than 10×10^{-6} and 10 μrad at $k=2$, respectively.

If the variation of the reactance and loss angle with voltage or current is not too large, accurate setting of voltage or current is not required. The actual voltage applied to the bridge during the measurements can be obtained by measuring the output voltage of the output of the current-comparator-based active voltage divider DIV using a known calibrated voltmeter with an uncertainty of less than 50×10^{-6}.

An important consideration in the measurement of three phase shunt reactors is the location of system grounds. Preferably only one ground should be present and that should be at the neutral of the shunt reactor under test. Otherwise significant zero sequence voltages or currents may be present which will cause large deviations in the apparent power factor of the three different phase thereby reducing the accuracy attainable with the bridge.

V. MEASUREMENT RESULTS

As explain in Section III, before connecting the EHV three-phase shunt reactor HVSR to the step-up transformer SUT, the load and no-load losses of SUT have to be measured first. During the load loss measurement of SUT, its high voltage winding is shorted and the low voltage winding is energized, while for no-load loss measurements its high voltage winding is open circuited.

Since the SMIT loss measurement system can only measure test voltages up to 100 kV line-to-ground, while the output voltage of SUT would be up to at least 200 kV line-to-ground (345 kV line-to-line) when used to drive the 3-phase 345 kV shunt reactor, the no-load losses of the SUT were measured/characterized to provide a complete no-load losses curve from 0.5 kV up to 55 kV to allow extrapolation when it is used with test voltages up to 200 kV line-to-ground. The best fit curve is used for proper extrapolation of the no-load losses of the SUT up to 200 kV line-to-ground.

During the actual loss measurements of the 3-phase shunt reactor using the SMIT loss measurement system in conjunction with the inductance bridge, each phase was measured twice since the inductance bridge can only measure per phase losses. The phase test high voltage was set by using the voltage measurements of the output of the voltage divider DIV using a known/calibrated digital voltmeter.

Therefore, the SMIT loss measurement system also measures not only the corresponding phase losses of the 3-phase shunt reactor, including the losses of the step-up transformer SUT, but also measures the total 3-phase losses of the shunt reactor SR, including that of SUT, denoted as P_{SUT+SR} and P_{SR}, respectively.

The total loss measurements of P_{SUT+SR} = 287.2 kW was done at 24.87 kV, 797.3 A, resulting in a test power factor (PF) of 0.0048. The no-load loss SUT was measured by interpolation between 2 measurements: (a) 23.15 kV, 1.973 A, 68.93 kW; (b) 24.57 kV, 2.069 A, 77.96 kW), resulting in 77.49 kW with an approximate PF of 0.5. The load loss of SUT was measured at 2.049 kV, 797.3 A resulting in 40.51 kW with a test PF of 0.0083. Therefore, the total no-load plus load losses of SUT is (77.49 + 40.51) = 118.0 kW

Table 1 shows a summary of the measurement results of the impedance of the shunt reactor SR and power losses using the inductance bridge and the SMIT loss measurement system.

The load loss measurements of SUT at 2.049 kV and a load current of 797.3 A was too ensure that the SUT is operating at the same nominal load current when the SR is connected to SUT and the SR is operating at the proper 55 MVAr rating,, 345 kV, 92 A.

As can be seen from Table 1, the agreement of the SR impedance measured by the inductance bridge and the SMIT loss measurement system is within 0.1%. This indicates that the voltage and current settings of 24.87 kV and 797.3 A to measure the SR losses using SUT is appropriately confirmed by the inductance bridge.

VI. Discussions and Uncertainties

The step-up transformer SUT is used to supply the reactor. The total losses measured on the supply side of the step-up transformer include the losses of the transformer too. The no-load and load losses have been measured before the test at the corresponding voltage and current used during the reactor test. The total measured losses of the reactor SR are corrected for these losses. The total loss measurements of P_{SUT+SR} = 287.2 kW was done at 24.87 kV, 797.3 A, resulting in a test power factor (PF) of 0.0048. From [6] it was found that at this test point the SMIT measurement system reads

Table 1

Phase	Impedance		Losses	
	Bridge	SMIT	Bridge	SMIT
	Ω	Ω	kW/Ph	P_{SR} kW
A	2172	2166	72.47	168.6
B	2163	2166	56.76	170.1
C	2169	2167	44.98	168.9
Z_{AVE}	2168	2166	P_{BR} = 174.21	P_{AVE} = 169.2

high by 0.2%. For the load and no load with their corresponding estimated power factor, there are no corrections required as per [5]. Thus, the corrected value of P_{SUT+SR} is (0.998 x 287.2) = 286.6 kW, providing a difference of 0.6 kW than the previous measured value. This in turn means that the corrected measured average value of the shunt reactor P_{SR} shown in Table 1 is now (169.2 + 0.6) = 169.8 kW.

It is known from [7] that in step-up operation using SUT, the flux density in the core leg will not change much, but the flux density in the core yoke will be lower due to the leakage flux. The leakage flux from the windings enters the core yokes and due to the phase relation this leakage flux is in opposite phase with the flux in the yoke, decreasing the flux density in the yoke. This lower flux density will give lower losses in the yoke. The losses from the reactor measurement are corrected with the total no-load losses of the core of the step-up transformer, but as these losses are lower in the yoke when the unit is loaded, this correction is too much.

This effect has been calculated using a simple leakage flux model. The flux in the core leg of the step-up transformer during the reactor measurement is 1.435 T. The no-load losses of the step-up unit measured at this flux density are 77.49 kW. During step-up operation the flux density in the core leg will not change much, but in the yoke the flux density will be lower due to the leakage flux entering the yoke. The leakage flux entering the yoke has been calculated with a leakage flux model and this leakage flux changes the flux density in the yoke by 0.069 T, so the resultant flux density in the yoke will be 1.366 T. The no-load losses for the step-up transformer measured at this flux density are 70.00 kW. As the core leg has a flux density of 1.435 T but the yoke has 1.366 T, the losses for these parts of the core are different. Assuming a uniform loss distribution in the core the amount of the yoke and of the legs both can be estimated based on magnetic length. The total magnetic length of the yokes in this step-up transformer is 10.024 meters and in the legs 13.749 meters. Based on these magnetic lengths the yoke is 42.2% of the total core. The total core losses during the reactor measurement then become 42.2% * 70.00 + 57.8% * 77.49 = 74.33 kW. In this way it is found the core losses will be lower then used in the correction by an amount of approximate 3.2 kW, denoted as (P_{FLUX}) .

In this calculation it is assumed the losses are distributed uniformly in the core. As in practice the losses will be higher in the corners where the single sheets have their joints, the real losses are higher in these joints and lower in the other parts of the core. On the other hand, the leakage flux entering the core will enter perpendicular to the rolling direction of the core steel and this will locally increase the losses. Both these effects are very complicated to analyze and it is therefore difficult to give accurate estimates for losses in this specific loaded case. The value mentioned should therefore be considered as having a rather large estimated uncertainty of about ± 0.5 kW for the purpose of using it as a correction term and to explain the cause of the difference between the two measurement methods. Therefore, the corrected average measured power loss of the shunt reactor P_{SR} = 169.8 kW will now be (169.8 + 3.2) = 173.0 kW.

Since the SMIT loss measurement system has an estimated uncertainty of 0.5% of reading (*k=2)*, then the uncertainty of the P_{SR} = 173.0 kW, which is derived from (P_{SUT+SR} – P_{SUT} + P_{FLUX}) is ± ((286.6 x 0.005) ± (118 x 0.005) ± 0.5)) kW = ± 2.5 kW. Thus, the uncertainty of P_{SR} = 173.0 kW is estimated to be about ((2.5/173.0) x 100%) = 1.4 % at (*k=2*).

The uncertainty of the inductance bridge as previously mentioned in Section IV is estimated to be less than 10 x 10^{-6} and 10 µrad at *k=2* in magnitude and phase, respectively. The high voltage reference capacitor is a SMIT 50 pF low loss gas dielectric reference capacitor rated at 500 kV with a negligible voltage dependency up to at least 200 kV with an uncertainty of less than 10 x 10^{-6} and 10 µrad in magnitude and phase, respectively. The bridge two-stage current transformer current range extender has a magnitude and phase uncertainty of 5 x 10^{-6} and 5 µrad, respectively. Thus, the inductance bridge has an estimated overall root-sum-square uncertainty (*k=2*) of 15 x 10^{-6} and 15 µrad in magnitude and phase, respectively.

The results of the total power loss measurement of the 3-phase shunt reactor using the inductance bridge is P_{BR} = 174.2 kW, as shown in Table I, with a test PF of 0.003173. Therefore, a phase uncertainty of 15 µrad in the inductance bridge results in an estimated uncertainty of 0.5% (*k=2)*. Thus, the agreement between the power loss measurements using the inductance bridge and the SMIT transformer loss measurement system is ((174.2-173.0)/174.2) x 100% = 0.7 %, well within the combine uncertainties of the two loss measurement systems of the NRC inductance bridge and that of SMIT

IV. CONCLUSION

The application of the NRC inductance bridge to verifying the losses of the 3-phase shunt reactor that was simultaneously measured using the SMIT loss measurement system has been described, thereby also providing the proper traceability of the loss measurement of the shunt reactor. The agreement between the two loss measurement systems was well within the measurement uncertainties of the two systems.

REFERENCES

[1] E. So, P.M. Miljanic, and D.J. Angelo, "A computer-controlled load loss standard for calibrating high-voltage power measurement systems," *IEEE Trans. Instrum. Meas.*, vol. 44, no. 2, pp. 425 – 428, April 1995.

[2] E. So, "A microprocessor-controlled high-voltage current-comparator-based capacitance bridge," *IEEE Trans. on Power Delivery*, Vol. 5, No.2, pp. 533 – 537, April1990.

[3] E. So, "A current-comparator-based high-voltage inductance bridge," CPEM 2008 Conf. Digest, pp. 710-711, June 2008.

[4] E. So, "The application of the current comparator in instrumentation for high voltage power measurements at very low power factors," *IEEE Trans. Power Delivery, vol. PWRD-1*, no. 1, pp. 98-104, January 1986.

[5] E. So, R. Arseneau, and D. Angelo, "An Improved Current-Comparator-Based Power Standard With an Uncertainty of 2.5 µW/VA (k = 1)," *IEEE Trans. Instrum.Meas.*, vol. 62, no.6, pp. 1704-1709, June 2013.

[6] E. So, "In-situ calibration of transformer loss measuring system 1 for SMIT Transformers, Nijmegen, The Netherlands," NRC Calibration Report Number EPM- 2012-0029-01, June 26, 2013.

[7] A.K. Bose, C. Kroon and J. Wildeboer, "The loading of the magnetic circuit," *CIGRE International Conference on Large High Voltage Electric Systems*, Paper 12-09, August 30 – September 7, 1978 Session.

BIOGRAPHY

Eddy So (M'74–SM'84–F'90) received the M.Sc. and D.Sc. degrees in electrical engineering from The George Washington University, Washington, DC, USA. In 1977, he joined the National Research Council (NRC) of Canada, Ottawa, ON, Canada. In 1979–1989, he was an Adjunct Professor with the University of Ottawa, Ottawa, and Carleton University, Ottawa. In 1991–2004, he was the Director of the Electromagnetic and Temperature Standards Section, Institute for National Measurement Standards, NRC of Canada, where he is currently a Principal Research Officer with the Electrical Power Measurements Group, Measurement Science and Standards Portfolio.

His research interest includes the development of measurement techniques and instrumentation for accurate measurements of high-voltage active/reactive power and energy under difficult operating conditions. Dr. So is a Registered Professional Engineer in the Province of Ontario. He was the Past Chair of the Power System Instrumentation and Measurements Technical Committee of the IEEE Power Engineering Society (now the IEEE Power and Energy Society) and is the Chair of its Electricity Metering Subcommittee, the Chair of its Working Group on Low-Power-Factor Power Measurements, and its Standards Coordinator. In 2002–2008, he was the Chair of the IEEE Conference on Precision Electromagnetic Measurements Executive Committee.

Rob Verhoeven was born in the Netherlands in 1974. He received his M.Sc Degree in Electrical engineering from Eindhoven Technical University in 2000. He started in 2000 at SMIT Transformers as Design Engineer and was involved in transformer and reactor design and development. In 2005 and 2006 he worked for a Grid owner in Belgium and as a Consultant at KEMA. At the end of 2006 he returned to SMIT as the Manager of the test department and since 2008 a member of the management team of SMIT Transformers. In 2003-2006 he was a member of the IEC working group TC14-

60076-6 MT3 on reactors and in 2010-2013 a member of the IEC working group TC14-60076-3 MT3 on Insulation levels, dielectric tests and external clearances in air.

Luc Dorpmanns was born in the Netherlands in 1975. He received his M.Sc Degree in Electrical engineering from Eindhoven Technical University in 1998. After working 3 years with a local high voltage grid operator he joined SMIT Transformers in 2001 as Design Engineer and was involved in transformer design, modeling and development. In 2007 he worked for 2 years in R&D of electrical motors at another company before returning to SMIT Transformers in 2009. Since then he is working as Technical Specialist Testing in SMIT Testing laboratory. He is involved in development of measurement and testing techniques for high voltage transformers, phase shifters and reactors up to 800 kV as well as investments for test bay extensions. He is a member of the Dutch National Standards Committee For High Voltage bushings and currently member of Cigre Working group A2.48 on shunt reactors.

Dave Angelo was born in Trenton, ON, Canada, in 1959. He received the Diploma degree in electrical engineering from Loyalist College, Belleville, ON, in 1980. In 1980, he joined the National Research Council of Canada, Ottawa, ON, where he is a Technical Officer with the Electrical Power Measurements Group, Measurement Science and Standards Portfolio. Since 1982, he has worked in precision ac power measurements.