Resistively Shielded Optical Voltage Transducer

Farnoosh Rahmatian, Member, IEEE
NxtPhase Corporation
Vancouver, BC, Canada

Patrick P. Chavez, and
Nicolas A. F. Jaeger, Member, IEEE
University of British Columbia
Vancouver, BC, Canada

Abstract: A high-voltage (HV) optical voltage transducer (OVT) using resistively shielded electric field sensors is presented for use in HV transmission systems. The OVT is built in a hollow-core polymer insulator filled with low-pressure dry nitrogen gas. A 138 kV prototype has been tested for accuracy under various severe dynamic field disturbances including salt-clay pollution (clean fog test) and melting ice on the insulator. The test results show that the OVT meets ANSI/IEEE 0.3% accuracy classes under these extreme field disturbances. The prototype has also been tested and successfully passed various HV dielectric tests including lightning impulse tests (BIL) at ±650 kV, chopped impulse tests at –750 kV, power frequency withstand at 275 kV, and partial discharge < 5 pC.

Keywords: Electric fields, electric field measurement, electric field effects, Gaussian quadrature, high-voltage techniques, ice, optics, pollution, transducers, voltage measurement

I. INTRODUCTION

In recent years, fueled by deregulation, the need for high-precision measurement of high-voltage (HV) electric power has resulted in significant investment in new HV voltage and current measuring systems. Optical instrument transformers, specifically, have received significant attention due to their advantages over conventional instrument transformers at transmission voltages. These advantages include linear performance, wider dynamic range, safer insulation, lighter weight, smaller footprint, easier and cheaper installation, elimination of magnetic saturation and ferroresonance, and compatibility with digital secondary devices (meters, relays, and SCADA systems).

Optical current transducers (OCTs) typically use optical fibers to interrogate an optical current sensor in the HV environment and hence provide excellent galvanic isolation between high voltage and ground. Neither oil nor SF_6 is used in their insulation systems. Optical voltage transducers (OVTs), on the other hand, typically bring high-voltage and ground potentials in close proximity and hence need SF_6 or other complicated insulation [1] - [6]. The OVT presented in this paper is designed to avoid the need for complicated and environmentally hazardous insulation. It uses multiple miniature optical electric field sensors in a resistive, field-grading, shield to measure voltage. Its novel design (see [7] and [8]) results in accurate measurement of voltage while HV and ground conductors are kept far apart, making the insulation system simple and safe. For insulation, it uses a hollow-core composite insulator filled with low-pressure dry nitrogen. The OVT prototype reported upon here was designed to demonstrate 0.3% revenue metering accuracy while benefiting from a safer insulation system. In the following sections, the design of the OVT is described, and test results for accuracy under various severe field disturbances are presented.

II. OVT DESIGN

The prototype is a 138kV transmission class OVT. It uses three 20-mm long optical electric field sensors (EFSs), strategically positioned (see [7]) inside a hollow cylindrical resistor across which the voltage is to be measured. The resistor itself is mounted inside a HV composite insulator, see Fig. 1. The insulator is 1.525 m in length, and the three optical sensors are located at 1.232 m, 0.748 m, and 0.260 m above the base of the insulator. The resistive shield represents ~ 90 MΩ of resistance, which results in less than 1mA of current at the rated voltage (80.5 kV line-to-ground). The electronics associated with the OVT provides both analog (16-bit) and digital (4 V rms at rated voltage) outputs. The insulator is filled with dry nitrogen at ~ 16 PSI. The optical sensors are connected to the electronics chassis using a multi-strand fiber-optic cable. In the electronics module, the voltage, V, is calculated using

$$V = -\int_0^b E_x(x)dx \approx -\sum_{i=1}^{N} \alpha_i E_x(x_i) \,, \qquad (1)$$

where $N = 3$ is the number of EFSs, $E_x(x_i)$ is effectively the vertical component of electric field measured at the location of each sensor (x_i) and α_i is an appropriate weight factor determined using the quadrature method, see [7]. In this prototype $\alpha_1 \approx \alpha_2 \approx \alpha_3 \approx 1$. The digital data is provided at a high speed, giving a rated time delay of only ~50 µs for the OVT.

Fig. 1. A 138kV Optical VT inside a fog test chamber (before applying pollution).

III. TEST RESULTS

Achieving high accuracy measurement of voltage in a three-phase environment using miniature electric field sensors is not trivial. There are many sources of electric field disturbance that, if not properly accounted for, can erroneously affect the accuracy of voltage measurement. The OVT uses resistive shielding to moderate and limit these "external" field disturbances and uses a distributed electric field sensor system, through a quadrature method (see [7] - [10] for more detail), to eliminate voltage error. Various sources of practical field perturbation exist in an HV substation. These range from the ever present neighboring phase structures and voltages to nearby service trucks and varying climatic conditions, including fog, snow, ice, and pollution.

It has previously been shown that proper use of a few (e.g., three) electric field sensors in a quadrature method can give highly accurate measurement of voltage in the presence of sources of low order electric field disturbance, see for example [7], [9], and [10]. These include the presence of nearby (within the allowable safety guidelines) voltage sources, ground planes, large metallic objects, and trucks. In such cases, electric field variation distribution is a relatively smooth function and there is no need for additional electric field shielding. However, in the presence of sources of localized intense electric field disturbance the distribution is not smooth and either a large number of EFSs or additional electric field shielding is required in order to maintain accuracy. Such sources of localized, intense, and often dynamic field distribution changes include wet pollution, rain, melting frost, ice, or snow on the insulator. The OVT presented here uses a high-resistance cylindrical shield to moderate and smooth the perturbations caused by sources of electric field disturbance such that the application of the quadrature method using only three electric field sensors results in an accurate voltage measurement. Various tests representing extreme electric field disturbance conditions were performed to demonstrate the effectiveness of the design and the immunity of the OVT to all practical perturbations.

The prototype under test was designed to be a revenue metering class 138 kV OVT meeting ANSI/IEEE C57.13 0.3% accuracy class [11]. To demonstrate HV dielectric withstand capability, it was tested in the HV laboratory at Powertech Labs, Surrey, British Columbia, Canada. It successfully passed the power frequency withstand test, at 275 kV, partial discharge tests (< 5 pC), lightning impulse tests, at 650 kV (15 shots each polarity), and chopped lightning impulse tests, at –750 kV (3 shots), as specified in IEC 60044-2 [12]. Table 1 contains the results of the partial discharge tests.

Table 1. Partial discharge tests on a 138kV OVT prototype.

Voltage (kV)	Partial Discharge (pC)	Requirement per IEC 60044-2
80.5 (rated voltage)	< 1	< 5 pC
89	0.4	< 5 pC
97	0.4	< 5 pC
138	0.5	<10 pC
161	0.5	NA
220	8.3	NA
161	3.2 – 5	NA
138	2.4	<10 pC
97	0.5	< 5 pC
89	0.5	< 5 pC
80.5	0.5	< 5 pC

The OVT was also tested for accuracy (linearity) and met the requirements of IEC 0.1% and IEEE 0.3% revenue metering classes (see [11] and [13]). Table 2 provides the results of accuracy measurements. Please note that the accuracy of the measurements (i.e., test equipment) was ~ 0.05% and 0.05°.

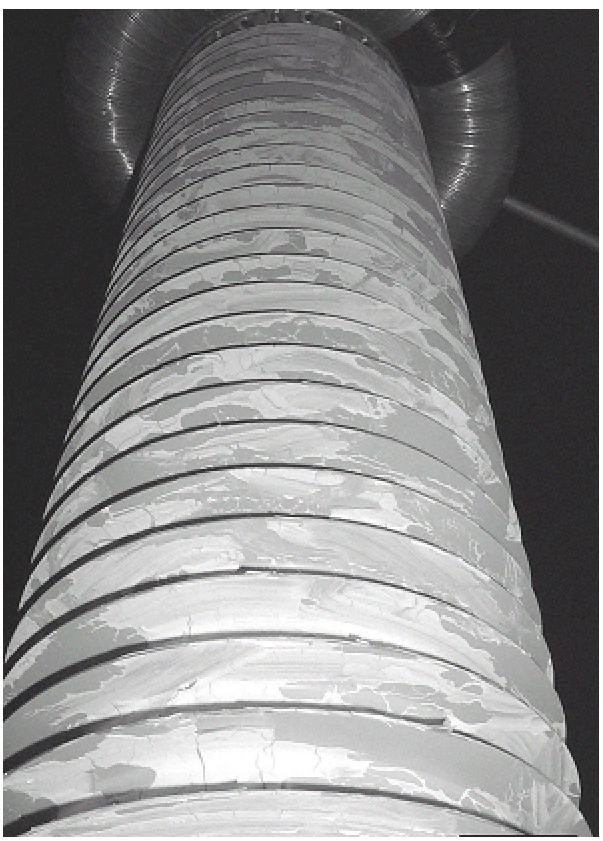
Table 2. Accuracy tests on a 138kV OVT prototype.

Voltage (kV)	Ratio error (%)	Phase error per IEC 60044-7
80.5 (rated voltage)	-0.01	4.8'
64	-0.01	4.8'
80.5	0.00	4.8'
97	0.01	4.8'
80.5	-0.01	4.8'

64	-0.02	4.2’
120	0.01	4.8’

The OVT was next put in a fog chamber and energized to rated voltage, 80.5 kV in presence of fog. It maintained its accuracy within IEC 0.1% and IEEE 0.3% revenue metering classes. After this test, the insulator’s silicone sheds were washed with iso-propanol to remove the silicone’s hydrophobicity. Then a mixture of water, salt, and clay (Kaolin) was painted on the silicone sheds to simulate a heavily polluted insulator, see Fig. 2. The OVT was then tested under clean fog for accuracy. The results are given in Table 3.

(a)



(b)

Fig. 2. OVT under heavy pollution in a fog chamber; a) wet, b) dry.

Table 3. Accuracy tests on a heavily polluted 138kV OVT prototype.

Voltage (kV)	Time fog on (minutes)	Ratio error (%)	Phase error
80.5	0	-0.11	-6.6’
80.5	5	-0.11	-6.0’
80.5	10	-0.09	-5.4’
80.5	15	-0.04	-4.2’
80.5	20	-0.02	-3.0’
80.5	30	-0.02	-1.2’
80.5	40	-0.02	0’
80.5	50	-0.04	0.6’
80.5	60	-0.04	1.2’
80.5	70	-0.05	1.2’
80.5	80	-0.07	1.2’
80.5	86	-0.09	1.2’

These results indicate that, even under pollution and deliberately destroyed hydrophobic properties of the silicone sheds, the prototype met IEC 0.2% and IEEE 0.3% accuracy class requirements.

Electric field disturbances due to melting ice on a polluted insulator are, arguably, the most severe field perturbations that may appear in a substation. To simulate this condition, the OVT was rinsed with water (some pollution still remaining on the insulators and the hydrophobicity of the silicone sheds still absent) and placed inside an environmental chamber. Then temperature was reduced to ~ -20°C overnight. The morning after, the insulator was covered by ice during a 3-hour process by spraying the insulator with freezing tap water (one layer sprayed and built every 10-15 minutes). Fig. 3 shows the insulator covered with ice. Next the chamber temperature was increased to above zero, allowing the ice to melt over a 3-hour period. Fig. 4 shows the OVT when the ice is partially melted, and Fig. 5 shows the OVT at the end of the test.

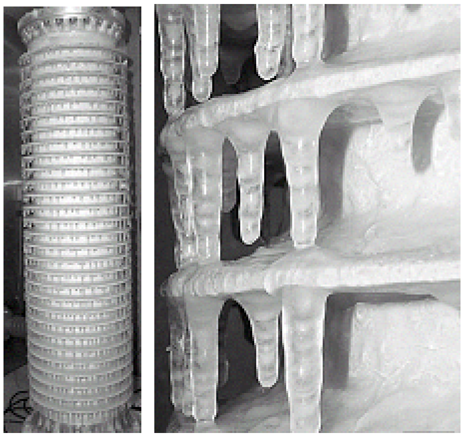


Fig. 3. OVT covered with ice at -18°C.

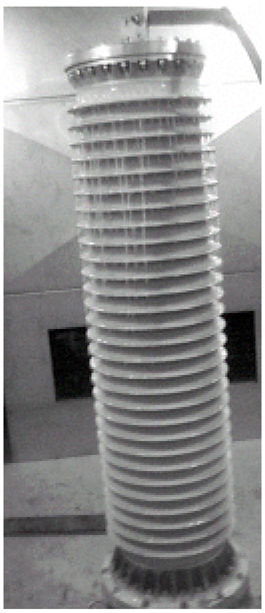
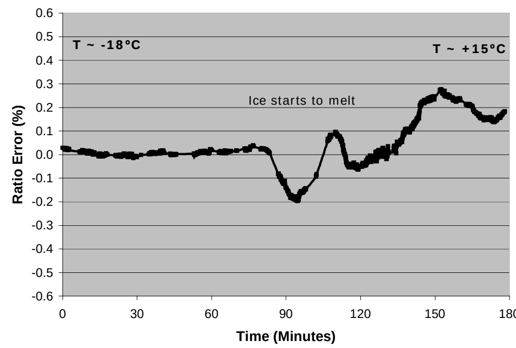


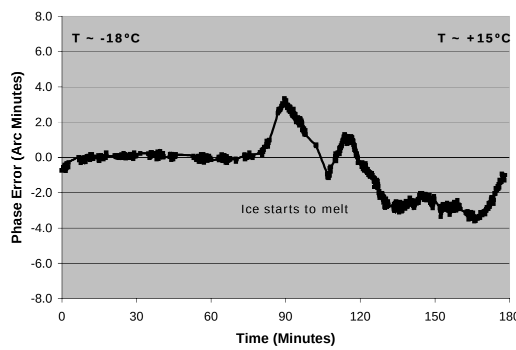
Fig. 4. Ice partially melted on the OVT. Chamber temperature ~ 8°C.

Fig. 5. OVT at the end of the ice test. Chamber temperature ~ 15°C.

Fig. 6 shows the results of the test as a function of time. Due to a lack of availability of a temperature- and condensation-compliant HV bushing for the environmental chamber, only ~ 30 kV was applied to the OVT during this test. In fact, this lower voltage represents a worse scenario (as concerns the accuracy of the OVT) as compared to energization at the rated voltage — lower voltage allows for the formation of smaller drybands and therefore relatively more severe localized field disturbances. As shown in Fig. 6, the OVT meets the 0.3% accuracy requirements that it was designed for. It should be noted that field disturbances at the location of the optical electric field sensors are significantly moderated, but not eliminated, through the use of the resistive shield. The individual sensors will sense a significantly large electric field perturbation, see Fig. 7, but the quadrature method (1) eliminates the impact of these field variations on the voltage measurements, see Fig. 6.

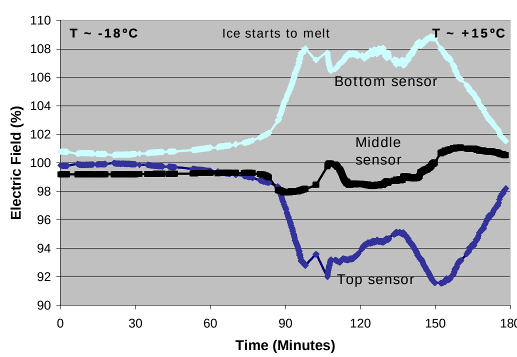


(a)

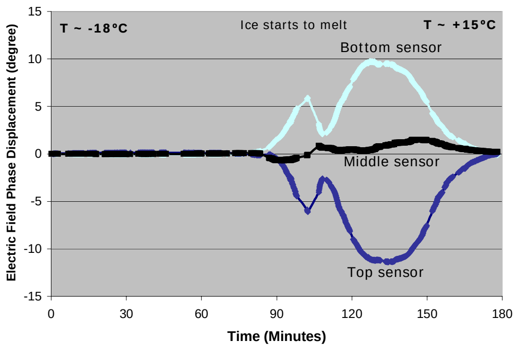


(b)

Fig. 6. Accuracy of OVT under melting ice: a) ratio error, b) phase error.



(a)



(b)

Fig. 7. Measurements of EFSs under melting ice: a) ratio, b) phase displacement.

IV. CONCLUSIONS

The novel optical voltage transducer presented here demonstrates excellent linearity and accuracy suitable for stringent revenue metering applications. It maintains its high accuracy even in the presence of sources of extreme field perturbations, such as pollution and melting ice, while offering a safe, environmentally friendly, insulation system. It provides all the advantages of optical technology including wide bandwidth and galvanic isolation of high voltage and ground conductors. Due to its novel design, the OVT, combined with a compact OCT, allows for a single-column SF_6-free optical power metering system suitable for revenue metering and protection applications in HV power transmission systems.

V. ACKNOWLEDGEMENTS

This work was funded with the aid of the BC Advanced Systems Institute and the Natural Sciences and Engineering Research Council of Canada.

VI. REFERENCES

[1] T. Sawa, K. Kurosawa, T. Kaminishi, and T. Yokota, “Development of optical instrument transformers,” *IEEE Transactions on Power Delivery*, vol. 5, no. 2, April 1990, pp. 884-891.

[2] L. H. Christensen, “Design, construction, and test of a passive optical prototype high voltage instrument transformer,” *IEEE Transactions on Power Delivery*, vol. 10, no. 3, July 1995, pp. 1332-1337.

[3] S. Weikel and G. Stranovsky, “Application of an electro optic voltage transducer at 345 kV,” EPRI Optical Sensors for Utility T&D Applications Workshop, Portland, Oregon, July 20-21, 1995.

[4] J. C. Santos, M. C. Taplamacioglu, and K. Hidaka, “Pockels high-voltage measurement system,” *IEEE Transactions on Power Delivery*, Vol. 15, No. 1, January 2000, pp. 8-13.

[5] C. P. Yakymyshyn, M. Brubaker, P. Johnston, and C. Reinhold, “Manufacturing challenges of optical current and voltage sensors for utility applications,” SPIE Conference on Sensors and Controls for Advanced Manufacturing, October 14-17, 1997.

[6] K. Bohnert, J. Kostovic, and P. Pequignot, “Fiber optic voltage sensor for 420 kV electric power systems,” *Optical Engineering*, vol. 39, no. 11, November 2000, pp. 3060-3067.

[7] P. P. Chavez, F. Rahmatian, and N. A. F. Jaeger, “Accurate voltage measurement by the quadrature method,” submitted to *IEEE Transactions on Power Delivery*, November 8, 2000.

[8] P. P. Chavez, F. Rahmatian, and N. A. F. Jaeger, “Accurate voltage measurement with electric field sampling using permittivity shielding,” submitted to *IEEE Transactions on Power Delivery*, November 30, 2000.

[9] F. Rahmatian, P. P. Chavez, and N. A. F. Jaeger, “A 230 kV optical Voltage Transducer,” to be submitted to *IEEE Transactions on Power Delivery*.

[10] F. Rahmatian, D. Romalo, S. Lee, A. Fekete, S. Liu, N. A. F. Jaeger, and P. P. Chavez, “Optical Voltage Transducers for High-Voltage Applications,” 2nd EPRI Optical Sensor Systems Workshop January 26–28, 2000, Atlanta, Georgia.

[11] *IEEE Standard Requirements for Instrument Transformers*, IEEE Standard C57.13-1993, 1993.

[12] International Standard IEC 60044-2 (1997), *Instrument Transformers – Part 2 Inductive Voltage Transformers*, International Electrotechnical Commission (IEC), Geneva, Switzerland.

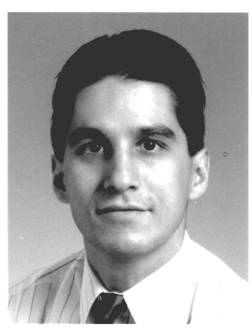
[13] International Standard IEC 60044-7 FDIS (1998) *Instrument Transformers – Part 7 Electronic Voltage Transformers*, International Electrotechnical Commission (IEC), Geneva, Switzerland.

VII. BIOGRAPHIES

Farnoosh Rahmatian (S’ 89, M’ 91) was born in Tehran, Iran, in 1969. He received the B.A.Sc. (Hon.), M.A.Sc., and Ph.D. degrees from the University of British Columbia, Vancouver, B.C., Canada, in 1991, 1993, and 1997, respectively, all in electrical engineering.

Since 1997, he has been the Director of Research & Development at NxtPhase Corporation, also in Vancouver, working on precision high-voltage optical instrument transformers for use in high-voltage electric power transmission systems.

He is also an adjunct professor at the Department of Electrical and Computer Engineering at the University of British Columbia, a member of IEC TC38 Working Group on instrument transformers, Standards Council of Canada, IEEE Power Engineering Society, and IEEE Lasers and Electro-Optics Society.



Patrick P. Chavez was born in Vancouver, BC, Canada, in 1971. He received his B.A.Sc. and M.A.Sc. degrees from the University of British Columbia, Vancouver, BC, Canada, in 1995 and 1997, respectively, where he is currently pursuing a Ph.D. All of his degrees are in electrical and computer engineering. He is also an advisor to NxtPhase Corporation, Vancouver, BC, working on optical high-voltage instruments. His fields of interest include high-voltage instrumentation, computer-aided design in electromagnetics and optics, and numerical analysis in industrial applications.

Nicolas A. F. Jaeger (M’ 89) was born in New Rochelle, NY, in 1957. He received his B.Sc. degree from the University of the Pacific, Stockton, CA, in 1981, and the M.A.Sc. and Ph.D. degrees from the University of British Columbia (UBC), Vancouver, BC, in 1986 and 1989, respectively, all in electrical engineering.

Since 1989 he has been a faculty member in UBC's Department of Electrical and Computer Engineering, where he is now a Professor, and since 1991 he has been the director of the University's Centre for Advanced Technology in Microelectronics.

He is a past recipient of the Canadian Institute of Energy's "Research and Development" Award, the BC Advanced Systems Institute's "Technology Partnership" Award, and the Natural Sciences and Engineering Research Council of Canada and the Conference Board of Canada's "Synergy" Award.