# 138 kV and 345 kV Wide-Band $SF_6$-Free Optical Voltage Transducers

Farnoosh Rahmatian, *Member*, *IEEE*, Patrick P. Chavez, and Nicolas A. F. Jaeger, *Member*, *IEEE*

***Abstract*--This paper describes the design and testing of novel, environmentally friendly, 138 kV and 345 kV optical voltage transducers (OVTs) for metering and protection relaying applications in high-voltage electric power transmission systems. Each OVT uses three miniature optical electric field sensors housed inside a resistive shield. The locations of the electric field sensors, the electrical and geometrical parameters of the resistive shield, and the formula for deriving voltage from the electric field measurements are all chosen using the quadrature method to achieve very accurate voltage measurements. The resistive shield is, in turn, housed inside a hollow composite insulator filled with low-pressure dry nitrogen. Conventional accuracy and dielectric withstand tests demonstrate that the OVTs meet IEC 60044-7 0.2 and IEEE/ANSI C57.13 0.3 accuracy class standards and insulation requirements. Further tests demonstrate their wide bandwidth (>40 kHz) and show that they successfully reject the effects of the severest possible electric field disturbances on the voltage measurement.**

***Index Terms*--electric field effects, electric field measurement, electric fields, Gaussian quadrature, high-voltage techniques, integration (mathematics), numerical analysis, optics, transducers, voltage measurement.**

## I. INTRODUCTION

OPTICAL voltage transducer (OVT) technology offers an attractive alternative to conventional instrumentation transformer technologies, e.g., inductive voltage transformers and capacitive voltage transformers. Following in the footsteps of their already successful and proven optical current transducer counterparts, OVTs offer several advantages over conventional transformers for measuring voltage. Among these are small size, light weight, wide bandwidth, and large dynamic range. Use of optical fiber to transmit sensor measurements from the high-voltage environment ensures galvanic isolation of the observer and immunity of the measurement to electromagnetic interference.

Generally, existing industrial OVTs [1]-[6] suffer from one remaining drawback. As with conventional transformers, they have high-voltage (HV) and grounded electrodes in close proximity with one another having one or more optical sensors positioned between them. This requires special, environmentally unfriendly insulation, such as oil or $SF_6$ gas, to support the resulting high electric field stresses.

Here, novel 138 kV and 345 kV OVTs that are each suitable for both metering and relaying applications and have all the benefits of the existing OVT technologies but do not require special insulation are described. As with the previously reported OVTs [7], [8], these OVTs are based on the quadrature method, but they also employ permittivity-shielding to enable accurate voltage measurement even in the presence of the severest possible electric field disturbances, first reported in [9]. Furthermore, a complete series of tests for evaluating the accuracy and insulation performances of these OVTs according to IEC and IEEE instrument transformer standards were performed, and the results are presented.

## II. PRINCIPLES OF DESIGN AND OPERATION

Two central concepts form the basis of operation of the OVTs presented here: the quadrature method [10] and permittivity-shielding [11].

The quadrature method is used to determine the required number of electric field sensors, their positions, and the combination of their measurements for a desired voltage measurement accuracy, for a particular OVT structure, and for an expected worst-case electric field disturbance ("stray field effect") at the locations of the sensors. The expression for the measured voltage in terms of the electric field sensor readings is given by a weighted sum, effectively a numerical integration:

$$V_{ba} \equiv -\int_a^b E_x(x)dx \approx -\sum_{i=1}^{N} \alpha_i E_x(x_i), \qquad (1)$$

where $V_{ba}$ is the measured voltage between points $b$ and $a$, $E_x$ is the $x$-component of the electric field along the $x$-axis, $N$ is the number of sensors, $x_i$ is the position of the $i$th sensor, and $\alpha_i$ is the weight of the $i$th sensor's reading. In each OVT, the $x$-axis is a straight line between the OVT's two internal electrodes, and $a$ and $b$ are the points where the $x$-axis meets the surfaces of the two electrodes.

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Permittivity-shielding in the form of hollow resistive tubes surrounding the *x*-axis and the sensors between the electrodes is used to significantly reduce stray field effects. It is the most important aspect of the OVT's structure that influences the outcome of the quadrature method. It has the effect of significantly reducing the number of required electric field sensors for maintaining accuracy in the presence of any stray field effects.

The bulk of the OVT is that of an HV composite insulator. Internal electrodes are mounted at the ends of the insulator, protruding slightly from the insulator's flange edges, and are, consequently, separated by a large distance. For 138 kV OVTs this distance is ~1 m, and for the 345 kV OVTs it is ~2.2 m. As a result, no oil or $SF_6$ gas is required, and the insulator is filled with low-pressure (~170 kPa above atmospheric pressure) nitrogen gas for insulation.

Between the electrodes is mounted a hollow, cylindrical resistive tube. The resistances of the shielding tubes are ~100 MΩ and ~200 MΩ for 138 kV and 345 kV OVTs, respectively.

Three optical electric field sensors are mounted inside the resistive shield according to the quadrature method. Basically, one sensor is halfway between the electrodes, and the other two sensors are located above and below the middle sensor, near the electrodes. Optical fibers transmit light to and from these sensors. Away from the HV environment, the sensor signals are detected, processed, and weighted and summed according to (1) using analog and digital electronics to give a measure of the voltage. The rated time delay, due to this processing, is near 40 µs. Digital phase compensation is used to give a rated phase displacement of 0° at rated frequency (60 Hz).

## III. HIGH-VOLTAGE LABORATORY TEST RESULTS

One 138 kV OVT and one 345 kV OVT, as described above, were constructed and tested in an HV laboratory (see Fig. 1). Fiber-optic cable connected each OVT to the electronics that resided in the control room, where digital data acquisition took place. The output of the digital electronics passes through a D/A converter and a power amplifier to give the analog voltage output that was used for testing. The 138 kV OVT has a variable rated transformation ratio of 1200:1 or 700:1, and the 345 kV OVT has a rated transformation ratio of 3000:1 or 1800:1, as per [15].

Various tests were performed on the OVTs in accordance with IEC and IEEE standards [12]-[16], and they include standard and special accuracy testing and insulation testing.

### *A. Accuracy Performance*

Using a standard bridge as the reference, ratio and phase errors were recorded over a wide range of voltages. The OVTs meet IEC 0.2 and IEEE 0.3 revenue metering class accuracies, and maintain these accuracies over a range outside of the standard requirements. Fig. 2 and Fig. 3 show transformer correction factors (TCFs), ratio correction factors (RCFs), and phase errors for the 138 kV OVT and 345 kV OVT, respectively. It should be noted that it is the dynamic range of the power amplifier, not the OVTs' native digital output, that limited the range of the OVTs' measurements.

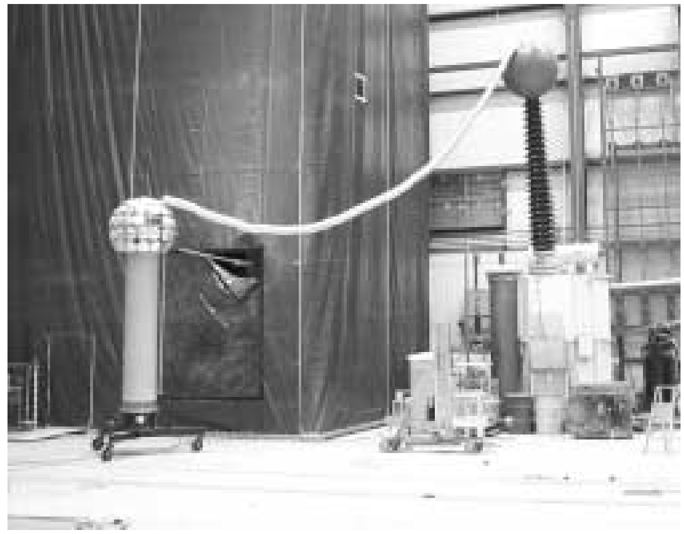

Fig. 1. High-voltage test set-up for fog-pollution tests with reference divider on the left, power transformer (voltage source) on the right, and fog chamber behind them.

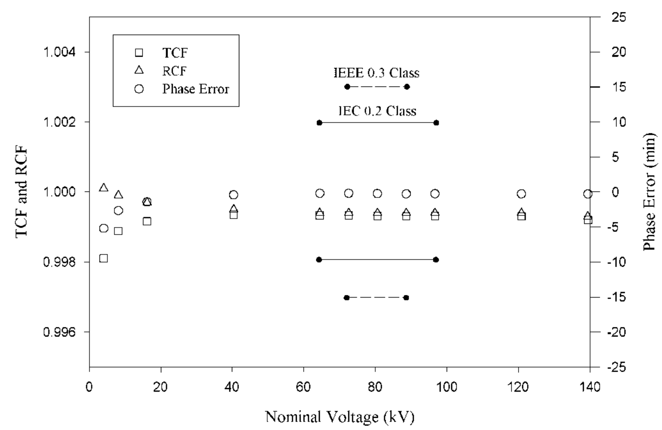


Fig. 2. TCFs, RCFs, and phase errors for the 138 kV OVT.

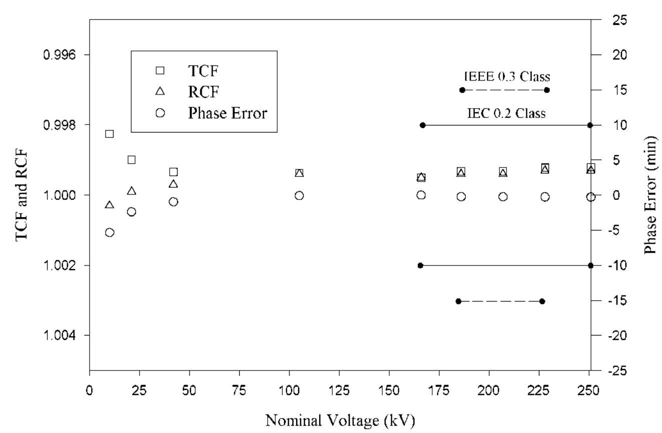


Fig. 3. TCFs, RCFs, and phase errors for the 345 kV OVT.

The OVTs have a bandwidth of near 40 kHz. Although it is difficult to demonstrate their wide-band performance, the harmonic content of the 138 kV OVT's output was compared to that of the reference divider, which has a bandwidth of ~3 kHz. For this test, the applied voltage was generated using a step-up power transformer without tuning circuitry (see Fig. 1) in order to obtain a harmonic-rich signal. The total harmonic distortion (THD) in the reference signal and the OVT signal were measured to be 5.21% and 5.27%, respectively. Table I shows magnitude measurements, as a percentage of the magnitude of the fundamental 60 Hz component, of the harmonic components in both the reference and OVT signals up to the $15^{th}$ harmonic. Excellent agreement between the reference and OVT is demonstrated (all deviations are less than the uncertainty of the test system).

Table I. Measurements of harmonic content.

| Harmonic No. | Reference (% of fundamental) | OVT (% of fundamental) |
|---|---|---|
| 1 (fundamental) | 100 | 100 |
| 2 | 0.05 | 0.03 |
| 3 | 4.31 | 4.37 |
| 4 | 0.02 | 0.02 |
| 5 | 2.75 | 2.76 |
| 6 | 0.21 | 0.21 |
| 7 | 0.96 | 0.96 |
| 8 | 0.04 | 0.04 |
| 9 | 0.51 | 0.53 |
| 10 | 0.03 | 0.03 |
| 11 | 0.16 | 0.17 |
| 12 | 0.01 | 0.01 |
| 13 | 0.13 | 0.13 |
| 14 | 0.01 | 0.01 |
| 15 | 0.04 | 0.04 |

In order to test the OVTs' accuracies in the presence of severe stray field effects, fog-pollution tests were conducted. These consist of applying a salt-water-clay mixture on the entire shed surface and allowing it to dry (see Fig. 2). Then, the OVT is exposed to thick, artificial fog inside a fog chamber, and measurements are taken at the rated voltage. As the moisture builds up on the OVT's surface, conductive regions form, and these affect the electric field nearby. In fact, these produce the severest kinds of stray field effects that can be encountered by an OVT in outdoor operation.

Fig. 2. 345 kV OVT with dried artificial pollution on shed surface.

Table II and Table III show ratio erors, phase errors, and TCFs during fog-pollution tests for the 138 kV OVT and the 345 kV OVT, respectively. Both OVTs maintain IEC 0.2 class accuracy (±0.2%, ±10 min.) and IEEE 0.3 class accuracy (0.997 < TCF < 1.003) during the test.

Table II. Fog-pollution ratio and phase errors for 138 kV OVT.

| Voltage (kV) | Time since energization (minutes) | Ratio error (%) | Phase error (minutes of arc) | TCF |
|---|---|---|---|---|
| 80.5 | 1 | 0.14 | 1.8 | 0.999294 |
| 80.5 | 5 | 0.10 | 1.2 | 0.999463 |
| 80.5 | 11 | -0.05 | -0.6 | 1.000269 |
| 80.5 | 15 | 0.00 | -1.8 | 0.999308 |
| 80.5 | 21 | -0.07 | -3.0 | 0.999547 |
| 80.5 | 25 | -0.11 | -4.2 | 0.999486 |
| 80.5 | 31 | -0.13 | -4.8 | 0.999456 |
| 80.5 | 35 | -0.15 | -5.4 | 0.999425 |
| 80.5 | 41 | -0.15 | -5.4 | 0.999425 |
| 80.5 | 45 | -0.14 | -6.0 | 0.999094 |
| 80.5 | 51 | -0.17 | -6.0 | 0.999395 |
| 80.5 | 55 | -0.16 | -6.6 | 0.999064 |
| 80.5 | 61 | -0.13 | -6.6 | 0.998763 |

Table III. Fog-pollution ratio and phase errors for 345 kV OVT.

| Voltage (kV) | Time since energization (minutes) | Ratio error (%) | Phase error (minutes of arc) | TCF |
|---|---|---|---|---|
| 209 | 1 | 0.13 | 6.6 | 1.00124 |
| 209 | 7 | 0.10 | 4.8 | 1.000847 |
| 209 | 13 | 0.07 | 6.0 | 1.001608 |
| 209 | 19 | 0.03 | 3.0 | 1.000854 |
| 209 | 24 | 0.01 | 2.4 | 1.000823 |
| 209 | 30 | 0.01 | -1.2 | 0.999438 |
| 209 | 40 | 0.01 | -2.4 | 0.998977 |
| 209 | 45 | 0.02 | -4.8 | 0.997954 |
| 209 | 49 | 0.00 | -4.2 | 0.998385 |
| 209 | 55 | -0.01 | -4.2 | 0.998485 |
| 209 | 60 | -0.01 | -4.2 | 0.998485 |

Throughout the pollution test, significant visible and audible arcing was present due to the existence of conductive regions along the length of the insulator. Arcing effects are essentially sparks that occur across small resistive gaps separating the conductive regions when the local electric field intensifies to the point of material (air) breakdown (typically when the voltage is near a peak). These dynamic field distortions also affect the electric field at the sensor locations, and they appear as fast transients in the field sensor measurements.

Fig. 3 shows the 345 kV OVT's voltage and electric field measurements of the individual sensors for one full cycle of the 60 Hz applied voltage during the fog-pollution test. From Fig. 3, it can be observed that while there exist sharp, fast transients in the sensors' signals due to the arcing, the voltage signal is smooth, accurately matching the applied 60 Hz signal. It is also pointed out that the voltage signal is simply a direct calculation of the weighted sum, (1), at each time sample without using any filtering techniques. So, Fig. 3 demonstrates the synergistic effectiveness of the combined use of resistive shielding, for lessening severe stray field effects, and the quadrature method, for efficiently numerically integrating the field, to eliminate the effects of field disturbances on the OVTs' voltage measurements. Additionally, Fig. 3 demonstrates the sensors' ability and, therefore, also the OVT's ability to measure fast transients. This is further evidence of the OVTs' wide bandwidth, which is important for protection relaying and power quality applications.

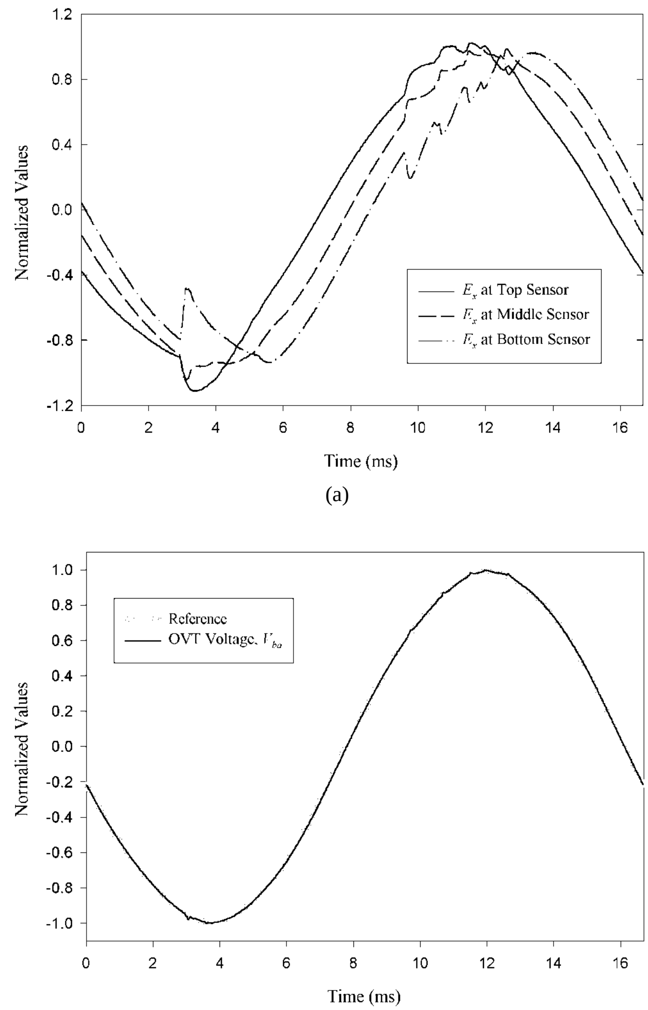


Fig. 3. 345 kV OVT (a) electric fields and (b) voltage waveforms during fog-pollution test.

## B. Insulation Performance

The OVT design is essentially that of a high-voltage post insulator with two simple internal electrodes near its ends and a few extra dielectric and high-resistance internal components (sensors and shield). Consequently, it inherits the advantageous electrical properties of the insulator, particularly with respect to HV withstand.

The 138 kV OVT was subjected to standard full-wave and chopped lightning impulse tests as well as power-frequency withstand tests. The lightning impulse waveform has a peak voltage of 650 kV and front and tail times of 1.2 µs and 50 µs, respectively. The chopped impulses have peaks of 750 kV and tails chopped at 3 µs to 5 µs. Positive- and negative-polarity full-wave and chopped-wave impulses were performed. The 345 kV OVT full-wave and chopped-wave impulses have the same characteristics except that their peaks are 1300 kV and 1500 kV, respectively. Both OVTs passed these tests successfully, with no sign of insulation damage.

The 345 kV OVT was also subjected to switching impulses under wet conditions. The switching impulses have front and tail times of 250 µs and 2500 µs, respectively, and positive peaks of 950 kV. The OVT also passed this test successfully.

Additionally, the OVTs passed power-frequency withstand tests. These involve applying 275 kV and 575 kV at rated frequency for one minute to the 138 kV and 345 kV OVTs, respectively.

Finally, partial discharge tests were also performed on both OVTs. The results are given in Table IV and Table V. The OVTs perform well within the requirements.

Table IV. Partial discharge test results for the 138 kV OVT.

| Voltage (kV) | Partial Discharge (pC) | Requirement per IEC 60044-2 |
|---|---|---|
| 80.3 | < 1 | < 5 pC |
| 83.7 | < 1 | < 5 pC |
| 92 | < 1 | < 5 pC |
| 100 | < 1 | <5 pC |
| 145 | 1.8 | < 10 pC |
| 167 | 2.3 | NA |
| 220 | 11 | NA |
| 220 | 7.3 | NA |
| 167 | 3.2 | NA |
| 145 | 2.8 | < 10 pC |
| 100 | 1.9 | < 5 pC |
| 92 | < 1 | < 5 pC |
| 83.7 | < 1 | < 5 pC |
| 80.3 | < 1 | < 5 pC |

Table V. Partial discharge test results for the 345 kV OVT.

| Voltage (kV) | Partial Discharge (pC) | Requirement per IEC 60044-2 |
|---|---|---|
| 209 | 0.7 | < 5 pC |
| 251 | 2.7 | < 5 pC |
| 365 | 3.6 | < 10 pC |
| 365 | 5.3 | < 10 pC |
| 251 | 4 | < 5 pC |
| 209 | 1.2 | < 5 pC |

## IV. CONCLUSION

Novel wide-band 138 kV and 345 kV OVTs that measure voltage by using three optical electric field sensors, the quadrature method, and resistive shielding both passed thorough accuracy and insulation testing according to IEC and IEEE standard requirements. They met IEC 0.2 class and IEEE 0.3 class accuracy standards and maintained their accuracy in the presence of the severest stray field effects, i.e., those caused by extreme pollution deposited on the OVT surface. Along with their high accuracy, tests also demonstrated their wide bandwidth and large dynamic range. This indicates the suitability of a single such OVT to be used in revenue metering, protection relaying, and power quality control applications simultaneously. They also have the added benefit of not needing $SF_6$ gas or oil for insulation, unlike all other instrument transformers for voltage measurement presently available in industry.

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## VI. 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.

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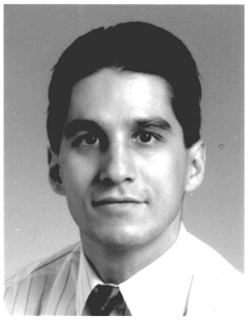

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He is a past recipient of the Canadian Institute of Energy's "Research and Development" Award, the BC Advanced Systems Institute's "Technology Partnership" Award, and the Natural Sciences and Engineering Research Council of Canada and the Conference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