Wide-Band 138 kV Distributed-Sensor Optical Voltage Transducer: Study of Accuracy under Pollution and other Field Disturbances

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 138 kV optical voltage transducer (VT) using shielded distributed electric field sensors is presented for use in high-voltage (HV) electric power transmission systems. Since HV and ground are kept far apart, the VT does not require oil or SF₆ for insulation; instead, it uses the environmentally friendly dry nitrogen as an insulating gas. A prototype has been tested for accuracy under various severe field disturbances including the presence of conductive pollution-like layers on the insulator and the presence of other HV sources nearby. The test results show that the VT meets IEC 0.2% and IEEE 0.3% accuracy classes under these extreme field disturbances. Data that demonstrates wide bandwidth of the VT are also presented. Another prototype has been tested and has successfully passed standard IEC HV dielectric withstand tests including power frequency withstand at 275 kV, partial discharge < 5 pC, lightning impulse tests (BIL) at ±650 kV, and chopped impulse tests at -750 kV.

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

I. INTRODUCTION

Measurement of voltage and current in a high-voltage (HV) transmission network is a critical requirement for control and protection of the system. Recently, as a consequence of the deregulation of power utilities, accurate measurement of voltage and current at high voltages for revenue metering has become even more important. Various types of conventional and non-conventional voltage and current transducers are in use, each having their own advantages and disadvantages. In recent years, various optical voltage and current transducers have been introduced into the market. Optical transducers provide significant advantages over conventional instrument transformers. These include high accuracy, wide bandwidth, wide dynamic range, light weight (easier to install), safer design, and compatibility with emerging digital measurement and control systems (e.g., meters and relays). They are also very compact. For example, optical voltage and current sensors may be combined in one HV housing to provide a power metering unit. Optical current transducers (CTs) typically provide safer insulation systems, compared to conventional CTs, since they use optical fibers for transmitting signals to and from the sensor head in the HV environment; they typically do not use oil-paper or SF₆ insulation. Most optical voltage transducers (VTs), on the other hand, still use pressurized SF₆ or other complicated insulation, see for example [1]-[6]. The optical voltage transducer (OVT) presented in this paper uses a novel resistively shielded distributed electric field sensor design [7], [8]. The design allows for accurate measurement of voltage without bringing high voltage and ground close to one another, hence avoiding the need for SF₆ gas. In the following sections, we will describe the OVT’s structure and present test results depicting the performance of the OVT under various conditions.

II. OVT DESIGN

The optical voltage transducer uses three miniature optical electric field sensors, each approximately 20 mm long, critically positioned (see [7]) inside a hollow resistive tube which is, in turn, positioned inside a HV polymer insulator, see Fig. 1. The resistance of the resistive shield is selected to be ~ 90MΩ so that it carries less than 1mA of current when the OVT is energized at the rated voltage (80.5kV line-to-ground). The insulator is 1.525 m long, with the three optical sensors located at 1.232 m, 0.748 m, and 0.260 m from the base of the insulator. The insulator is filled with dry nitrogen at ~ 12 PSI. A multi-strand fiber-optic cable connects the optical sensors to the OVT electronics. In the electronics module, the electric fields at the locations of the optical sensors are calculated and combined using

\[ V = \int_0^b E_\alpha(x)dx \approx \sum_{i=1}^N \alpha_i E_\alpha(x_i) , \]  

(1)
to obtain \( V \), the voltage applied to the OVT. Here, \( N = 3 \), \( E_\alpha(x_i) \) is essentially the vertical component of electric field, measured at the location of each sensor, \( x_i \), and \( \alpha_i \) is an...
appropriate weight factor determined using the quadrature method, see [7]. Here, $\alpha_1 = \alpha_2 = \alpha_3 = 1$. The electronics provide both digital and analog low energy outputs. Data is provided at a high speed, and the rated time delay of the OVT is only $\sim 50 \mu s$.

The OVT under test is a revenue metering class OVT specified to meet ANSI/IEEE C57.13 0.3% accuracy class [11]. It has previously been shown that the use of the quadrature method, without resistive shielding, can effectively reduce the effects of perturbations such as the presence of neighboring phase voltages, or a nearby truck, or a nearby ground plane on voltage measurement to less than 0.3% [9], [10]. With the addition of resistive shielding to the design, the OVT is even more resistant to these perturbations. To demonstrate this immunity, the OVT’s primary terminals were grounded and a standoff, located 0.43 m away from the OVT, was energized to 50 kV, see Fig. 2. This represents an extreme condition that is never allowed in a real substation. For a 138 kV class system, the spacing between phases is typically 2 m or longer, and in no case is less than 1.4 m. Hence, a distance of 0.43 m in this test is at least 3 times more severe than the worst case neighboring phase interference. Since the primary terminals of the OVT were grounded, the expected output of the OVT was zero. The measured value of the NXVT secondary was 0.02% of what it would have shown if the 50 kV signal applied to the neighboring column were applied across the OVT’s primary terminals. This is effectively less than the accuracy limit of the test system and is significantly better than the 0.3% IEEE C57.13 [11] and 0.2% IEC 60044 [12], [13] accuracy class requirements.

Fig. 1. A 138kV Optical VT.

**III. TEST RESULTS**

The OVT uses the values of the electric fields measured at various points in space between the two conductors between which the voltage is to be determined. It is designed so that practical changes in the electric field distribution around the OVT would not cause significant error in the voltage measurement. It relies on resistive shielding and the quadrature method for maintaining its accuracy at all practical conditions. For more details on the OVT’s theory of operation please consult [7]-[10]. These practical perturbations can be caused, for example, by the presence of a neighboring phase structure in a 3phase substation environment, a moving truck nearby, pollution on the insulator sheds, or other climatic condition changes such as snow and rain. To show the effectiveness of the design and the immunity of the OVT to these perturbations, a series of tests were performed depicting extreme and quite unrealistic conditions.

A more severe perturbation of the electric field distribution can be caused by moisture on polluted insulators. Pollution combined with moisture can result in drybanding on the insulator and can cause severe electric field disturbances.

Fig. 2. OVT grounded while the neighboring column, 0.43 m to its right, is energized at 50 kV.
around it. This is a significant problem in many coastal and other highly polluted areas. These perturbations cause two categories of problems. First they may compromise the quality of insulation and cause flashovers if the insulators are not regularly cleaned. The solution to this problem is a matter of dielectric design and is out of the scope of this paper. Suffice to say that the OVT should be treated in the same manner as any other HV equipment in a polluted area (e.g., post insulators). The second category relates to the possible effects of pollution on the accuracy of the OVT. Error in the measurement is to be kept to below the allowable error for the accuracy class, in this case 0.3%. To simulate various drybanding conditions, aluminum foil was used to represent a moment of time when low-resistance wet pollution layers are present at various locations on the insulator. Aluminum is, of course, significantly more conductive than wet pollution layers (e.g., salt water) and represents an unrealistically extreme case. Also, to avoid external flashovers during these “aluminum foil tests,” the tests were conducted at 40 kV, about half the rated voltage. It is understood that the percentage errors in accuracy measurements for any constant geometry are independent of the voltage applied (linear system). This was verified through repeating tests at 5kV, 25kV, and 40kV on many occasions. Table 1 contains the results of the measurements made under the various pollution conditions simulated using aluminum foil. Fig. 3 shows a case of dryband formed in the middle of the insulator. Fig. 4 shows a similar scenario except that the conductive foil is covering only one side of the insulator. Fig. 5 and 6 depict a dryband condition near the top and the bottom of the OVT, respectively. Fig. 7 shows a case of double dryband, or alternatively, conductive band in the middle of the OVT. Finally, Fig. 8 shows a case of drybands at the top and the bottom of the OVT on opposite sides of the column. In all cases the ratio error is less than 0.2%, and the phase error is less than 2 minutes of arc; i.e., the OVT meets the accuracy requirements of IEEE/ANSI C57.13 0.3% class and IEC 60044 0.2% class, even in the presence of such severe field disturbances.

Table 1. Accuracy measurements under various drybanding (DB) conditions. Aluminum foil is used to simulate a low-resistance pollution layer.

<table>
<thead>
<tr>
<th>Perturbation Type</th>
<th>Case Shown in Fig. #</th>
<th>Ratio Error (%)</th>
<th>Phase Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle DB</td>
<td>3</td>
<td>0.18</td>
<td>0.5</td>
</tr>
<tr>
<td>Middle DB, one side</td>
<td>4</td>
<td>0.11</td>
<td>-0.5</td>
</tr>
<tr>
<td>Top DB</td>
<td>5</td>
<td>0.12</td>
<td>1.9</td>
</tr>
<tr>
<td>Top DB, one side</td>
<td></td>
<td>0.13</td>
<td>0.8</td>
</tr>
<tr>
<td>Bottom DB</td>
<td>6</td>
<td>0.12</td>
<td>1.5</td>
</tr>
<tr>
<td>Bottom DB, one side</td>
<td></td>
<td>0.10</td>
<td>0.2</td>
</tr>
<tr>
<td>Middle wet band</td>
<td>7</td>
<td>-0.09</td>
<td>-1.1</td>
</tr>
</tbody>
</table>

Fig. 3. OVT covered with aluminum foil to simulate a dryband condition in the middle of the column.
It is important to note that field disturbances at the location of the optical electric field sensors are significantly moderated, but not eliminated, through use of the resistive shield. The high level of accuracy comes from the use of equation (1) in the electronics and proper positioning and weighting of the optical sensors as determined by the quadrature method. For example, Table 2 shows the changes in the measurements of each of the three electric field sensors and the resultant voltage in the case of middle dryband shown in Fig. 3.
Another benefit of optical instrument transformers is their wide bandwidth. Typical conventional HV VTs have bandwidths less than 1.5 kHz. Capacitively coupled VTs (CCVTs) in particular have even narrower bandwidths. The OVT tested here has a bandwidth of ~50 kHz; however, generating HV high frequency signals for the purpose of demonstration has been very difficult. Fig. 9 shows the spectrums (up to 2100 kHz) of measurements made using a standard capacitive divider (reference divider) and our OVT simultaneously. The signal is generated using a step up transformer that provides a somewhat distorted, harmonic-rich, 60 Hz signal. It can be seen that the harmonic measurements made by the OVT and the reference divider match almost perfectly.

A separate 138kV resistively shielded OVT was tested at Powertech Labs, Surrey, British Columbia, Canada, for high voltage dielectric withstand. It successfully passed the power frequency withstand test, at 275 kV, partial discharge tests, < 5pC, lightning impulse tests, at 650kV, and chopped lightning impulse tests, at 750 kV, as specified in IEC 60044-2 [12].

IV. CONCLUSIONS

The optical voltage transducer presented here provides a safe, environmentally friendly design, which offers excellent accuracy and very wide bandwidth as well as other advantages that optical instrument transformers generally
promise. It meets most stringent revenue metering accuracy requirements even under extreme field perturbation and pollution conditions. The OVT can easily be combined with an optical CT to provide a single-column optical power metering unit, ideally suited for high accuracy revenue metering and protection applications in HV electric power transmission systems.

V. ACKNOWLEDGEMENT

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


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 Laser and Electro Optic 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.