A Wide-Band High-Accuracy SF$_6$-Free Optical Voltage Transformer

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Optical voltage and current transducer technologies (based on the electro-optic or piezoelectric effects and the Faraday magneto-optic effect, respectively) are emerging in the power sector as advantageous alternatives to the conventional instrument transformer technology (based on inductive and/or capacitive coupling) for accurately and safely measuring electricity. High-voltage (HV) instrument transformers are used in many applications including revenue metering, protection, control, and power quality monitoring. Revenue metering involves the quantification of the power delivered (at 50 Hz or 60 Hz), for which accuracy is of primary importance. Protection and control applications are mainly concerned with the ability to observe signals that may be significantly larger and faster than regular signal levels (50Hz or 60Hz, nominal voltage and current levels) normally present on the transmission lines. Power quality monitoring, which primarily involves the observation and measurement of the harmonic content in the power delivered, is also an important application in high-voltage measurement but has been limited by the frequency range of conventional instrument transformers. In contrast to a conventional instrument transformer (inductive or capacitive), an optical transducer typically has a substantially wider bandwidth and a larger dynamic range and maintains high accuracy over its large dynamic range, making it possible to use a single transducer for all of the above-mentioned applications. Additionally, optical transducers are naturally lighter in weight and smaller in size enabling easier transportation, installation, and maintenance. Furthermore, due to use of optical fibers for transmitting the measurement signal to and from the optical sensors, optical transducers offer electrical isolation of the observer as well as immunity to electromagnetic interference.

In order to measure voltage using electric field measurements, one or both of two basic principles must be put into effect: electric field line integration and electric field shielding. Implementations of a line integration of the electric field have involved sandwiching a single, large Pockels-effect [1], [2] or fiber-optic/piezoelectric [3] sensing element or a uniformly distributed Pockels-effect [4] or fiber-optic/piezoelectric [5] sensing element between a high-voltage terminal and a grounded terminal, which senses the longitudinal component of the electric field between the terminals. This gives a measure of the line integral of the longitudinal component of the electric field, which is proportional to the

voltage. Implementations of electric field shielding have involved substantially surrounding a region between high-voltage and grounded terminals with metallic walls [6]-[10] and placing an optical electric field sensor somewhere in the enclosed region. The geometry in the region is fixed and is isolated from external electrical influences, i.e., "stray field effects", so the electric field sensed at any point in this region gives a measure of the voltage between the terminals. Due to the limited size of the sensing elements (typically < 25 cm) in the case of the line-integration implementations and due to practical space limitations in the case of metallic shielding, the metallic terminals in both cases must be relatively close to each other, resulting in large electric field stresses being present at high voltages. Therefore, special, environmentally unfriendly insulation, such as SF_6 gas, has been required to support these high stresses in such OVTs.

The NXVT, on the other hand, is a novel OVT that uses an efficient method of electric field line integration, known as the quadrature method [11], and a new method of electric field shielding, known as permittivity-shielding [12], together with three optical electric field sensors to accurately measure high voltage. The quadrature method is used to choose positions and weights of the sensors and their outputs to give an optimal line integration of the electric field, while permittivity shielding is used to reduce stray field effects caused by nearby phases, movement of nearby equipment, and pollution deposits on the NXVT's exterior. These methods allow the NXVT to have internal electrodes that are widely spaced apart, thereby removing the need for special insulation, such as SF_6 gas. Instead, the NXVT uses nitrogen gas (at >14 psi-g) for insulation.

The NXVT is housed inside an off-the-shelf composite insulator. Hollow, cylindrical resistors, providing the permittivity-shielding, are mounted inside the insulator extending between two electrodes that are also mounted internally at the ends of the insulator. Three miniature Pockels-effect electric field sensors are positioned inside the resistors according to the quadrature method. The diameters of the insulators are approximately 0.3 m and 0.5 m, and their heights are approximately 1.5 m and 2.7 m for 138 kV and 345 kV NXVTs, respectively. Fig. 1 shows a 138 kV NXVCT system being installed in a substation. Optical fibers connect the electric field sensors in the insulators to the associated electronics in the control room.

The NXVTs have digital, low-voltage analog (4V), and high-voltage analog (69V or 115V) output signals. The digital output is native to the NXVT, while the analog outputs are derived from the digital output. All the outputs have a rated time delay of ~ 40 μs, mostly due to digital processing. The rated phase displacement (at 60 Hz) is set to 0° using digital phase compensation. They were compared with the output of a standard reference capacitive divider for determining accuracy.

Accuracy tests were conducted according to IEC and ANSI/IEEE instrument transformer standards [13]-[16] at Powertech Labs in Surrey, BC. 115 kV, 138

kV, and 345 kV NXVTs were tested, and all demonstrated better than IEC 0.2 class (±0.2%, ±10 min.) and ANSI/IEEE 0.3 class (0.997 < TCF < 1.003) accuracies down to 5% and beyond 150% of the rated voltage with and without burdens. Fig. 2 displays the accuracy performance of a 138 kV NXVT in terms of transformer correction factors (TCFs), ratio correction factors (RCFs), and phase errors. The "turn ratio" of this 138 kV NXVT is 1200:1 (i.e., 80.5 kV : 67 V). Fig. 3 shows similar results for a 115 kV NXVT at 2.5 VA burden (power factor 0.8). The turn ratio for the 115 kV NXVT is 600:1 (i.e., 69 kV : 115 V).

In order to demonstrate the NXVT's usefulness for power quality monitoring, the harmonics content of a distorted voltage source were measured using a 138 kV NXVT and were compared with the output of the reference divider (having a bandwidth of 3 kHz).   The applied voltage was produced using a step-up transformer with no tuning circuitry to supply the voltage. The total harmonic distortion measured by the reference divider and the NXVT was 5.21% and 5.27%, respectively.   Table 1 gives a comparison of the magnitudes of the measured harmonic components (up to the 15th harmonic) showing excellent agreement between the reference and the NXVT (uncertainty in the test system is ~0.05% of the fundamental).

Table I. Measured harmonics.

Harmonic #	Reference (% of fundamental)	NXVT (% 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

Special accuracy tests were also conducted to verify the accuracy of a NXVT with artificial pollution deposited on its surface, simulating a severe stray field effect. The artificial-pollution test is in accordance with [17] and consists of applying a salt-clay-water mixture onto the shed surface of a NXVT (see Fig.4),

allowing it to dry, and then checking the NXVT's accuracy during the time it is exposed to a thick fog. As the moisture builds up on the shed surface, it dissolves the pollution layer along the length of the NXVT, forming uneven regions of variable resistivity along its length and distorting the nearby electric field significantly. Plenty of arcing due to the dynamic, sharp electric field distortions around those regions along the shed surface was present during the testing (see Fig. 4). The NXVTs maintained their accuracy (class 0.2) throughout the test (see [18] for details) and rejected severe stray field effects, making them suitable for harsh pollution conditions in outdoor substations.

Insulation tests on the NXVTs were also performed. Standard positive- and negative-polarity full and chopped wave impulses with peak values of 650 kV (full) and 750 kV (chopped) for the 138 kV NXVT and 1300 kV (full) and 1500 kV (chopped) for the 345 kV NXVT were performed with no occurrence of insulation damage. The 345 kV NXVT was also subjected to switching impulses (peak = 950 kV) under wet conditions and passed without difficulty. Finally, a one-minute withstand test (at 275 kV for the 138 kV NXVT and at 575 kV for the 345 kV NXVT) with partial discharge (PD) testing before and after were also passed successfully by the NXVTs.

Several 138 kV NXVTs were also tested over temperature from -40°C to $+55^{\circ}$C. Fig. 5 shows the performance of an NXVT over this temperature range. The tests were conducted in the environmental chamber of Powertech Labs, Surrey, British Columbia, Canada, and the applied temperature profile is compliant with IEC 60044-8 [19]. The NXVT maintains its 0.2% accuracy over the entire temperature range.

A three-phase system of 138 kV NXVCTs was installed at Hydro Quebec's Rolls Royce substation in early October 2001 (see Fig. 1). The NXVCTs are basically NXVTs each having an optical current sensor head mounted on the top flange of the insulator. The system will be used for metering, relaying, and power quality measurements.

To summarize, several NXVTs have been manufactured and tested. They have been shown to maintain their high accuracy over a wide temperature range, over a very wide bandwidth, and under various environmental disturbances including pollution and ice. They have successfully passed all the HV dielectric withstand requirements for these devices and are compliant with relevant IEC and IEEE standards governing HV instrument transformers. These devices do not use any SF_6 or oil for insulation and are now commercially available at various voltage classes up to 345 kV in the form of optical voltage transformers (NXVTs) or combined optical voltage and current transformers (NXVCTs).

References

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Fig. 1. A 138 kV NXVCT system being installed at Hydro Quebec's Rolls Royce
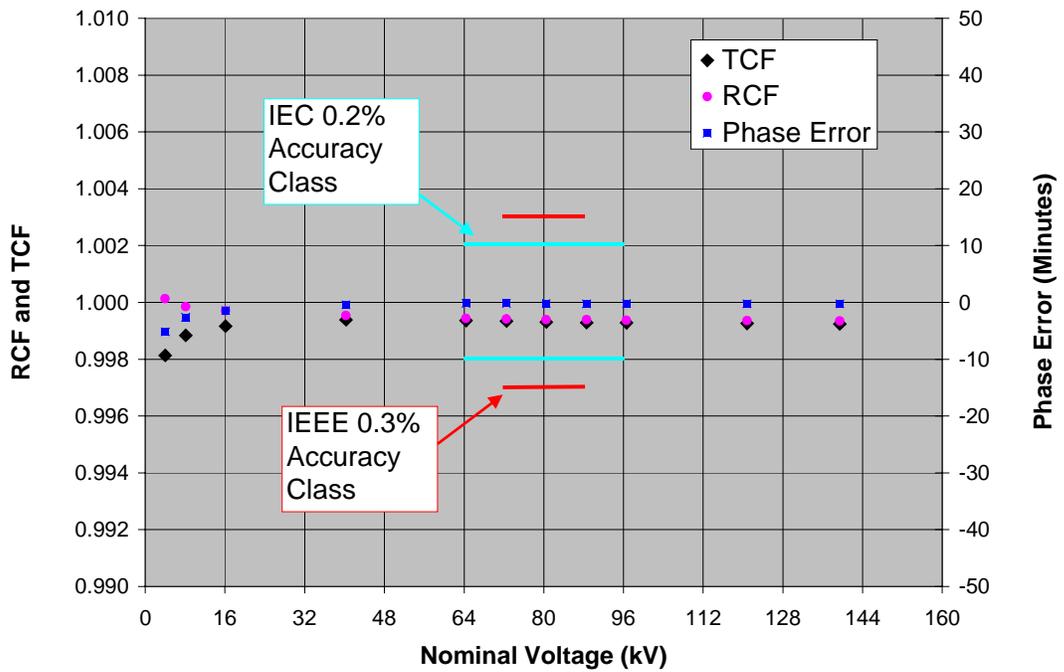substation near Montreal, Quebec, Canada

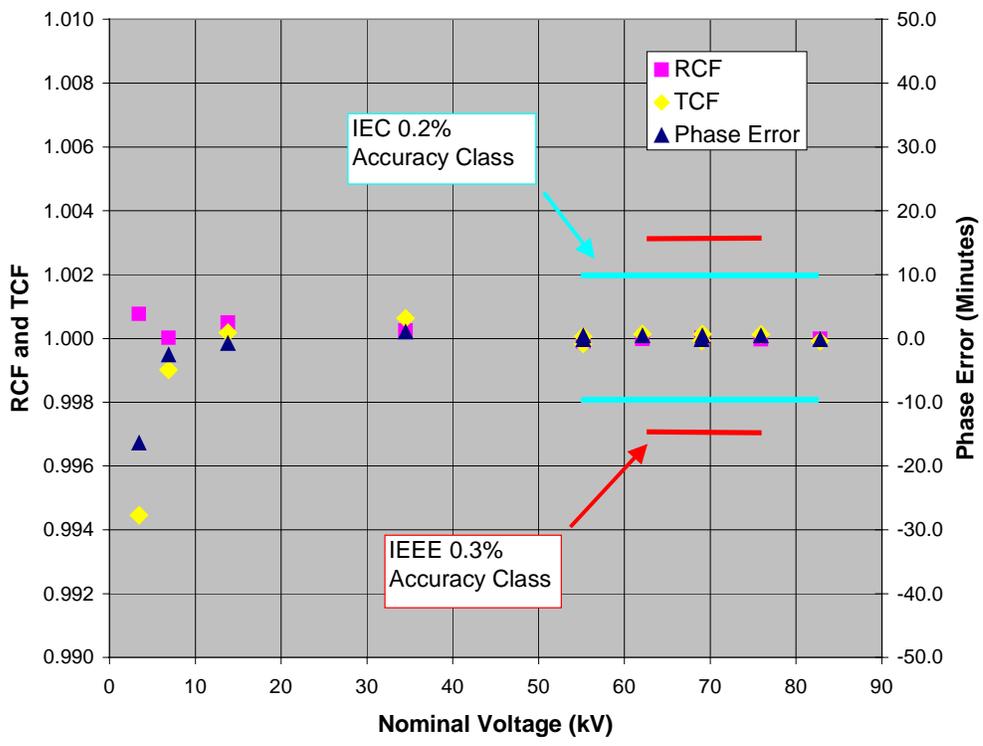Fig. 2. TCFs, RCFs, and phase errors for a 138 kV NXVT.

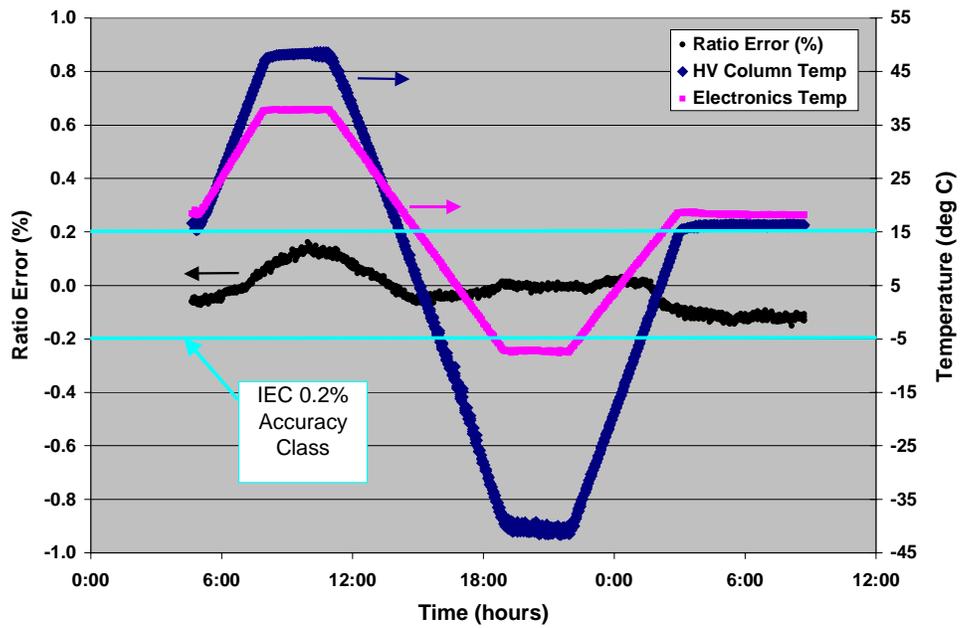Fig. 3. TCFs, RCFs, and phase errors for a 115 kV NXVT, at 2.5 VA (PF=0.8) burden.
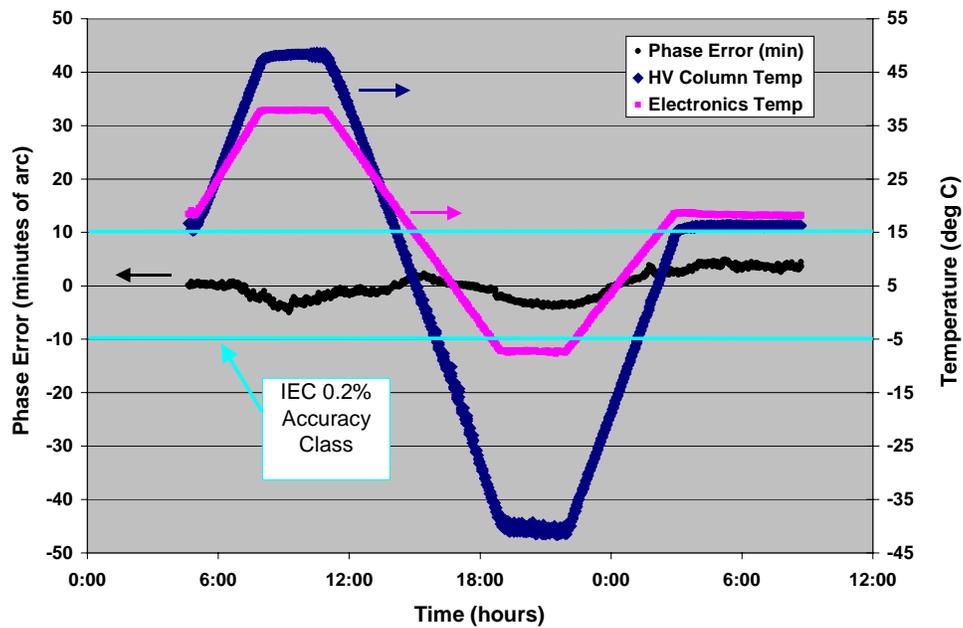
(a)

7/6/2001

(b)

Fig. 4. A 345 kV NXVT under pollution test. (a) Artificial pollution on the surface of the NXVT before the test, (b) some dryband arcing during the test.

Fig. 5. Temperature dependence of the accuracy of a 138 kV NXVT. (a) ratio error and (b) phase error.