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Application of Kerr electro-optic effect to electric field measurements in transformer oils

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This paper presents an original method suitable for measurement of electric field distribution in liquid dielectrics (nanosecond time domain). Electric field is reconstructed in two steps: 1) multiangular laser scanning of inter-electrode space provides projections for each laser beam, 2) using a numerical algorithm called Modified Arithmetic Reconstruction Technique (MART) electric field is reconstructed in the plane of laser scanning. Finite Difference Method (FDM) is used to compare and verify experimental results for symmetrical and asymmetrical electrode configurations. Comparison of experimental (Computerized Laser Tomography) and numerical approach (FDM) confirmed that experimental approach is accurate enough to be used in initial design of many oil-immersed dielectric systems.

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1. Introduction

Investigation of switching phenomena in gas insulated high voltage substations (GIS) proved existence of the very high and very fast over voltages during switching operations. Sparking phenomena during switching of disconnects can produce very high and very fast transient voltages (FT voltages) on the system bus. Frequency of these transient voltages is rather high compared to other transients in the power system (several MHz to few hundred MHz) [1,2].

One of the basic requirements for a more reliable design of any high voltage machine is a complete insight into the FT voltage distribution. An oil-immersed dielectric system (especially a power transformer) is a machine particularly vulnerable to this type of over-voltage. Standard measuring technique, based on voltage dividers and current probes, is not typically designed for measuring very fast transient voltages. Even the verification of their characteristics is a challenge.

This paper offers an alternative diagnostic approach: multi-angular laser scanning of the space in which electric field is investigated. Use of Kerr electro-optic effects in transformer oil offers a non-intrusive approach and acceptable measurement accuracy for experimental investigation of FT related problems. The aim of this work is to develop an experimental methodology, as well as to suggest instrumentation capable of in-depth inspection of fast electric processes in transformer oil.

2. Experimental scanning of fast electric fields

Computerized Tomography (CT) is a non-intrusive diagnostic method developed for medical applications in the early seventies. Essentially, a unidirectional X-ray source translates and rotates around the object being scanned. "Projection" value of a particular X-ray beam is recorded simultaneously with the spatial position of the X-ray source. In tomography, the term "projection" refers to residual part of initial X-ray intensity, attenuated by traversing the object. Computerized data acquisition is used to minimize scan time and achieve the highest possible accuracy. Using the appropriate numerical reconstruction algorithm, spatial (3D) density of a scanned object is calculated from multiple projections.

Computerized Laser Tomography (CLT) uses the same experimental concept, with four important differences to classical X-ray Computerized Tomography:

1. In X-ray Tomography attenuation is directly proportional to density of the analyzed object (linear relationship between density and X-ray attenuation). Computerized Laser Tomography uses Kerr effect to record the change in polarization angle, which has quadratic dependence on electric field along traversing path;

2. Cumulative attenuation of X-rays is independent of the direction of traverse through an object. Computerized Laser Tomography requires a laser beam perpendicular to the direction of electric field in order to provide proper projections for numerical reconstruction;

3. Very strong electric field is required to produce measurable Kerr electro-optic effect in commonly used dielectric liquids. To avoid electrical breakdown of dielectric liquid, very short square pulses are used (600 ns or less). Generation and measurement of such short square-shaped voltage pulses is a challenging task in itself;

4. X-ray attenuation produces a simple decrease of initial signal to a certain lower value. As far as Kerr electro-optic effect is concerned, multiple rotations of the polarized laser beam may occur when a sufficiently strong electric field is applied or when traversing path is long

enough. Rotation of the polarized laser beam greater then 90° causes undesirable loss of correlation between electric field and angle of rotation. To eliminate this problem, gradual increase of electric field (particularly during the initial stage of measurement) is highly recommended.

CLT measurement and reconstruction of an unknown electric field between electrodes in a chosen plane provides "planar" (2D) mapping of measured electric field. Spatial (3D) presentation of an unknown electric field can be accomplished by the compilation of multiple planar (layer based) electric fields [3,4]. Cumulative attenuation along a traversing path (X-ray) or cumulative increase of polarization angle (Laser beam), is used to integrate the aforementioned effects [5]. Traversing path is the shortest distance between a source of irradiation and a corresponding detector.

Kerr electro-optic effect is a manifestation of influence of an external electric field on molecular structure of a dielectric liquid (polarization). A liquid exposed to a strong electric field shows birefringence properties when illuminated by monochromatic light. Under the influence of an electric field, a liquid shows properties of a uniaxial crystal, with optical axis parallel to the direction of the applied electric field. When such a liquid is exposed to a non-polarized light in the direction of the optical axis, its polarization does not change. A non-polarized light beam transmitted trough such a liquid would be non-polarized again.

However, if a non-polarized laser beam penetrates a liquid at an incident angle with respect to the direction of the optical axis, transmitted light has two polarized components. Polarization planes of the mentioned components are perpendicular to each other. Phase difference between the components oscillating in two perpendicular planes is:

$$\Delta\phi = 2\pi B l E^2 \tag{1}$$

where B is the Kerr electro-optic constant, l is the range of electric field influence, and E is the electric field at distance l.

Equation (1) shows the relationship between the phase difference and the applied electric field, from which the electric field can be determined.

Several reasons make this approach attractive for High Voltage measurements:

1. Frequency range of instruments based on Kerr electro-optic effect is very broad: 0 Hz to 10 GHz (measurement accuracy 1 %);

2. Optical response to an electric field step function is extremely short (typically 10-50 ps);

3. Electro-optic measurement principles exert no influence on the electric field to be measured. Classical concepts (galvanic connection of the probe to the instrumentation) introduce significant distortions of the field to be measured (particularly important in very high frequency transients measurements);

4. Because of the very short response time, square-shaped voltage pulses produce effects very similar to those of a stationary (DC) electric field.

Electric field distribution in the scanning plane (2D) is calculated using a numerical approach. Spatial electric field distribution (3D) can be obtained by multi-layer scanning in a sufficient number of parallel planes.

Numerical reconstruction of electric field in a particular plane is done using MART approach (Multiplicative Arithmetic Reconstruction Technique). MART algorithm is based on a symmetrical partition of the scanning plane using identical squares (non-overlapping cells). In a general case, each cell assumes averaging (nonuniform field distribution). Accuracy of this kind of reconstruction is limited by cell dimensions and, indirectly, by the diameter of the laser beam. Dimension of the laser beam must be lower then the cell size. Cell dimension of 2 mm was accepted for numerical reconstruction in this work (laser beam diameter was around 1mm). It should be emphasized that higher resolution of measurement and reconstruction is required only in miniature electrode systems. In majority of HV applications the chosen resolution (2 mm cell dimension) is adequate and accurate enough. In some experiments, sudden change of the reconstructed electric field between neighboring cells is observed. This is a clear indication that the chosen cell size is too large and that it needs to be reduced [6].

All three arithmetic reconstruction techniques are tested for convergence and accuracy (classical, additive and multiplicative concepts). Highest accuracy and fastest convergence is achieved by MART (Multiplicative Arithmetic Reconstruction Technique). Furthermore, to insure measurement repeatability and improve accuracy, three measurements are typically conducted for each position of the laser during the scanning process. "Weighting" coefficients are used to speed-up convergence of this iterative method [7].

3. Measuring equipment

High voltage (HV) components, optical devices and, finally, the computer-controlled position and data acquisition system, are all designed to meet specific requirements in nanosecond time-domain measurements. Coaxial design of HV pulse generator and terminating water resistor minimize stray capacitance. Electromagnetic shielding of all connecting cables and measuring equipment is accomplished by putting them into a Faraday cage (insulated form the ground potential). During the experiments, all electronic equipment is switched to the "battery operation" provided by two Uninterruptible Power Supplies (UPS) located inside a Faraday cage. This approach practically eliminates electromagnetic interference created by the operation of the HV pulse generator. The only connection to the measuring equipment outside of the shielded cabin is a glass optical fiber.

A low power (0.5 mW) laboratory class He-Ne laser is used in all experiments. Low optical power is intentionally used to eliminate possible ionization effects in the dielectric liquid. Long exposure of the dielectric liquid to the laser beam (48 h) showed no significant ionization effects - minimal change of the breakdown voltage mean value (1 %). Diameter of the laser beam was 0.8 mm. Initial 30-minute warm-up procedure of the laser ensured its stable output for the duration of the measurements.

Two crystal polarizers (1:1000) were mounted inside two high precision rotators. An optical collimator provided efficient optical coupling of the laser beam to the optical fiber. A very massive (150 kg) optical bench secured precise optical alignment of the laser and the optical collimator. Special legs and brackets were used to minimize vibration of optical components.

Axis of optical polarization for both polarizers was at 45° with respect to the applied electric field. This approach provides maximum optical signal at the receiver when electric field does not exist. This is a "reference" optical signal (recorded on any oscilogram when electric field is zero).

Square waveform of the pulse electric field used in all tests is a very convenient way to avoid inaccuracy caused by mechanical vibrations affecting optical parts of the measuring system. Additional benefit of the parallel arrangement of two polarizers is the possibility to address inherent inconsistencies of crest values of HV pulses produced by a cable generator.

A high-end optical receiver (frequency range 0 - 400 MHz) was used for conversion of an incoming optical signal into an electrical signal connected directly to a digital oscilloscope. Fiber optic cable and optical connector eliminate possible degradation of the incoming optical signal due to optical misalignment. A digital oscilloscope (2 Gsample/s) was used to record HV current pulses and corresponding optical impulses.

Very high positional accuracy during scanning (position error <0.03 mm) was provided by the custom designed X-Y table driven by two servomotors. IEEE-488 interface and appropriate software provided full PC control of digital oscilloscope and efficient data transfer from an oscilloscope to a personal computer (PC).

3.1. Verification procedure

Initial experimental results are verified by numerical procedure known as FDM (finite difference method). Several corrections and "fine-tuning" steps are implemented during calibration stage of this experiment.

High Voltage Cable Generator (CG) discharges electrostatic energy stored in a high voltage cable of predetermined length. CG produces current (voltage) pulses of very short rise/fall time. If CG is terminated with the characteristic impedance of a cable (50 Ω), a square-shaped high voltage pulse is generated while CG is discharging. For the particular CG, pulses of total duration of 600 ns were generated in all experiments.

Cable generator described above was typically charged to the voltage of 100 kV. When spark gap is activated, a well defined square voltage pulse is created (amplitude is 50 kV, duration is 600 ns and rise/fall time is typically 3 ns).

Electromagnetic transient program (EMTP) and direct parameter identification is used to verify measurements and perform necessary calibrations. Direct comparison of measured and calculated values of discharge current is used as a tool to identify all other relevant circuit parameters.

A very similar verification and calibration concept is used to measure and calculate the electric field. A simplified version of the commonly used FDM (Finite Difference Method) is developed and used.

3.2. Kerr-cell

Laser beam illumination of layers of transparent materials (Kerr-cell chamber), is one of the crucial challenges in this experiment (different attenuation, reflection and refraction coefficients). A great deal of design effort was invested into minimizing undesirable optical effects, particularly because of the analog nature of the measured signal. To achieve minimal signal disturbance, high quality materials and a very meticulous manufacturing and assembly process is used. However, high quality materials and careful design alone are not sufficient to resolve the stated problem.

To eliminate this problem, a different experimental approach is implemented. As a first step, parallel-axes configuration of the two polarizers is used. Parallel polarizers provide maximum optical signal on a receiver when no electric field is applied on a Kerr-cell. Additionally, square shape of the voltage pulse allows easy separation of undesirable disturbances from the signal produced by the Kerr effect. The exact value of an optical signal change caused by Kerr effect is, in fact, a difference between the "reference" optical signal (no voltage on a Kerr-cell) and a value of the optical signal when the crest value of the voltage pulse is applied. Calculation of the difference between the reference and the measured optical signal is simplified by the fact that both of these values are recorded on the same oscilogram.

The second experimental challenge is the fact that tomography always requires multiple illumination (irradiation) angles. Typically, a Kerr-cell has four sides, so different laser beam incidence angles produce uneven reflection/refraction patterns. To address this issue, rotation of the object (electrode system) is used rather than rotation of the light source and the detector.

The third challenge was the fact that the Kerr electro-optic constant is rather low in a transformer oil, so that a very strong electric field needs to be created. Another benefit of the short duration voltage pulse is the fact that breakdown voltage is much higher for sub-microsecond pulses. Additionally, even though 600 ns pulses are used in all experiments, much shorter pulses could be used (i.e. 50 ns). This could be essential for experiments with relatively small electrode systems (very strong electric field will provide sufficient measurement accuracy and will not cause electrical breakdown of transformer oil).

Even though the Kerr constant of transformer oil is almost 40 times lower then the Kerr constant of nitrobenzene, "direct" approach and measurements with "real" liquid dielectric eliminates questionable interpretation of results. Additional benefit of the "direct" approach is the fact that transformer oil is not as dangerous as nitrobenzene (very toxic and explosive liquid).

Two electrode systems are used: a) Symmetrical (axial symmetry) - used for verification and calibration and b) Asymmetric - used to test accuracy of the concept.

4. Results and discussion

No notable changes of vital electro-optic and dielectric characteristics of transformer oil after repetitive electrical discharges are observed (10, 20, 50, 100 and 200 discharges with NO breakdown). Kerr constant, breakdown voltage, dielectric losses (tg δ), and resistance remained rather similar to initial (starting) values of fresh transformer oil.

Measurement of the value of the Kerr constant for a particular transformer oil proves that this constant is rather small: 1.8×10^{-15} (m/V^2).

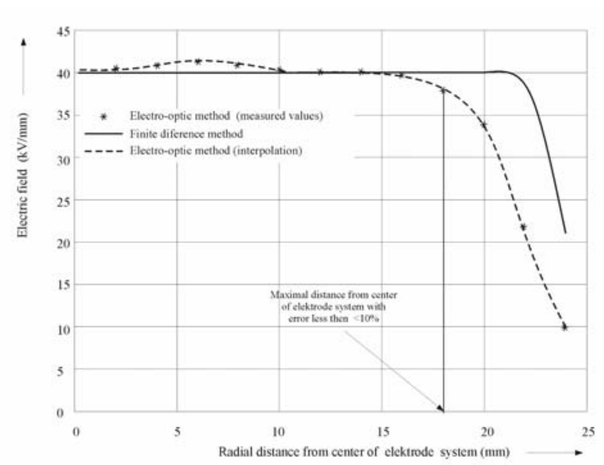

Fig. 1. Electric field strength vs. distance from the center of electrode system (numerical approach using FDM (finite difference method), normal experimental approach (direct tomographic reconstruction), enhanced experimental approach (tomographic reconstruction with zooming)).

Fig. 1 shows two graphs for a chosen axi-symmetrical electrode system:

1. Numerically calculated value of electric field as a function of radial distance (Finite Difference Method - FDM); 2. Reconstructed Electric field using Laser Tomography Method (no matrix "zooming" is used). Calculated FDM curve is assumed to be referential because of the homogenous field is well known for this electrode system. Reconstructed (experimental) curve shows some discrepancies caused manly by insufficient number of experiments (rather coarse matrix of results). However, Fig. 1 shows that even a limited number of experiments will provide reasonable accuracy of electric field in general electrode system in a chosen plane of observation.

Fig. 2 shows surface plots of the electric field in a non-symmetrical electrode system using the suggested experimental method. Fig. 3 is a contour plot of the same experiment.

5. Conclusion

Presented electro-optic tomographic concept is:

1. Completely noninvasive - transient voltage to be measured is not affected by measuring apparatus. This fact makes a very clear distinction between tomographic and other "classical" measuring methods.
2. Nondestructive - complex dielectric system stays intact after experiments.
3. Accuracy and resolution of an electric field reconstruction is dependent on the number of experiments performed. Typically, the highest gradient of an electric field is located in a particular areas, so that a higher scanning resolution enables more accurate reconstruction.

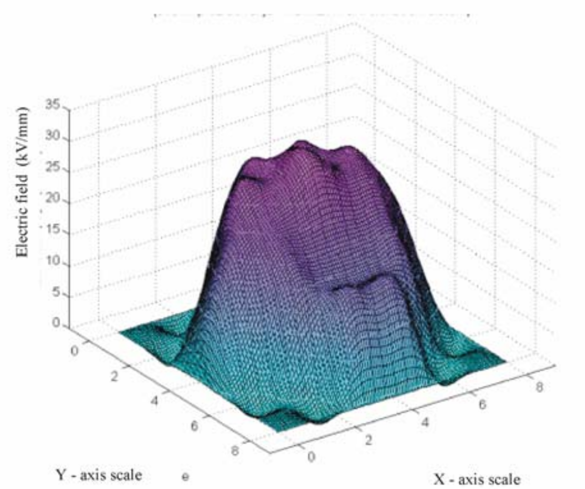

Fig. 2. Surface plot of the reconstructed electric field for a non-symmetrical electrode system.

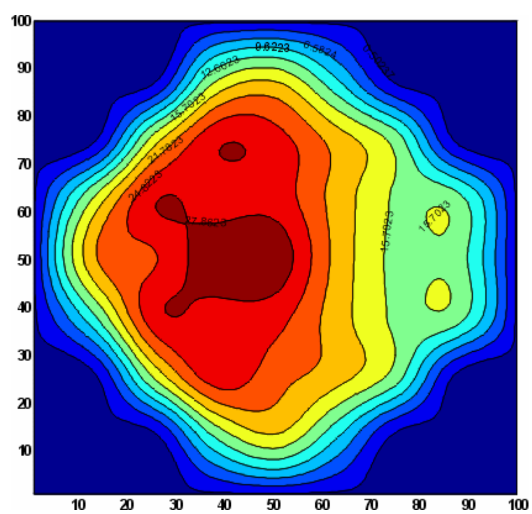

Fig. 3. Contour plot of the reconstructed electric field for a non-symmetrical electrode system.

4. Direct identification (comparison of calculated and measured voltage and current pulses using EMTP program), allows easy and reliable optimization of parameters of a testing circuit (cable generator, conductive links and Kerr-cell).

5. Presented experimental concept could be inaccurate or even completely ineffective in some electrode systems. Accuracy of tomographic reconstruction could be affected by non-perpendicularity of electric field lines to the laser beam. In some extreme cases, optical path between the source and the receiver may be impossible to establish, making this concept nonfunctional.

6. Optical transparency of a dielectric liquid (visible part of optical spectra) simplifies the suggested concept, but nontransparent dielectric liquids could be analyzed as well using an infrared laser and a matching infrared detector.

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