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Design, construction, and test of a passive optical prototype high voltage instrument transformer.

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Abstract - This paper describes an optical voltage transformer (OVT) for the 132-150 [kV]-system based on the Pockels effect in a $Bi_4Ge_3O_{12}$ crystal. Different from the majority of OVTs reported this construction does not use any capacitive voltage division. To accomplice this it was necessary to redesign the optical modulator. A prototype of the OVT has been constructed and tested.

I. INTRODUCTION

Especially numerous faults in oil-insulated current transformers - with devastating consequences - have increased the motivation for finding alternative ways of performing current- and voltage measurements.

Optical based measuring systems for high voltage purposes provide a series of advantages not obtainable with conventional techniques and thus make optical current- and voltage transformers interesting alternatives to the electrical transformers of today. These advantages are: 1) Optics provides total galvanic separation between the measuring point at high voltage (HV) potential and the measuring equipment at ground potential. 2) Transmission of measuring signals in optical fibers is immune to induced electromagnetic noise even in the EMI-environment of switchyards and other high voltage installations. 3) Optics and especially optical fibers make the insulation costs independent of the voltage level and thus give an economical advantage at voltage levels above 100 [kV]. 4) The use of optics is expected to reduce the weight of the transformers. 5) Optical transformers are expected to have a larger bandwidth than conventional transformers. 6) The output-signals from an optical transfor-

mer are easily interfaced with computers and electronically operated equipment such as digital relays.

This paper describes the development of an optical voltage transformer (OVT) for the 132-150 [kV] system. The OVT is made passive, which means that it does not require any energy supply in order to operate. The basic principal of the OVT is to modulate the irradiance of the light - directed to the OVT by an optical fiber - according to the potential difference between the HV-line and the ground potential. The modulation of the light is accomplished by placing a material - that has an optical property (the birefringence), which is sensitive to the electrical field strength (Pockels effect) - inside the OVT.

II. OVT DESIGN.

The OVT consists of three main elements: 1) The HV-elements that secure the internal and external insulation as well as define the electrode configuration. 2) The optical modulator modulates the irradianse of the light sent to the modulator in accordance with the E-field strength in the modulator. It also transmits the modulated light signal back to the signal processing electronics. 3) The electronics drives the light source, detects the modulated light from the OVT, and processes the electronical signals.

The optical signals and hence the electronics of this OVT is not different from the numerous other OVTs described in the literature and is therefore not dealt with in this paper.

The concept of the OVT presented in this paper represents an alternative to the OVT-concepts commonly presented in the literature, which is based on the voltage divider principal.

A capacitive voltage divider containing at least 3 electrodes is usually used. This OVT - developed by the author - uses only 2 electrodes - one connected to ground potential, the other connected to the HV-potential to be measured.

Between the 2 electrodes an E-field is created. A transverse-mode Pockels-modulator is mounted on the ground-electrode without mounting a second electrode to the Pockels-crystal.

In that way the crystal is not encapsulated but is free to expand in height and width. This reduces the amount of mechanical induced stress birefringence due to thermal expansion.
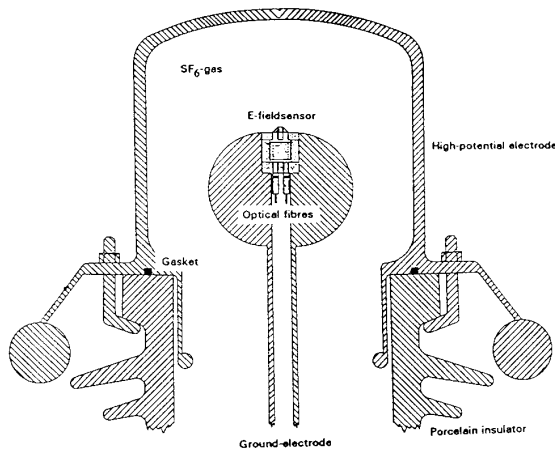
Fig. 1. Sectional view of the OVT.

The crystal is simply exposed to the E-field present on the site where it is located.

The strength and direction of the E-field in the crystal are influenced partly by the shape of the electrodes, respectively the shape of the optical modulator, partly by the difference in relative permittivity of the crystal and the surrounding insulation media, which in this case is SF_6-gas (alternatively a mixture of N_2 and SF_6 can be used).

It is quite clear from the sectional view of the OVT shown in Fig. 1 that the E-field sensitive light modulator is encapsulated in the HV-electrode. This is a feature that makes the OVT insensitive to electro magnetic noise coming from the surrounding environment, e.g., circuit breakers and other line conductors.

The course of the equipotential lines in- and around the OVT is shown in Fig. 2. The most critical part in the design - with respect to the course of the equipotential lines - is the part around the interface between the porcelain insulator and the HV-electrode. This part of the OVT has been enlarged in
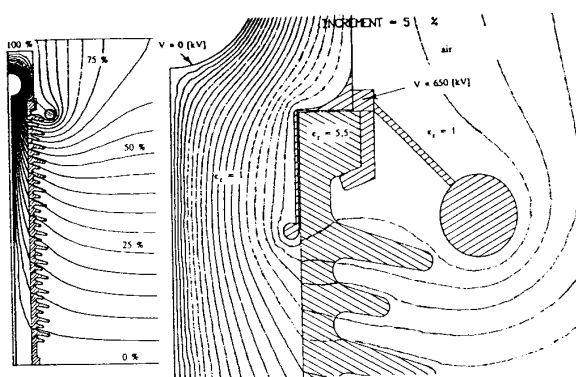

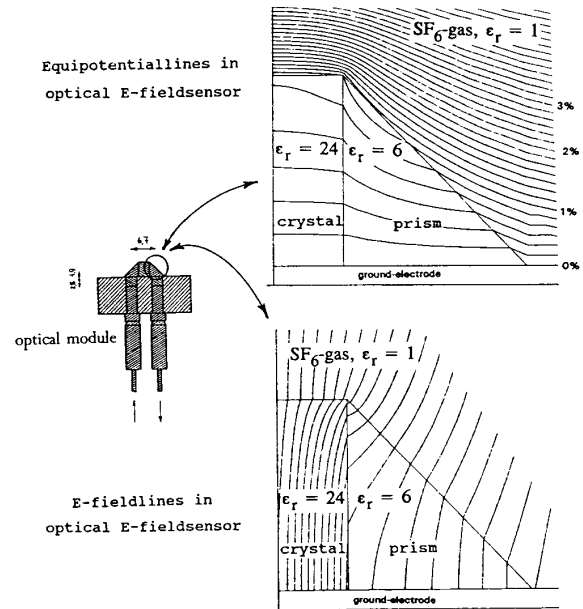Fig. 2. The course of the equipotential lines in- and around the OVT.

Fig. 3. The equipotential- and E-field lines in- and around the optical components mounted on top of the ground electrode.

Fig. 2.

It is of course of great interest to study the equipotential lines on top of the ground electrode (where the optical modulator is mounted). This part of Fig. 2 has been enlarged and is shown seperately in Fig. 3.

Since the crystal is not an ellipsoid shaped body surrounded by a homogeneous material it is not possible to derive an analytic expression of the coupling of the E-field outside the crystal to the E-field inside the crystal.

It is thus necessary to calculate the E-field distribution using a numerical E-field mapping program (the solution derived is a 2D, static, axisymmetric solution with $V_{HV\text{-electrode}} = 100\%$).

A sectional view of half the crystal and one of the prisms with the equipotential lines and the corresponding E-field lines is shown in Fig. 3.

In Fig. 3 it is seen that the relatively large ε_r in the crystal ($\varepsilon_{r,\ crystal} = 24$) forces out the equipotential lines from the crystal to the surrounding materials with lower ε_r ($\varepsilon_{r,glass} = 6$ & $\varepsilon_{r,\ SF6} = 1$).

The E-field strength inside the Pockels crystal is thus smaller than it would have been in the same location had the crystal not been present.

It is also seen from Fig. 3 that the E-field distribution in the crystal is inhomogeneous with respect to the field strength as well as with respect to the direction of the E-field vectors.

This has, however, no effect on the measurement performance of the OVT.

III. INTERIOR of the OVT.

Fig. 1 shows the ground electrode of the OVT, which consists of a hollow copper rod containing two optical fibers (multimode 200/230 μm). On top of the rod the actual ground electrode is mounted. That electrode contains the optical module.

Looking at Fig. 1 it is worth noticing the simplicity of the OVT-construction compared to conventional voltage transformers. The entire OVT consists of only 25 components including the optical modulator! (excl. screws, and electronics).

It is obvious from Fig. 1 & 3 that the OVT does not measure the potential difference between ground potential and the line conductor potential in accordance with the definition of potential difference between point a and b (V_{ab}) - given by (1).

$$V_{ab} \doteq - \int_{a}^{b} \bar{E} \cdot d\bar{l} \qquad (1)$$

Instead the OVT is based on a "point"-measurement of the E-field strength on top of the ground electrode. For this design to work properly it is necessary to assume that the RMS-value of the field strength is proportional to the RMS-value of the potential difference between the two electrodes (Later it is confirmed by measurements that this assumption is valid in the operating range of the OVT).

A. The Optical Modulator.

The assembly of the entire optical module is illustrated in Fig.4.

The light is led to the modulator through one of the optical fibers. At the modulator the light gets semicollimated by the GRIN-lens terminating the fiber.

After the lens the light passes a linear polarizer, which polarizes the light at an angle of 45° relative to the plane of
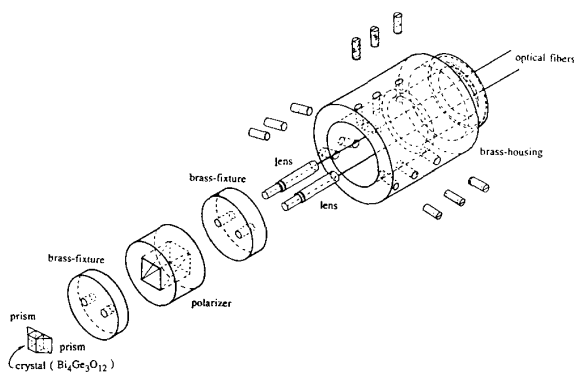

Fig. 4. Exploded view of the optical modulator.

incidence of the prism.

At the prism a total internal reflection (TIR) takes place directing the beam of light through the Pockels-crystal towards the second prism at which a similar total internal reflection directs the beam back into the optical module.

Besides redirecting the beam, the TIR serves as an optical phase retarder substituting a conventional quarter waveplate -[1] & [2].

Back in the optical module the light passes the polarizer for the second time. This time the E-field induced modulation in the state of polarization is converted into an E-field dependent modulation of the irradiance of the light.

By the aid of another GRIN-lens the light is then coupled into the second optical fiber leading it to a signal processing unit.

B. The Pockels-crystal.

The Pockels-effect is closely related to the symmetry properties of the crystalline material in which it is present.

The Pockels-effect is present in some uni-axial as well as in some bi-axial materials.

The bi-axial materials, however, are left out of consideration, because the orientation of the optical axes depended on the wavelength of the light used and the temperature of the crystal -[3].

Considering only uni-axial crystals the Pockels effect is present in 15 out of the 32 point symmetry groups - [4].

Symmetry-group.	Piezo-electric.	Nat. bire-fringence.	Optical activity.	Pyro-electric.
4	✔	✔	✔	✔
$\bar{4}$	✔	✔	✔	-
422	✔	✔	✔	-
4mm	✔	✔	-	✔
$\bar{4}$2m	✔	✔	✔	-
3	✔	✔	✔	✔
32	✔	✔	✔	-
3m	✔	✔	-	✔
6	✔	✔	✔	✔
$\bar{6}$	✔	✔	-	-
622	✔	✔	✔	-
6mm	✔	✔	-	✔
$\bar{6}$m2	✔	✔	-	-
23	✔	-	✔	-
$\bar{4}$3m	✔	-	-	-

Table 1. Symmetry group related properties, [6].

To assist in the selection of the Pockels-crystal material table 1 gives an overview of symmetry group related properties having an influence on the selection of the point symmetry group.

Since the Pockels effect is only present in non-centrosymmetric crystals, all Pockels crystals are piezo-electric as well.

Since pyro electricity induces a temperature dependent E-field in the crystal and hence contributes to the temperature dependence of the Pockels modulator, all symmetry groups exhibiting pyro electricity are excluded.

Next - groups having optical activity are eliminated again in order to exclude a property subject to influence from external physical conditions such as temperature changes.

With respect to natural birefringence there are both pros and cons.

In favour of natural birefringence one could argue that it reduces the relative influence from intrinsic birefringence, e.g., due to imperfections in the crystal or mechanical stresses originating from cutting and grinding the crystal.

The disadvantage with the presence of natural birefringence is that the orientations of the optical axes as well as the indices of refraction associated with the optical axes are dependent upon the temperature.

It is estimated that the temperature dependence of the natural birefringence is of greater significance than intrinsic birefringence due to intrinsic stress and imperfections. This is especially true if the crystal gets annealed after all the mechanical processes have been completed - [5].

Excluding groups with natural birefringence leave only the symmetry group $\overline{4}$3m.

The $\overline{4}$3m symmetry group includes among others: $Bi_4Ge_3O_{12}$, ZnS, ZnSe, GaAs and GaP. Apart from GaAs - which is not transparent at λ < 1000 [nm] - all the other materials are suitable.

The choice fell upon $Bi_4Ge_3O_{12}$ partly because of promising aspects of temperature stability, and partly because $Bi_4Ge_3O_{12}$ is frequently used in scintillation detectors and therefore grown in large quantities by several manufactures making $Bi_4Ge_3O_{12}$ easily available.

With the chosen orientations of the direction of the E-field vector and the light path relative to the symmetry planes of the $Bi_4Ge_3O_{12}$ crystal the E-field induced optical phase retardation (Γ) becomes (2).

$$\Gamma_{Pockels} = \delta(\overline{E}) = \frac{2\pi}{\lambda} \, l \, n^3 \, r \, |\overline{E_{vertical}}| \qquad (2)$$

where:$\lambda \sim$ wavelength of light, $l \sim$ length of light path in crystal, $n \sim$ index of refraction, $r \sim$ electrooptic coefficient.

IV. TEST of the OVT.

A. The Temperature Dependency.

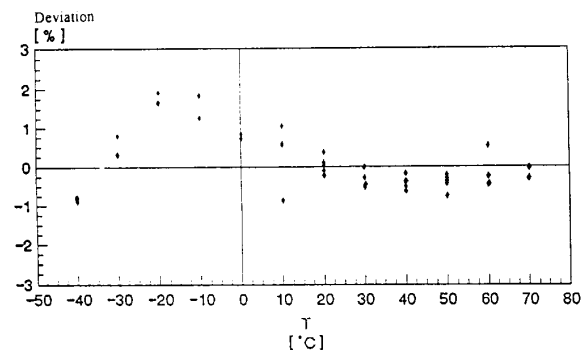A graph depicting the temperature dependency of the optical

Fig. 5. The temperature dependency of the optical module in the range: -40[°C] < T < +70[°C].

module in the temperature range: -40[˙C]< T < +70[˙C] is shown in Fig. 5.

The temperature dependent ratio-error of the optical module is: ± 1.3 [%] in the temperature range [-40 ; +70] [˙C] and ± 0.5 [%] in the range [0 ; +70] [˙C] - [6].

B. Transformation Ratio.

The transformation ratio has been recorded and is presented as a graph showing the RMS-value of the AC-output voltage as a function of the RMS-value of the applied voltage to the OVT. The graph is shown in Fig. 6.

At input voltages below 100 [kV] two separate measurements have been made at each point plotted in the graph in Fig. 6. The reproducibility of the measurement is, however, so good that it is difficult to distinguish the two points corresponding to the two measurement cycles. At voltages
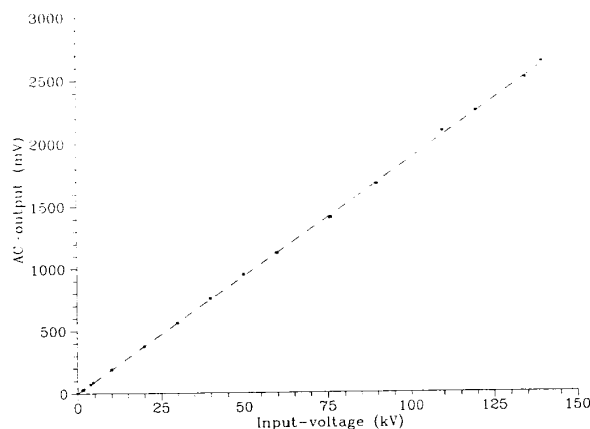

Fig. 6. AC-output voltage as a function of the voltage applied to the OVT.

above 100 [kV] only one measurement was made at each point plotted in Fig. 6.

The graph in Fig. 6 reveals an outspoken linear relationship between the input- and the output- voltage. This is confirmed by the correlation coefficient, which is:

$$c_{input,\ AC\text{-}output} = 1.00$$

A linear approximation thus fits the measurement points very well as shown in Fig. 6. The linear approximation as well as the correlation coefficient has been calculated under the assumption that the measured data points are normally distributed. The linear approximation can be described as (3).

$$V_{AC\ out,\ lin\ \text{-}approx'.} = 1.9 \cdot 10^{-5} \cdot V_{AC\text{-}input} \cdot 2.5 \cdot 10^4 \qquad (3)$$

It is seen from (3) that the linear approximation includes the point (0 ; 0) - the offset of $2.5 \cdot 10^{-4}$ [V] is negligible - and the inclination corresponds to a transformation ratio (input voltage relative to output voltage) of (4) - [6].

$$n_{AC} = 53.5 \cdot 10^3 \pm 0.5 \cdot 10^3 \ , \quad at \ k = 2 \qquad (4)$$

where k = 2 indicates that the uncertainty corresponds to the 2σ value.

C. The Weight of the OVT.

The weight of the prototype OVT amounts to - [6]:
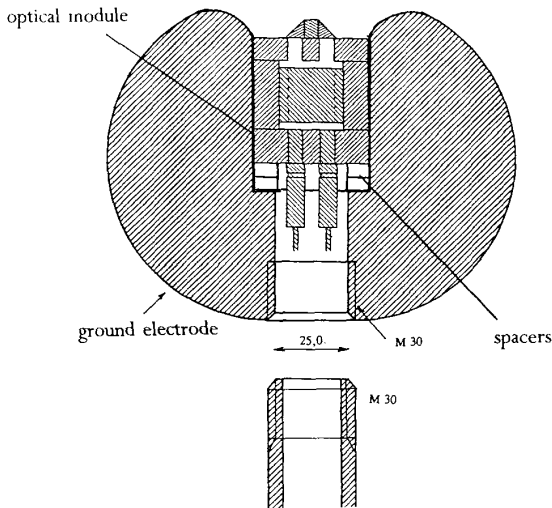
$$mass_{OVT} \approx 275 \ [kg].$$

Fig. 7. Implementation of an adjustable transformation ratio by changing the shape of the ground electrode slightly.

which is just about half the weight of conventional voltage transformers for the same voltage range - [7] & [8].

The reduced weight of the OVT is caused by the simplicity of the interior of the OVT. It also helps to reduce the weight that the OVT is gas insulated (the oil-weight of conventional transformers amounts to 60-80 [kg]).

The reduced weight of the OVT is mainly an advantage in transporting and handling the transformer.

V. An OVT with Adjustable Transformation Ratio.

By changing the shape of the ground electrode slightly as shown in Fig. 7 it is possible to make the transformation ratio of the OVT adjustable.

In the design of the ground electrode shown in Fig. 7 the optical module can be adjusted downwards into the ground electrode, which shields the Pockels-crystal for the E-field thus reducing the modulation of the light.

The adjustment of the optical module can be controlled by inserting spacers or by turning it up or down on a thread.

VI. Future for the OVT.

I believe that by the turn of this century OVTs will begin to penetrate the market of voltage transformers for the transmission system. There are, however, three requirements that must be fulfilled before the OVTs can have any success: 1) Other high voltage components - capable of interfacing directly with the signals from the OVT - have to be developed. This applies especially to digital relays. 2) Standards specifying requirements and tests for OVTs have to be elaborated. 3) Field trials and long term test installations have to be performed to secure long term stability of the OVTs.

VII. Conclusion.

Based on the Pockels effect in the cubic crystal $Bi_4Ge_3O_{12}$ a prototype optical voltage transformer (OVT) for the 132-150 [kV] system is described. The OVT consists of two main parts: an optical module, which modulates the transmitted irradiance as a function of the E-field strength in the Pockels-crystal and a SF_6-gas insulated high-voltage part that secures proper insulation as well as creates the E-field in the Pockels-crystal.

Different from most other OVTs reported in the literature this OVT design is not based on a capacitive voltage divider but instead measures part of the E-field strength between two electrodes connected to the voltage-difference of interest.

An implementation of an adjustable transformation ratio by changing the top part of the ground electrode is described.

The mass of the OVT is 275 [kg], which is about half the mass of a conventional voltage transformer for the same

system voltage.

The temperature dependent ratio-error of the optical module has been recorded to: $\pm$ 1.3 [%] in the temperature range [-40 ; $+70$] [°C] and $\pm$ 0.5 [%] in the range [0 ; $+70$] [°C]. Working with the reduction of the temperature dependency revealed, that the adhesive used to bind the optical components to the ground electrode is of major importance.

At room temperature the transformation ratio (n) is found to be within the following 2σ range: $n = 53.5 \cdot 10^3 \pm 0.5 \cdot 10^3$ for primary voltages in the interval [1.4 ; 140] [kV] with a nominal voltage of $V_n = 132/\sqrt{3}$ [kV].

The prototype OVT fulfills the temperature stability and ratio-error requirements of conventional protection transformers without any use of compensation. With the implementation of a temperature compensation along with a refinement of the signal processing electronics, it is presumed realistic that the OVT can fulfill the requirements of conventional instrument transformers as well.

Beside using optical fibers for signal transmission, this design of the OVT has further increased the immunity to electromagnetic noise by designing the actual measurement to take place "inside the high voltage electrode". The E-field sensitive Pockels-crystal is thus encapsulated by a Faraday-like cage.

VIII. ACKNOWLEDGMENT.

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