HIGH-VOLTAGE SENSOR WITH AXIALLY OVERLAPPING ELECTRODES

A voltage sensor comprises an insulator (1) with mutually insulated electrodes (E_{ij}, E_j) embedded therein. The electrodes are coaxial and cylindrical and overlap axially along part of their lengths. They are mutually staggered and control the surfaces of electric equipotential such that there is a substantially homogeneous electric field outside the insulator (1) and a substantially homogeneous but higher field within a sensing cavity (7) within the insulator (1). The field within the sensing cavity (7) is used to measure the field. This design allows to produce compact voltage sensors for high voltage applications.
High-voltage sensor with axially overlapping electrodes

Technical Field

The invention relates to a voltage sensor for measuring a voltage between a first and a second contact point, in particular to a voltage sensor with an insulator, such as a body of an insulating material, extending between the contact points and with electrodes arranged in said body. The invention also relates to an assembly of several such voltage sensors arranged in series.

Background Art

Optical high-voltage sensors often rely on the electro-optic effect (Pockels effect) in crystalline materials such as Bi$_2$Ge$_3$O$_{12}$ (BGO) [1]. An applied voltage introduces a differential optical phase shift between two orthogonal linearly polarized light waves propagating through the crystal. This phase shift is proportional to the voltage. At the end of the crystal the light waves commonly interfere at a polarizer. The resulting light intensity serves as a measure for the phase shift and thus the voltage.

US 4,904,931 [2] and US 6,252,388 [3] disclose a sensor where the full line voltage (up to several 100 kV) is applied over the length of a single BGO crystal. The crystal length is typically between 100 mm and 250 mm. An advantage is that the sensor signal corresponds to the true voltage (i.e. the line integral of the electric field along the crystal). However, the electric field strengths at the crystal are very high. In order to obtain sufficient dielectric strength, the crystal is mounted in a hollow high-voltage insulator made of fiber-reinforced epoxy filled with SF$_6$-gas under pressure for
electric insulation. The electrodes at the crystal ends are designed so that the field along the crystal is reasonably homogeneous. The insulator diameter is sufficiently large to keep the field strength in the air outside the insulator below critical limits. Typically, the field strength decreases with increasing radial distance from the crystal.

US 6,252,388 [4] describes a voltage sensor which uses several small electro-optical crystals mounted at selected positions along the longitudinal axis of a hollow high-voltage insulator. The crystals measure the electric fields at their locations. The sum of these local field measurements serves as an approximation of the voltage applied to the insulator. Here, the field strengths at a given voltage are significantly lower than with the design of [2] and insulation with nitrogen at atmospheric pressure is sufficient. However, since the sensor does not measure the line integral of the field but derives the signal from the field strengths at a few selected points between ground and high voltage, extra measures (permittivity-shielding) to stabilize the electric field distribution are necessary to avoid excessive approximation errors [5].

A drawback of the above concepts is the requirement of an expensive high-voltage insulator of large size. The outer dimensions are similar to the ones of corresponding conventional inductive voltage transformers or capacitive voltage dividers. Thus, the attractiveness of such optical sensors is limited.

Ref. [6] describes a sensor where the voltage is partitioned on several quartz crystals, each with a length of e.g. 150 mm. Here, the piezo-electric deformation of the crystals under the applied voltage is transmitted to an optical fiber, which carries at least two different light modes. The light waves travelling through the fiber experience a differential optical phase shift in proportion to the voltage. The ends of each crystal
are again equipped with electrodes that provide a relatively homogenous field distribution at the crystals. The electrodes of adjacent crystals are interconnected with electric conductors. The voltage partitioning reduces the electric field strengths compared to a solution with a single crystal and thus makes it possible to mount the crystals in a relatively slender high-voltage insulator of relatively low cost. The hollow volume of the insulator is filled with soft polyurethane. A drawback is that relatively large corona rings are required in order to ensure that the voltage drops at the individual crystals are of comparable magnitude. Furthermore, enhanced electric field strengths occur particularly at the outer surface of the insulator near the positions of the individual electrodes: The peak fields must be kept below the breakdown field of air and therefore prevent still smaller insulator diameter.

Ref. [7] describes an electro-optical voltage sensor of the type as in [2, 3], but with an electro-optic crystal embedded in silicone. A hollow high-voltage insulator of large size and SF₆-gas insulation is thus avoided. As in [6] the voltage may be partitioned among several crystals.

Other prior art is a concept as known from high-voltage bushings. There is often a need in high-voltage systems to pass high-voltage conductors through or near by other conductive parts which are at ground potential (for example at power transformers). For this purpose the high-voltage conductor is contained within a feed-through insulator. The insulator contains several layers of metal foil concentric with the high-voltage conductor and insulated from each other. By appropriately choosing the length of the individual cylinders of metal foils, the distribution of the electric field within and near the bushing can be controlled in such a way that a relatively homogeneous voltage drop from high-voltage to
ground potential occurs along the outer surface of the bushing \[8, 9, 10\].

Disclosure of the Invention

The problem to be solved by the present invention is therefore to provide a voltage sensor for measuring a voltage between a first and a second contact point of alternative design.

This problem is solved by the voltage sensor of claim 1. Accordingly, the voltage sensor comprises an insulator. The insulator is elongate and extends along an axial direction between the first and the second contact points. An electric field sensor is arranged within a sensing cavity inside the insulator. Typically, the length of the sensing cavity is significantly shorter than the length of the insulator. Further, a plurality of conductive electrodes is arranged in the insulator. The electrodes are mutually separated by the insulating material and capacitively coupled to each other. At least a subset of the electrodes (or the whole set of the electrodes) is arranged such that each electrode of the subset axially overlaps at least another one of the electrodes from the subset.

The electrodes allow to control the surfaces of electric equipotential such that on the outer surface of the insulator the voltage drops over the full length of the insulator while inside the insulator the voltage drops over the (shorter) length of the sensing cavity. Preferably the voltage drops essentially homogeneously both along the outer surface of the insulator and over the length of the sensing cavity.

Whereas in the absence of the voltage sensor the normal to the surfaces of equipotential is essentially parallel to the axial direction, the normal is
perpendicular to the axial direction in the vicinity of the electrodes if such electrodes are present.

The electrodes allow to concentrate the electric field within the sensing cavity with a field strength larger than the (average) field strength at the outside of the voltage sensor, i.e. larger than the voltage between the contact points divided by the distance between the contact points.

Advantageously, at least one of the electrodes is a shield electrode radially surrounding said sensing cavity. The electrode can capacitively be coupled to two subsets of electrodes and it prevents the high electric field within the sensing cavity from extending into the air outside the sensor.

Advantageously, the voltage sensor comprises two sets of mutually staggered electrodes.

The invention in its preferred embodiments provides a high-voltage sensor with a slender and lightweight insulator of low cost. The electrodes provide electric field steering and, optionally, obviate the need for electrodes directly applied to the field sensor. A solid-state insulation may suffice (no oil or gas).

The invention also relates to an assembly of such high-voltage sensors in series. Hence, a combination of several modules of the same high-voltage sensor can be used for measuring a large range of different voltage levels.

Other advantageous embodiments are listed in the dependent claims as well as in the description below.

**Brief Description of the Drawings**

The invention will be better understood and objects other than those set forth above will become apparent from the following detailed description thereof. Such description makes reference to the annexed drawings, wherein:
Fig. 1 is a sectional view of a voltage sensor,

Fig. 2 shows (a) a single voltage sensor as well as assemblies of two (b) and four (c) voltage sensors,

Fig. 3 shows (a) a sectional view of field sensor within a voltage sensor and (b) the arrangement of two field sensors,

Fig. 4 shows an optical field sensor and the alignment of the axes of the electro-optic crystal, the retarder, and the polarizers,

Fig. 5 shows (a) an optical field sensor with polarizers operated in transmission, (b) an optical field sensor with retarder and polarizers operated in transmission, (c) an optical field sensor with polarizer operated in reflection, (d) an optical field sensor with retarder and polarizer operated in reflection, (e) an optical field sensor with reflective prism, and (f) a series arrangement of two optical field sensors,

Fig. 6 shows the source and signal processing module and its optical connections to a series of optical field sensors,

Fig. 7 shows a field sensor with end electrodes,

Fig. 8 shows (a) electrode layers with overlapping ends (seen in axial direction) and (b) electrodes forming closed cylinders,

Fig. 9 shows alternative electrode assemblies for a given rated voltage: (a) voltage sensor with a single field sensor of length 21, (b) voltage sensor with two separate field sensors each of length 1, and

Fig. 10 shows an optical field sensor operated in reflection with optics for generation of two signals at quadrature from a single sensing element.
Modes for Carrying Out the Invention

Definitions

The term "high voltage" designates typically voltages exceeding 10 kV, in particular exceeding 100 kV.

The terms "radial" and "axial" are understood in respect to the axial direction (along axis 8, z-axis) of the sensor, with radial designating a direction perpendicular to the axial direction and axial designating a direction parallel to the axial direction.

A given electrode "axially overlapping" another electrode indicates that there is a range of axial coordinates (z-coordinates) that the two electrodes have in common.

Voltage sensor with electric field steering

Fig. 1 shows an embodiment of a voltage sensor. The present embodiment comprises an elongate, advantageously rod-shaped body of an insulating material forming an insulator 1, such as epoxy resin or paper impregnated with epoxy resin. It extends between a first contact point 2 and a second contact point 3, both of which may be equipped with metal contacts 4 for contacting neighboring voltage sensors or voltage potentials. In the present embodiment insulator 1 is cylindrical. It has a central bore 5 filled with a filler material.

An electric field sensor 6, in the present embodiment an optical field sensor, such as a cylinder-shaped crystal of Bi$_4$Ge$_3$O$_{12}$ (BGO) or Bi$_4$Si$_3$O$_{12}$ (BSO), is placed inside bore 5 within a sensing cavity 7. Sensing cavity 7 is advantageously at a center between first contact point 2 and second contact point 3 in order to minimize the distortion of the electrical field around the voltage sensor.

A reference plane 16 perpendicular to axis 8 of the device and arranged at the center of sensing cav-
ity 7 is used in the following as geometric reference for describing the geometry of some of the electrodes. Note: Here it is assumed that sensing cavity 7 is located in the middle between contact points 2 and 3. Asymmetric positions of sensing cavity 7 will be briefly considered further below. Further, it is noted that the term "cavity" does not imply that there is an absence of insulating material in the respective region.

A plurality of electrodes E is arranged in insulator 1. The electrodes E are mutually separated by the insulating material of insulator 1 and capacitively coupled to each other. In the present embodiment, the electrodes E are formed by metal cylinders (consisting e.g. of thin aluminum foil) of different axial extensions concentric to longitudinal axis 8. The electrodes E control the surfaces of equipotential and the distribution of the electric field outside and inside insulator 1. The lengths (i.e. axial extensions) of the individual electrodes E and their radial and axial positions are chosen such that the surfaces of equipotential are spaced essentially equidistantly along the full length of the outer surface of insulator 1 and are concentrated, but again with essentially equal distances, in sensing cavity 7. As a result the applied voltage \( V \) drops uniformly along the outer rod surface as well as along the sensing cavity. Preferably, the length of the field sensor is such that the sensor is essentially exposed to full voltage drop, i.e. the sensor length is at least the length of the sensing cavity.

At least one of the electrodes E is a shield electrode \( E_3 \) and radially surrounds sensing cavity 7, thereby capacitively coupling the two sets of electrodes that are separated by reference plane (16).

One electrode, designated \( E_{1_1} \), is electrically connected to first contact point 2, and subsequently called the "first primary electrode". Another electrode, designated \( E_{2_1} \), is electrically connected to
second contact point 3, and subsequently called the "second primary electrode". These two electrodes carry the potential of the contact points 2 and 3, respectively. The other electrodes form a capacitive voltage divider between the two primary electrodes and therefore are at intermediate potentials.

In addition to shield electrode $E_s$, the electrodes comprise a first set of electrodes, named $E_{1-j}$ with $i = 1 \ldots N_1$, and a second set of electrodes, named $E_{2-j}$ with $i = 1 \ldots N_2$. For symmetry reasons, $N_1$ advantageously equals $N_2$. In the embodiment of Fig. 1, $N_1 = N_2 = 6$, but the actual number of electrodes may vary.

The electrodes $E_{1-j}$ of the first set are arranged in a first region 10 of insulator 1, which extends from the center of sensing cavity 7 to first contact point 2, while the electrodes $E_{2-j}$ of the second set are arranged in a second region 11 of insulator 1, which extends from the center of sensing cavity 7 to second contact point 3.

Electrode $E_{1-j}$ of the first set of electrodes forms the first primary electrode and electrode $E_{2-j}$ of the second set forms the second primary electrode. These electrodes are radially closest to longitudinal axis 8, with the other electrodes being arranged at larger distances from longitudinal axis 8.

As mentioned above, the various electrodes overlap in axial direction and are of a generally "staggered" design. Advantageously, one or more of the following characteristics are used:

a) For each set $j$ ($j = 1$ or 2) of electrodes, the electrodes $E_{j-j}$ and $E_{j-j+1}$ axially overlap along an "overlapping section". In this overlapping section the electrode $E_{j-j}$ is arranged radially outside from the electrode $E_{j-j}$.

b) For each set $j$ of electrodes:
   - Each electrode has a center end (as illustrated by reference number 14 for some of the electrodes...
in Fig. 1) facing reference plane 16 of the sensor and a contact end (as illustrated by reference number 15) axially opposite to center end 14,

- Center end 14 of electrode \( e_{3-j_+} \) is closer to reference plane 16 than center end 14 of the electrode \( e_{3-j} \) and contact end 15 of electrode \( e_{3-j_+} \) is closer to reference plane 16 than contact end 15 of the electrode \( E_{j-j} \), hence electrode \( E_{j-j_+} \) is shifted axially towards the center as compared to electrode \( E_{j-j} \), and \( e_{3-j_+} \) is shifted radially towards the outside as compared to \( e_{3-j} \).

- Contact end 15 of the electrode \( e_{3-j_+} \) has an axial distance \( C_{j-j} \) from contact end 15 of the electrode \( E_{j-j} \), and center end 14 of electrode \( E_{j-j_+} \) has an axial distance \( e_{3-j} \) from center end 14 of electrode \( E_{j-j} \), and

- The electrodes \( e_{3-j} \) and \( E_{j-j_+} \) axially overlap between contact end 14 of electrode \( e_{3-j_+} \) and center end 14 of electrode \( e_{3-j} \).

\[ c \) The distances \( B_{j-j} \) and \( c_{j-j} \) can be optimized according to the desired field design. In particular, for obtaining a stronger field within sensing cavity 7 than outside the voltage sensor, the axial distance \( B_{j-j} \) is advantageously chosen to be smaller than the corresponding axial distance \( c_{j-j} \) for all \( i \) and \( j \).

\[ d \) For most designs, if a homogeneous field is desired in sensing cavity 7, the axial distances \( B_{j-j} \) should be substantially equal to a common distance \( B \), i.e. they should all be the same. Similarly, if a homogeneous field is desired at the surface and outside the voltage sensor, the axial distances \( c_{j-j} \) are advantageously substantially equal to a common distance \( c \), i.e. they are also all the same.

\[ e \) Shield electrode \( E_s \) should advantageously have an axial overlap with at least one electrode of the first set and also with at least one electrode of the second set. This, on the one hand, provides improved protection against the high electrical fields in sensing
cavity 7 reaching to the surface of the device. On the other hand, it provides good capacitive coupling between the two sets of electrodes via the shield electrode, thereby decreasing the corresponding voltage drop. To further improve this capacitive coupling as well as the field homogeneity within sensing cavity 7, shield electrode Es advantageously has an axial overlap with the radially outmost electrode Elg of the first set and the radially outmost electrode E2g of the second side and is arranged radially outside from these outmost electrodes Elg and E2g.

f) In order to evenly distribute the fields outside and inside voltage sensor the electrodes are advantageously arranged symmetrically in respect to reference plane 16 of the device.

g) For the same reason, the electrodes are advantageously cylindrical and/or coaxial to each other, in particular coaxial with the longitudinal axis 8.

Fig. 1 further illustrates some other advantageous aspects:
- Field sensor 6 (which is e.g. an electro-optical crystal) is advantageously cylindrical with a length l and is positioned in central bore 5 (diameter e) of insulator 1 (outer diameter D and length L), and within sensing cavity 7.
- Insulator 1 contains, as an example, six electrodes in both the first and the second set. These electrodes Ejj, as well as shield electrode Es, are advantageously of a metal foil, concentric with field sensor 6 and insulator 1.
- With bj and cj chosen as described above, preferably, the electrodes of the two sets are equally spaced in radial direction with a uniform separation distance P between neighboring electrodes, and also the radial distance between the outmost electrodes Elg, E2g of each set to shield electrode Es is equal to P.
Again, this contributes to distribute the electrical fields more evenly both inside and outside insulator 1.

- Preferably, the innermost, primary electrodes E₁₁ and E₂₁ protrude over the axial ends of field sensor 6 by a length a, i.e. field sensor 6 axially overlaps with both primary electrodes. The length a is advantageously sufficiently large so that the field strength in the immediate vicinity of the ends of field sensor 6 and beyond is essentially zero, i.e. field sensor 6 is exposed to the full voltage applied between contact points 2 and 3.

- Preferably, shield electrode Eₕ is positioned at mid-distance between the contact ends 2, 3.

- The primary electrodes E₁₁ and E₂₁ are in contact with the two electric potentials, e.g. ground and high-voltage potentials, at the corresponding contact points 2, 3 by means of the metal contacts 4.

- Preferably, insulator 1 is equipped with sheds, consisting e.g. of silicone, on its outer surface (not shown in Fig. 1), which provide increased creep distance between high-voltage and ground potential for outdoor operation.

The field steering by the electrodes E₁₃ and Eₕ avoids excessive local peak fields both outside and inside insulator 1. As a result the radial dimensions of insulator 1 can be relatively small without the danger of electric breakdown in the environmental air.

The electric field strength in the immediate vicinity of the two ends of field sensor 6 is essentially zero. The same is true within the bore 5 below and above the sensing element. As a benefit any components, in particular any optical components if an optical field sensor is used, are in a field-free region. This is especially advantageous if an optical field sensor is used, because the various auxiliary optical components, such as retarders, polarizers, and collimators 18, can be located in a field-free environment.
There is no need for field steering electrodes at the crystal ends, which simplifies the sensor assembly. The primary electrodes $E_{1j}$ and $E_{2j}$ are in electric contact with the contact points 2, 3 (e.g. ground and high voltage potential). The other electrodes are on intermediary potentials generated by the capacitive voltage divider formed by the electrodes.

Bore 5 is filled with a soft material, e.g. silicone, which provides sufficient dielectric strength. The silicone contains a filler material which ascertains sufficient compressibility and accommodates any thermal expansion of the silicone and insulator 1. The filler may for example consist of micron sized beads made of a soft material or of tiny gas bubbles (such as SF$_6$ gas). The silicone may also serve to hold the field sensor 6 in place and suppress effects of mechanical shock and vibration.

Due to its light weight the voltage sensor may be suspension-mounted in a high-voltage substation.

The dimensions of the voltage sensor and its parts depend on the rated voltage and are chosen such that the sensor meets the requirements of relevant standards for over-voltages, lightning and switching impulse voltages (e.g. Ref. 17). For example, insulator 1 of a 125 kV-module may be an epoxy rod having an overall length $L$ of about 1 m to 1.5 m and a diameter $D$ of 50 mm to 80 mm. The crystal may have a length $l$ of 150 mm and a diameter $d$ of 5 mm. The inner bore 5 of the rod may then have a diameter $e$ between 15 and 25 mm. The parameters $a$, $B_{j,j}$, $C_{j,j}$, $d$, $P$ are chosen such that the voltage applied to the rod ends drops as uniformly as possible over the length of the crystal within the bore and at the same time over the full length of the epoxy rod at its outer surface. The design may be optimized by using an adequate numerical electric-field simulation tool.
Choosing the distances $B_{ij}$ as well as $C_{ij}$ to be equal as described above also contributes to simple and cost efficient insulator fabrication.

Fig. 1 illustrates but one possible design of the electrodes. It must be noted that, depending on the required size and shape of the sensor, the design of the electrodes may vary.

For example, the electrodes may also be non-cylindrical, e.g. by having an oval cross section or by having varying diameter. The electrodes may e.g. be truncated conical (frustro-conical), their end sections 15 may be flared outwards or their end-sections 14 may be flared inwards.

Each electrode can consist of a continuous conductive sheet, such as a metal foil, or it may e.g. be perforated or have gaps.

**Modular design**

The voltage sensor described above may form a module in an assembly of several voltage sensors arranged in series, such as shown in Fig. 2a. In particular, a module containing a single field sensor 6 as described above may be designed for a rated voltage of e.g. 125 kV or 240 kV. Fig. 2a also shows schematically the sheds 19 applied to the outside of insulator 1.

For operation at 240 kV, two 125 kV modules may be mounted in series (Fig 2b). The primary electrodes $E_{2L}$ and $E_{12}$ of the neighbouring modules are in electric contact at the joint between the two modules. The voltage is then about evenly partitioned on the two field sensors 6. Alternatively, a single continuous insulator (with a length of about twice the length of the individual rods) which contains two field sensors 6 and two corresponding assemblies of field steering electrodes may be used instead of two separate epoxy rods.
It should be noted that distributing the voltage on two separate crystals of length 1 results in a smaller insulator diameter and thus lower insulator cost than applying the same voltage to a single crystal of length 21 as illustrated in Fig. 9. A single long crystal (Fig. 9a) requires more electrode layers and thus a larger insulator diameter than two shorter crystals (Fig. 9b) in order to keep the field strength between the layers below critical limits.

At even higher operating voltages, a corresponding number of lower voltage modules is arranged in series, e.g. four 125 kV modules for an operating voltage of 420 kV (Fig 2c). To achieve sufficient mechanical strength of the structure, these serial modules may be mounted in a standard hollow core high-voltage insulator 20 e.g. made of fiber-reinforced epoxy. The hollow volume between the modules and the outer insulator is filled with e.g. polyurethane foam, again, to provide sufficient dielectric strength and to some degree mechanically decouple the modules from the insulator. In an arrangement like in Fig. 2c the individual insulating bodies 1 are not equipped with silicone sheds but the external insulator is equipped with sheds 10 instead.

Furthermore, the geometry of the field steering electrodes may be chosen somewhat differently for the individual modules for further optimization of the field distribution. Additionally, there may be corona rings at the ground and high-voltage ends of the structure as well as at intermediate positions.

In case of several modules it may be sufficient to equip only one module or a subset of modules with an electric field sensor in case the voltage ratios remain sufficiently stable.
Field sensor assembly

Figs. 3a and 3b illustrate the assembly of field sensor 6 within bore 5 of insulator 1. The specific example is for an optical field sensor, even though similar techniques can, where applicable, also be used for other types of field sensors.

The main features are as follows:
- The whole structure is pre-assembled as a sub-unit and then inserted into bore 5. The remaining hollow volume of bore 5 is subsequently filled with silicone gel as mentioned above. Instead of filling the whole of bore 5, the silicone filling may be restricted to the high-field region in the vicinity of field sensor 6.
- Each field sensor 6, which may e.g. be formed by an electro-optical crystal, is mounted inside a support tube 22, e.g. made of fiber re-enforced epoxy, by means of soft braces 24 in the field free volume at the field sensor ends. Mechanical forces acting on the field sensor are thus kept at a minimum, i.e. the field sensor is mechanically decoupled from the insulating rod.
- For an optical sensor, the fibers 26 that guide the light to and from field sensor 6 have strain reliefs 28 that are part of support tube 22.
- On both sides support tube 22 is connected via flexible joints 30 to spacer tubes 32. The spacer tubes 32 extend to the ends of the insulator 1 or, in case of a series of several field sensors 6 in a single insulator 1, may extend to the adjacent field sensor 6 (Fig. 3b). The flexible joints 30 accommodate for differential thermal expansion of insulator 1 and the various tube segments as well as for a bending of the whole structure, e.g. due to wind forces. The spacer tubes 32 may be composed of several subsections, again with flexible joints in between them.
- If the field sensors 6 are operated in optical transmission as shown in Fig. 3, the return fiber 27 forms a semi-loop in an adequate hollow volume at the
end of an individual insulator 1 (not shown) or at the far end of the whole structure if the insulator is composed of several individual bodies 1 as in Fig. 2b, 2c.

Advantageously, the contact points 2, 3 of insulating insulator 1 are equipped with metal flanges (not shown in Fig. 1). The flanges are in electric contact with metal contacts 4 (or contacts 4 may be comprised by such metal flanges). The flanges facilitate the mounting of the voltage sensor and, in case of a series of several voltage sensor modules, the connection of neighboring modules. The metal flanges may also provide the hollow volume for the above mentioned semi-loop of the return fibers.

It should be noted that the individual electrodes of the two sets \( E_{1-j} \) and \( E_{2-j} \) may not form perfect cylinders but for manufacturing reasons may be formed of an aluminum foil, the ends of which overlap as illustrated in Fig. 8a with a thin layer of insulating material between the overlapping ends. Alternatively the overlapping foil ends are in direct contact and thus form electrically closed cylinders, as indicated in Fig. 8b.

Sensor modifications

a) Asymmetric location of sensing cavity

In the above description it has been assumed that the sensing cavity is located at mid distance between contact points 2, 3 of insulator 1. Depending on the particular environment of the voltage sensor, it may be conceivable that an asymmetric location of the sensing cavity with respect to contact points 2, 3 is more adequate. Preferably in that case, the two sets of electrodes \( E_{1-j} \) and \( E_{2-j} \) are also asymmetric and reference plane 16 as well as shield electrode \( E_s \) is moved from the center of the cavity towards the contact point at the far end of insulator 1. For example, if the sensor cavity is closer to contact point 2, reference plane 16 and shield
electrode \( E_s \) are shifted towards contact point 3. As a result axial distances \( b_{ij} \) are longer than axial distances \( b_{2j} \) and likewise axial distances \( c_{2j} \) are longer than axial distances \( c_{lj} \). The values within each set \( B_{lj} \) \( b_{2j} \) \( C_{lj} \) of axial distances may be chosen as equal or may be chosen differently in order to further optimize the field distribution depending on the particular situation. As an extreme case one set of electrodes \( E_{lj} \) or \( E_{2j} \) may be completely omitted.

b) Local field measurement

As the field distribution inside the sensing cavity is rather homogeneous and stable, a local (i.e. essentially point like) electric field measurement, for example at the center of the cavity, can be an option as alternative to or even in combination with a line integration of the field. A local electric field sensor in this sense is a sensor that measured the electric field along only part of the axial extension of the sensing cavity. The local field essentially varies in proportion to the applied voltage. The influence of thermal effects on the local field strength, e.g. due to the thermal expansion of sensing cavity 7, may be compensated in the signal processor, if the temperature is extracted as mentioned below.

As a further alternative to a perfect line integration of the electric field in sensing cavity 7 by means of a long crystal, the voltage may be approximated from several local (point like) field measurements, with the local field sensors arranged at several points within cavity 7 along axis 8. Particularly, such an arrangement can be of advantage, if the length of sensing cavity is chosen relatively long so that it is difficult to cover this length with a single crystal. Such an arrangement may be of interest in case rather high voltages (e.g. 420 kV or higher) are to be measured with a single voltage sensor module.
Still another alternative is to combine several crystals (with their electro-optic axes aligned) to form a longer continuous sensing section.

Furthermore, a combination of several electro-optic crystals with inactive material (such as fused silica) in between as described in [7] and interrogated by a single light beam may be employed.

c) Field sensor with contact electrodes

To ascertain that the total voltage drops over the length of field sensor (6), it can be of advantage if the ends of sensor (6) are equipped with electrodes that are in electric contact with the innermost electrodes $E_{1}$ and $E_{2}$. The electrodes may be bulk metal parts, transparent electrode layers such as indium tin oxide, or a combination thereof.

d) Voltage measurement in gas-insulated switchgear

Ref. 15 describes an optical voltage sensor for SF6 gas-insulated switchgear. Here, a piezoelectric crystal with an attached fiber is used to measure the voltage between two electrodes at the crystal ends. Other alternatives are an electro-optic crystal or any other kind of optical voltage sensor. The electrodes have considerably larger radial dimensions than the crystal in order to provide a reasonably homogeneous electric field distribution along the crystal.

A capacitively coupled electrode arrangement as shown in Fig. 1 may also be used for voltage sensors in gas insulated switchgear in order to avoid the large size electrodes of [15] . In this case, the two sets of electrodes $E_{1,i}$ and $E_{2,i}$ may again be embedded in an insulating rod as shown in Fig. 1. Alternatively, a solid insulation material may be omitted and be replaced by the insulating SF6 gas of the switchgear system. In the latter case the sets of electrodes may be kept in place by
means of insulating spacer parts between the various electrode layers.

Instead of SF6 gas another insulating gas such as nitrogen may be used. A further alternative is vacuum.

In other conceivable applications of the sensor, for example in electric power transformers, a liquid, commonly transformer oil, may be used as the insulating material.

In other words, insulator 1 can also be a liquid, gas or vacuum, in addition to a solid.

**Optical sensor elements**

As mentioned, field sensor 6 is advantageously an electro-optical field sensor, or, in more general terms, an optical sensor introducing a field-dependent phase shift between a first polarisation or mode and a second polarization or mode of light passing through it.

Advantageously, such an optical sensor comprises:

- an electro-optical device with field-dependent birefringence, in particular a crystal or a poled waveguide, such as a poled fiber, exhibiting a Pockels effect, or

- a piezo-electric device, in particular of crystalline quartz or a piezoelectric ceramic, and an optical waveguide carrying at least two modes, wherein said waveguide is connected to the piezo-electric device in such a manner that the length of the waveguide is field-dependent.

Ideally, a voltage sensor measures the path integral of the electric field between two electric potentials, e.g. ground and high voltage potential. This concept is particularly suited for outdoor installations because the measurement accuracy is not deteriorated by field perturbations, e.g. due to rain or ice or by cross-talk from neighboring phases. Electro-optic crystals of certain symmetry are well suited to implement this concept [3].
a) Pockels effect

An electric field applied to an electro-optical crystal induces an anisotropic change in the refractive index of the material (birefringence). This birefringence causes a phase shift between two orthogonally linear polarized light waves traversing the crystal (Pockels effect). By measuring this phase shift the applied voltage can be inferred.

One configuration of a field sensor which implements line integration of the electric field is shown in Fig. 4: The voltage is applied to the end faces of a crystal 33 with the light also entering and leaving the crystal through the end faces. The crystal material and its axis orientation have to be chosen such that only electric field components $E_y$ (pointing along the cylinder) contribute to the electro-optic phase shift $[1, 3]$. One suitable material is Bi$_4$Ge$_3$O$_12$ (BGO) in a [001] configuration, corresponding to the 4-fold crystal axis being parallel to the direction of light propagation.

The input light (heavy arrow) is linearly polarized by a first polarizer 34 (arrows indicate direction of transmitted polarization; the polarizer may be an in-fiber polarizer as well). To achieve maximum modulation contrast, the electro-optic axes of the crystal $x'$, $y'$ are preferably oriented under an angle of 45° with respect to the incoming linear polarized light. The phase shift $\Gamma$ caused by the electric field is converted to an amplitude modulation of the light by a second polarizer 36 placed at the output end of the crystal. To bias the phase retardation, a retarder 38 may be placed into the beam path (between the two polarizers 34, 36), which adds an additional phase shift $\phi$. The principal retarder axes, $e_1$ and $e_2$, are aligned parallel to the electro-optic axes, $x'$ and $y'$.

In general the intensity $I$ of the transmitted light is given by $I = I_0 \sin^2 \left( \frac{\Gamma + \phi}{2} \right)$. In the case of a $\lambda/4$-waveplate used as retarder 38 this becomes
The half-wave voltage $V_0 = \pi$ for $a < b < \nu \pi / 2$ the intensity then changes linearly with the voltage. Here $V$ is the voltage applied to the crystal, $\lambda$ is the wavelength of the light, $n_0$ is the refractive index of the crystal, and $r$ is the relevant Pockels coefficient. For BGO $\nu \pi$ is about 75 kV at a wavelength of 1310 nm.

\[
I = I_0 \sin^2 \left( \frac{\pi V}{2 V_\pi} + \frac{\pi}{4} \right)
\]

with the half-wave voltage

\[
V_\pi = \frac{\lambda_0}{2n_0^3 r}
\]

For abs ($V$) << $\nu \pi / 2$ the intensity then changes linearly with the voltage. Here $V$ is the voltage applied to the crystal, $\lambda$ is the wavelength of the light, $n_0$ is the refractive index of the crystal, and $r$ is the relevant Pockels coefficient. For BGO $\nu \pi$ is about 75 kV at a wavelength of 1310 nm.

b) Generation of quadrature signals

For typical voltages at high-voltage substations, the voltage $V$ is much larger than the half-wave voltage $V_\pi$, which results in an ambiguous sensor response. This ambiguity may be removed by working with two optical output channels that are substantially $90^\circ$ ($\pi/2$) out of phase (in quadrature) [11], or that have any other mutual phase shift that is not a multiple of $\pi$. The $90^\circ$-phase shift may be generated by splitting the light leaving the crystal into two paths by means of a beam splitter 67 and a deflection prism 68 and putting a quarter-wave plate 38 into one of the paths (Fig. 10) [3]. Further modifications are illustrated in [3]. Fig. 10 shows an arrangement where the sensor is operated in a reflective mode. Alternatively, the sensor may be operated in transmission, i.e. the optics for the generation of the quadrature signals is then arranged at the opposite crystal face so that the light passes the crystal only once.

Another option to remove the ambiguity is to operate the sensor with light of two different wavelengths [12].

In the sensor according to the present invention containing two or more crystals, such as in the as-
assembly of Figs. 2b, 2c or 3, a quadrature signal may also be generated by inserting a phase retarder 38 into the optical path at one of the crystals and operating the other crystals without a retarder, i.e. there is only one output channel per crystal (Fig. 4). Extra beam splitters and deflection prisms for a second channel as needed in [3] are thus avoided. As a result the device becomes significantly smaller, which allows to mount the sensing elements in a relatively narrow bore.

Preferably, the assembly is designed such that the voltage drops at each sensing element are the same. The signals from the individual crystals have then, as a function of the overall voltage, the same periodicity. In cases where the relative voltage drops at the various sensing elements may substantially vary due to environment perturbations of the electric field distribution, it may be of advantage with regard to the signal processing to generate two signals at quadrature from each individual sensor element (arrangement of Fig. 10). The periodicity of the two signals and their phase difference then remains constant (apart from the temperature dependence of the retarder) and is not affected by the field distribution.

Alternatively, the assembly may be designed such that the voltage drops over the different crystals differ. In this case the optical signals from the individual crystals have different periodicity. With appropriate signal processing this also allows to unambiguously reconstruct the applied voltage.

Fig. 5 shows the optical components in more detail. The components (polarizers, waveplate, fiber pigtailed collimators) are advantageously directly attached to the crystal, e.g. by an optical adhesive. The assembly of Fig. 5a is without a retarder while the assembly of Fig. 5b is with a retarder 38, in particular a quarter-wave retarder, to generate a quadrature signal.
In Fig 5a, 5b the crystals are operated in transmission. Alternatively only one fiber 26 may be used to guide the light to and from the crystal 33 as shown in Fig. 5c, 5d. In this case a reflector 40 at the other end of the crystal is used to direct the light back into the fiber. This configuration doubles the sensitivity of the sensing element. As a result of the double pass a \( \pi/8 \) retarder 38 is now advantageously used to generate a quadrature signal.

A reflective configuration may also be realized with two individual fibers 36 for light input and output light and a prism reflector 42 as shown in Fig. 5e.

Turning back to the configuration where an assembly comprising several field sensors is used, it has been mentioned that a retarder 38, in particular a \( \lambda/4 \) retarder, can be attributed to one of them, or, more generally, only to a subset (i.e. not all) of them, for adding an additional phase retardation to the light passing through the respective field sensor(s), which can then be used for quadrature demodulation. This is schematically depicted in Fig. 5(f).

Alternatively (or in addition) to adding one or more retarder(s) to such an assembly, it is possible to dimension at least one (or a subset) of the field sensors such that it generates an electro-optic phase shift that is substantially different from the phase shifts of the remaining field sensors, in particular of \( \pm \pi/2 \) or less at the maximum voltage to be measured. The respective field sensor(s) may e.g. be shorter than the other field sensor(s). In that case the signal of the respective field sensor(s) is unambiguous, which allows to correct for ambiguities in the (more accurate) signals of the other field sensor(s).

c) Sensor interrogation

The light is guided to and from the individual crystals by means of single or multimode optical fi-
The fibers may be embedded in the silicone filling inside bore 5 of the epoxy rods. The crystals may be operated in transmission or in reflection [3], as illustrated in Figs. 5 and Fig. 10.

In an arrangement comprising several voltage sensors in series, the field sensors 6 are preferably interrogated using a common light source 44 and signal processing unit 46 as shown in Fig. 6. Advantageously, the light from light source 44 is transmitted by a single fiber link 48 to the base of the sensor (this sensor end is at ground potential). Then the light is distributed to the individual field sensors 6 by a means of a fiber-optic beam splitter 56. The light is returned from each field sensor 6 to signal processor unit 46 by individual fiber links 50, 52, 54. All fibers (input and output) may be embedded in a common fiber cable 58.

Alternatively, the opto-electronics module may be mounted directly at the base of the sensor to avoid long fiber cables. Additionally, the opto-electronics module may be equipped with means for active or passive temperature control.

**Temperature compensation**

The phase shift introduced by retarder 38 typically is a function of temperature. Therefore the temperature at the location of the retarder can be extracted in the signal processor from two of the above mentioned quadrature signals as also mentioned in [3]. The temperature information can then be used to compensate for any temperature dependence of the voltage measurement. Commonly, the retarder temperature can be considered as a sufficiently good approximation of the overall temperature of the voltage sensor. The temperature dependence of the voltage measurement may be composed of several contributions: the temperature dependence of the electro-optic effect and additionally, in case of local field sensors, contributions from the temperature depend-
ence of the dielectric constants of the sensor material and surrounding materials as well from changes in the local electric field strength due to the thermal expansion of the insulator 1 with embedded electrodes.

Notes
When using electro-optical crystals as field sensors, several (or all) crystals may be interrogated by one light beam which traverses the crystals one after the other. This could for example be achieved by either shining a free space beam through all crystals (with the crystal axes properly aligned) or by interconnecting adjacent crystals with a polarization-maintaining fiber. The birefringent fiber axes are then aligned parallel to the electro-optic axes of the crystals.

Instead of bulk electro-optic crystals, electro-optic waveguide structures may be used [13].

The voltage sensor can also be used with other types of field sensors, such as piezo-optical sensors based on quartz crystals [6] or sensors based on poled waveguides, such as poled fibers [14].

As mentioned, the electrodes are advantageously metal foils embedded within insulating insulator 1 with longitudinal dimensions selected such that a voltage applied to the ends of insulator 1 homogeneously drops over the length of the field sensor inside the sensing cavity 7 and over the full length of insulator 1 at its outer surface. Excessive peak electric fields are avoided.

Optionally, and as schematically depicted in Fig. 7, the first and second ends 60, 62 of field sensor 6 can be electrically contacted to the first and second contact points 2, 3, respectively, e.g. by means of metal electrodes 64 or optically transparent conductive coatings (such as indium tin oxide layers) at the ends 60, 62 and wires 66 leading through bore 5. This design further improves measurement accuracy because it ensures that the
ends 60, 62 of field sensor 6 are at the potentials of the two contact points 2, 3, respectively.

In general terms and in an advantageous embodiment, the voltage sensor comprises an insulator 1 with mutually insulated electrodes \( E_{ij} \), \( E_s \) embedded therein. The electrodes are coaxial and cylindrical and overlap axially over part of their lengths. They are mutually staggered and guide the homogeneous field outside the sensor to a substantially homogeneous but higher field within the sensing cavity 7 within the insulator 1. A field sensor 6 is arranged within the sensing cavity 7 to measure the field. This design allows to produce compact voltage sensors for high voltage applications.

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Reference numbers
1: insulator
2, 3: contact points
4: metal contacts
5: bore
6: field sensor
7: sensing cavity
8: longitudinal axis
10, 11: first and second region
14: central end of electrode
15: contact end of electrode
16: reference plane
18: collimator
19: sheds
20: hollow core high-voltage insulator
22: support tube
24: braces
26: fibers
27: return fiber
28: strain reliefs
30: joints
32: spacer tubes
33: crystal
34, 36: polarizers
38: retarder
40: reflector
42: prism reflector
44: light source
46: signal processing unit
48, 50, 52, 54: fiber link
56: beam splitter
58: fiber cable
60, 62: ends of field sensor
64: metal electrodes, conductive coatings
66: wires
67: beam-splitter
68: deflection prism

5

a, b, j, c, j: axial distances
P: radial distances
Eij, Es: electrodes
L: length of insulator

10

l: length of crystal
D: diameter of insulator
d: diameter of crystal
e: diameter of bore
Claims

1. A high-voltage sensor for measuring a voltage between a first and a second contact point (2, 3) comprising

an insulator (1) of an insulating material extending along an axial direction between the first and the second contact points (2, 3),

a plurality of conductive electrodes (Eij, Es) arranged in said insulator (1), wherein said electrodes (Eij, Es) are mutually separated by said insulating material and capacitively coupled to each other,

at least one electric field sensor (6) arranged in a sensing cavity (7) of said insulator (1),

wherein, for at least part of said electrodes (Eij, Es), each electrode axially overlaps at least another one of said electrodes (Eij, Es),

wherein said electrodes (Eij, Es) are arranged for generating an electric field in said sensing cavity (7) having a mean field strength larger than said voltage divided by a distance between said first and said second contact point (2, 3).

2. The high-voltage sensor of claim 1 wherein at least one of said electrodes (Eij, Es) is a shield electrode (Es) radially surrounding said sensing cavity (7).

3. The high-voltage sensor of any of the preceding claims comprising at least a first primary electrode (El) electrically connected to the first contact point (2) and a second primary electrode (E2) electrically connected to the second contact point (3) and wherein said electrodes (Eij, Es) form a capacitive voltage divider between the first and the second primary electrodes (E1, E2).

4. The high-voltage sensor of any of the preceding claims wherein said field sensor (6) axially overlaps with said first primary electrode (E1) as well as
with said second primary electrode \((E_2)\) and in particular wherein said electric field sensor \((6)\) measures the line integral of the field over a length 1 of the said field sensor \((6)\).

5. The high-voltage sensor of claims 1 to 3 wherein said at least one electric field sensor \((6)\) is a local electric field sensor that measures said field over only part of an axial extension of the sensing cavity.

6. The high-voltage sensor of any of the preceding claims wherein said electrodes \((E_{ij}, E_s)\) comprise a first set of electrodes \(E_{1j-}\) with \(i = 1 \ldots N_1\) and a second set of electrodes \(E_{2j-}\) with \(i = 1 \ldots N_2\), with the electrodes \(E_{1j-}\) of the first set being arranged in a first region \((10)\) of said insulator \((1)\), which first region \((10)\) extends from a reference plane \((16)\) of said sensing cavity \((7)\) to said first contact point \((2)\), and with the electrodes \(E_{2j-}\) of the second set being arranged in a second region \((11)\) of said insulator \((1)\), which second region \((11)\) extends from said reference plane \((16)\) to said second contact point \((3)\), wherein said reference plane \((16)\) extends radially through said sensing cavity \((7)\), and in particular wherein \(N_1 = N_2\).

7. The high-voltage sensor of the claims 3 and 6 wherein a first electrode \(E_{1j-}\) of said first set forms said first primary electrode and a first electrode \(E_{2j-}\) of said second set forms said second primary electrodes.

8. The high-voltage sensor of any of the preceding claims 6 or 7 wherein, for each set \(j\) of electrodes, the electrodes \(E_{ij-}\) and \(E_{ij-+}\) axially overlap along an overlapping section, wherein, in said overlapping section, the electrode \(E_{ij-+}\) is arranged radially outside from the electrode \(E_{ij-}\).

9. The high-voltage sensor of any of the claims 6 to 8 wherein, for each set \(j\) of electrodes,
each electrode has a central end (14) facing said reference plane (16) and a contact end (15) axially opposite to said center (14) end, the center end (14) of the electrode $E_{j-1}$ is closer to said reference plane (16) than the center end (14) of the electrode $E_{j-1}$, and the contact end (15) of the electrode $E_{j-1}$ is closer to said reference plane (16) than the contact end (15) of the electrode $E_{j-1}$, the center end (14) of the electrode $E_{j-1}$, the center end (14) of the electrode $E_{j-1}$, and a contact end (15) axially opposite to said center (14) end, the center end (14) of the electrode $E_{j-1}$ is closer to said reference plane (16) than the center end (14) of the electrode $E_{j-1}$, and the contact end (15) of the electrode $E_{j-1}$ has an axial distance $B_{j-1}$ from the center end (15) of the electrode $E_{j-1}$, and the electrodes $E_{j-1}$ and $E_{j-1}$ axially overlap between the contact end (15) of the electrode $E_{j-1}$ and the center end (14) of the electrode $E_{j-1}$.

10. The high-voltage sensor of claim 9 wherein, for each set $j$ of electrodes, the axial distance $B_{j-1}$ is smaller than the axial distance $C_{j-1}$.

11. The high-voltage sensor of any of the claims 9 or 10 wherein, for each set $j$ of electrodes, the axial distances $B_{j-1}$ are substantially equal to a common distance $B$ and/or the axial distances $C_{j-1}$ are substantially equal to a common distance $C$.

12. The high-voltage sensor of any of the claims 6 to 11 and of claim 2 wherein said shield electrode ($E_s$) axially overlaps with at least one electrode of said first set and at least one electrode of said second set, and in particular wherein the shield electrode ($E_s$) axially overlaps with an radially outmost electrode ($E_{1g}$) of said first set and a radially outmost electrode ($E_{2g}$) of said second set and is arranged radially outside from said outmost electrodes ($E_{1g}$, $E_{2g}$) of said first and said second sets.

13. The high-voltage sensor of any of the claims 6 to 12 wherein the electrodes $E_{1g}$ of said first
set are equally spaced in radial direction and wherein the electrodes \(E_{2j}\) of said second set are equally spaced in radial direction.

14. The high-voltage sensor of any of the preceding claims wherein said electrodes are arranged symmetrically in respect to a reference plane (16) extending radially through said sensing cavity (7).

15. The high-voltage sensor of any of the preceding claims wherein at least part, in particular all, of said electrodes \((E_{1j}, E_n)\) are substantially cylindrical and/or coaxial to each other.

16. The high-voltage sensor of any of the preceding claims wherein said field sensor (6) is an optical sensor introducing a field-dependent phase shift between a first polarisation or mode and a second polarisation or mode of light passing through it, and in particular wherein said optical sensor comprises an electro-optical device with field-dependent birefringence, in particular a crystal, in particular of crystalline \(\text{Bi}_4\text{Ge}_3\text{O}_{12}\) (BGO) or \(\text{Bi}_4\text{Si}_3\text{O}_{12}\) (BSO), or a poled waveguide exhibiting a Pockels effect, or a piezoelectric device, in particular of crystalline quartz or a piezoelectric ceramic, and a waveguide carrying at least two modes, wherein said waveguide is connected to said piezoelectric device thus that a length of said waveguide is field-dependent.

17. The high-voltage sensor of claim 16, wherein said field sensor (6) has two optical output channels having a mutual phase shift that is not a multiple of \(\pi\), in particular a mutual phase shift of substantially \(\pi/2\).

18. The high-voltage sensor of any of the preceding claims wherein a first end (62) of said field sensor (6) is electrically connected to said first contact point (2) and a second end (64) of said field sensor.
(6) is electrically connected to said second contact point (3).

19. The high-voltage sensor of any of the preceding claims wherein the insulator (1) is a solid, liquid, gas, or vacuum.

20. An assembly of several high-voltage sensors of any of the preceding claims arranged in series.

21. The assembly of claim 20 with several high voltage sensors of claim 17, wherein an optical retarder (38), in particular a λ/4 retarder, is attributed to only a subset of the field sensors (6), for adding an additional phase retardation to light passing through the field sensor (6).

22. The assembly of any of the claims 20 or 21 with several high voltage sensors of claim 17, wherein a subset of said field sensors (6), in particular one of said field sensors (6), are/is dimensioned to generate a phase shift that is substantially different from the phase shifts of the remaining field sensors (6), in particular a phase shift of ±π/2 or less at a maximum voltage to be measured of said assembly.

23. The assembly of any of the claims 20 to 22, wherein only a subset of high voltage sensors is equipped with a field sensor.
INTERNATIONAL SEARCH REPORT

International application No
PCT/EP201Q/057872

A. CLASSIFICATION OF SUBJECT MATTER

INV. G01R15/24
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01R

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

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C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Date of the actual completion of the international search

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