

(51) International Patent Classification:
G01R 15/24 (2006.01)(21) International Application Number:
PCT/EP2012/060065(22) International Filing Date:
29 May 2012 (29.05.2012)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
11167811.6 27 May 2011 (27.05.2011) EP(71) Applicant (for all designated States except US): **ABB RE-SEARCH LTD** [CH/CH]; Affolternstrasse 44, CH-8050 Zürich (CH).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **STEIGER, Olivier** [CH/CH]; Forchstrasse 162, CH-8032 Zürich (CH). **JORIS, Pascal** [FR/CH]; Zürcheerstrasse 76, CH-5400 Baden (CH). **BOHNERT, Klaus** [DE/CH]; Loonstrasse 36, CH-5452 Oberrohrdorf (CH). **MARCHESE, Sergio Vincenzo** [CH/CH]; Herbstweg 45, CH-8050 Zürich (CH). **WILDERMUTH, Stephan** [DE/CH]; Hauptstrasse 27, CH-5243 Mülligen (CH).(74) Agent: **INGOLD, Mathias**; ABB Patent Attorneys, c/o ABB Schweiz AG, Intellectual Property CH-LI/IP, Brown Boveri Strasse 6, CH-5400 Baden (CH).

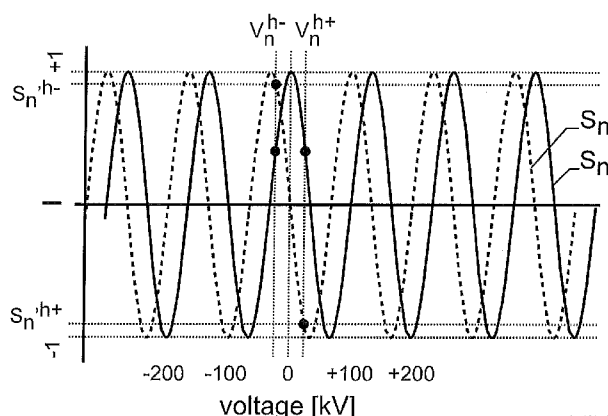
(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

- with international search report (Art. 21(3))
- before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))

(54) Title: FIBER-OPTIC VOLTAGE SENSOR

**FIG. 6a**

(57) **Abstract:** A method and device for measuring a voltage (V , V_n) between two terminals ($1a$, $1b$), in particular an AC voltage in the high-voltage regime, is disclosed. The method and/or device relies on an electro-optic effect in an electro-optical element (2; 2a, 2b, 2c). This electro-optic effect introduces, e.g., a different optical phase shift in two perpendicularly polarized light waves that travel through the electro-optical element (2; 2a, 2b, 2c). Thus, a signal indicative (S_n) of the electric field at the position or over the length of the n -th electro-optical element (2; 2a, 2b, 2c) can be measured. According to the invention, ambiguities in the signals (S_n) are resolved by using a hypothesis test on an additional reference signal or quadrature signal (S_n'). By arranging a plurality of these electro-optical elements in series between the terminals, advantages in terms of cost efficiency and insulation are achieved. Furthermore, a device for measuring a high-voltage is disclosed.

Fiber-Optic Voltage Sensor

Technical Field

The present invention relates to a method and
5 device for measuring a voltage, in particular an AC voltage in the high-voltage range.

Introduction and Background Art

Optical high-voltage sensors often rely on
10 electro-optic effects (such as Pockels effect and/or Kerr effect) in crystalline materials such as $\text{Bi}_4\text{Ge}_3\text{O}_{12}$ (BGO) (L. Duvillaret, S. Rialland, and J.-L. Coutaz "Electro-optic sensors for electric field measurements. II. Choice of the crystal and complete optimization of their orientation" J. Opt. Soc. Am. B 19 2704 (2002)).
15

US 4,904,931 and US 5,001,419 disclose a sensor in which the full line voltage (up to several 100 kV) is applied over the length of a single BGO crystal (typically between 100 mm and 250 mm length). The crystal
20 class of BGO is of symmetry such that the crystal measures the line integral $\int E \cdot ds$ over the crystal length, i.e. from ground to high-voltage potential. As a result, stray fields, e.g., from neighboring phases do not influence the measurement. The applied voltage introduces a
25 differential optical phase shift between two orthogonal linearly polarized light waves propagating along parallel optical paths through the same crystal. This phase shift is proportional to the applied voltage. The light waves interfere at a polarizer at the end of the crystal. The
30 resulting light intensity varies in proportion to a DC biased cosine function of the phase shift. At typical voltages in high-voltage substations, the phase shift may correspond to several multiples of π and thus results in ambiguous sensor output. The ambiguity is resolved by
35 adding a second optical output path to the crystal containing a quarter-wave retarder that introduces a 90° -phase offset between the interfering waves. A signal pro-

cessor reconstructs the waveform of the applied voltage from the two optical output signals at quadrature. Herein, a bidirectional cumulative count of zero crossings of the two electric signals is incremented or decremented depending upon which of the two electrical signals is leading. From the cumulative count of zero crossings a staircase approximation of the waveform is generated. Improved accuracy of the output signal is achieved by interpolating the stairstep waveform via adding or subtracting selectively the magnitude of the smaller of the two opto-electrical signals, with the sense of the adjustment being determined by the relative polarities of the two electrical signals. As the electric field strength at the crystal is typically very high, the crystal is mounted in a hollow high-voltage insulator made of fiber-reinforced epoxy and filled with SF₆ gas under pressure in order to obtain sufficient dielectric strength. The insulator diameter is large enough to keep the field strength in the air outside the insulator below critical limits.

US 6,252,388 describes a voltage sensor which uses several smaller electro-optic 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. In this case the electro-optic phase shift at each crystal is within $\pm 90^\circ$ at the rated voltage, i.e. there is no ambiguity in the sensor response.

US 5,247,244 discloses an electro-optic voltage measuring system in reflection and with temperature compensation. Again, the high voltage is applied along a single crystal and two optically parallel light beams are traversed through the full crystal length and are phase-shifted relative to one another. Temperature compensation is effected via measurement of capacitive current through

the electro-optic crystal, and a correction factor is derived and applied to the half-wave voltage and is used to calculate the instantaneous voltage value.

US 5,715,058 discloses another electro-optic
5 sensor for measuring high voltages in a reflective setup. High voltage is applied to the crystal and the crystal is traversed forth and back by a single light beam. This light beam is split only after exiting from the crystal into two optical paths that are phase-shifted relative to
10 one another. Temperature compensation is achieved by measuring a temperature-dependence of the phase shifting waveplate.

Disclosure of the Invention

15 It is a general objective of the invention to accurately measure voltages over a large range in a simple manner.

This objective is achieved by the method and the device of the independent claims. Exemplary embodiments are disclosed in the dependent claims and claim
20 combinations.

The invention relates to a method for measuring a voltage, in particular a full voltage and/or a partial voltage between a first terminal and second terminal, the first terminal being spatially separated from
25 the second terminal and the voltage creating an electric field between the terminals, the method comprising the steps of

arranging at least a first electro-optical
30 light transmitting element in the electric field between the first and the second terminal,

passing light through the first electro-optical light transmitting element,

measuring at least a first signal, e.g. S_n ,
35 from the first electro-optical light transmitting element and further measuring a second signal, e.g. S_n' , from the first or a second electro-optical light trans-

mitting element, wherein both signals are periodic functions of the voltage and have a relative phase shift other than zero, i.e. a relative phase shift with respect to each other, and possibly a relative phase shift with the applied voltage V or V_n ,

deriving the voltage and resolving an ambiguity in the deriving of the voltage (V) from the first and the second signal, characterized by the steps of:

(i) using the first signal as a base signal indicative of the electric field over the first electro-optical light transmitting element,

(ii) using the second signal as a reference signal for resolving the ambiguity in the deriving of the voltage,

(iii) determining from the first signal **at least** two hypotheses, e.g. h^+ and h^- , corresponding to different possible voltage values, e.g. $V_1^{h^+}$ and $V_1^{h^-}$, of the voltage, e.g. V_n for $n=1$,

(iv) deriving an expected value, e.g. $S_2^{h^+}$ and $S_2^{h^-}$, of the second signal for each of the hypotheses,

(v) comparing the expected values to a measured value of the second signal, and

(vi) taking a binary decision between the hypotheses by validating that hypothesis for which the expected value is closest to the measured value of the second signal.

In an embodiment, exactly two hypotheses are determined and exactly one reference signal per base signal is used, and/or closeness of the expected values to the measured value is determined using Euclidean distance.

In an embodiment, the base signal is a cosinusoidal of the voltage V or V_n , and the voltage under the first hypothesis is assumed to be proportional to $+\arccos$, and the voltage under the second hypothesis is assumed to be proportional to $-\arccos$.

In an embodiment, the relative phase shift is different from 90° .

In an embodiment, the base signal is normalized to a symmetric value range around zero, in particular the base signal is scaled and offset to a value range
5 $[+1, -1]$.

In another embodiment, the deriving of the voltage comprises reconstructing an improved waveform of the voltage with the steps of: determining first voltage
10 values of the voltage from the base signal, in particular by calculating an arccosine, determining second voltage values of the voltage from the reference signal, in particular by calculating an arccosine, and determining the improved voltage waveform from the first voltage values
15 and the second voltage values, in particular wherein the base signal and the reference signal are derived from the same light transmitting element.

A further embodiment comprises the steps of: for each n-th electro-optical light transmitting element, in particular for exactly one electro-optical light
20 transmitting element, normalizing the base signal and the reference signal to the same maximum and minimum amplitude, in particular to unity, selecting a weighting parameter β_n with $0 \leq \beta_n \leq 1$, and determining the improved
25 voltage waveform by calculating a weighted sum $V = \sum V_n = \sum \{\beta_n * V_{1n} + (1 - \beta_n) * V_{2n}\}$, with V_{1n} , V_{2n} = first and second voltage values of the n-th electro-optical light transmitting element. For example in the case of exactly one
30 electro-optical light transmitting element, the full voltage V is determined by calculating the weighted sum $V = \beta * V_{11} + (1 - \beta) * V_{21}$, with V_{11} , V_{21} = first and second voltage values of the exactly one first electro-optical light transmitting element.

A further embodiment comprises the steps of:
35 selecting the weighting parameter β_n such that the more linear of the base signal and the reference signal as a function of the voltage is given a bigger weight.

A further embodiment comprises the steps of:
selecting the weighting parameter $\beta_n=1$ when an absolute
value of the base signal is smaller than an absolute value
of the reference signal, and selecting the weighting
5 parameter $\beta_n=0$ when an absolute value of the reference
signal is smaller than an absolute value of the base signal.

A further embodiment comprises the steps of:
selecting the weighting parameter β_n as a continuous
10 function of the voltage, in particular according to
$$\beta_n = \cos^2(S_n * \pi/2) / (\cos^2(S_n * \pi/2) + \sin^2(S_n' * \pi/2)).$$

In another embodiment, the second electro-optical
light transmitting element is used, and the second
signal is measured from the second electro-optical
15 light transmitting element, and the hypotheses correspond
to different possible voltage values of the partial voltage
applied to the first electro-optical light transmitting
element.

Another embodiment comprises the steps of:
20 using at least two electro-optical light transmitting elements
and subjecting them to individual partial voltages,
measuring the first signal for each n-th electro-optical
light transmitting element and using it as the n-th
base signal indicative of the electric field over that
25 n-th electro-optical light transmitting element, determining
the second signal for each n-th electro-optical light
transmitting element and using it as the n-th reference
signal for resolving the ambiguity in the deriving
of the n-th partial voltage over that n-th electro-optical
30 light transmitting element, and for each n-th electro-optical
light transmitting element performing the method steps (iii),
(iv), (v) and (vi) to disambiguate the partial voltage
over that n-th electro-optical light transmitting element,
and determining the full voltage
35 between the first and second terminal from the partial
voltages.

In an embodiment, the electro-optical light transmitting elements are optically read out in parallel.

In another embodiment, exactly one electro-optical light transmitting element is used, and the hypotheses correspond to different possible voltage values of the full voltage between the first terminal and the second terminal.

Yet another embodiment comprises performing for each n-th electro-optic light transmitting element and its corresponding base signal and/or reference signal (S_n') the steps of: reconstructing a waveform of the measured voltage, in particular the full voltage and/or partial voltage between the first terminal and the second terminal, calculating a time average over a number of periods of the reconstructed waveform, determining from the time average an apparent DC offset voltage V_{DC} , and calculating a relative phase Δ_n of the base signal and/or reference signal (S_n'), in particular a relative phase shift with respect to the applied voltage V_n , according to $\Delta_n = V_{DC} * \pi / V_{h,n}$, with $V_{h,n}$ = half-wave voltage of the nth electro-optic light transmitting element.

Another aspect of the invention, in particular a further embodiment, comprises the steps of: (i) using the first signal as a base signal indicative of the electric field over the first electro-optical light transmitting element,

(ii) using the second signal as a reference signal for resolving the ambiguity in the deriving of the voltage, (iii) determining from the first signal two hypotheses corresponding to different possible voltage values of the voltage, (iv) determining the actual relative phase shift between the base signal and the reference signal, (v) determining from the base signal, the reference signal and the actual relative phase shift a synthetic quadrature signal having an ideal relative phase shift of 90° , and (vi) taking a binary decision between

the hypotheses based on the sign of the synthetic quadrature signal.

In an embodiment, the step (vi) of taking the binary decision comprises: selecting the more positive of the possible voltage values V_1^{h-} and V_1^{h+} , if the sign is negative and $\Delta=+90^\circ$, and selecting the more negative of the possible voltage values V_1^{h-} and V_1^{h+} , if the sign is positive and $\Delta=+90^\circ$; and vice versa if $\Delta=-90^\circ$.

In an embodiment, the step (v) comprises: calculating the synthetic quadrature signal ($S_n'^{\text{quad}}$) according to the formula $S_n'^{\text{quad}} = \cos^{-1}(2*\pi*\Delta) * S_n' + \tan(2*\pi*\Delta) * S_n$.

In an embodiment, at least two electro-optical light transmitting elements (sensor modules, e.g., comprising electro-optical crystals, poled waveguides, or piezo-electric devices), are arranged in the electric field between two spaced-apart terminals with the to-be-measured voltage applied to the terminals. Light, advantageously linearly polarized light, is then passed through the electro-optical light transmitting elements. By means of the properties of the electro-optical light transmitting elements, at least a first and a second signal indicative of the electric fields over the respective electro-optical light transmitting elements are then measured. These first and second signals are periodic functions of the applied voltage. Thus, by combining the at least two signals, the voltage between the first and the second terminal can be derived and ambiguities in the first signal are resolved using the second signal. Therefore, as an advantage over prior art, only one second signal (from one electro-optical light transmitting element) is sufficient to resolve ambiguities in the voltage calculation based on the first signal from the other electro-optical light transmitting element. This results in simpler optics which is cheaper and advantageous in terms of size.

In an embodiment, the first and the second signals have the same periodicity of the voltage V or are scaled such that they have the same periodicity of the voltage. Furthermore, the first and second signals have a relative phase shift other than zero, i.e., the phase of the second signal is shifted with respect to the phase of the first signal. In an embodiment, the nonzero phase shift of the second signal with respect to the first signal is introduced by a phase shifting element which is arranged in an optical path at the second electro-optical light transmitting element. This phase shifting element is, e.g., a $\lambda/4$ retarder and thus a quadrature readout is enabled.

In an embodiment, the phase shift of the second signal with respect to the first signal is dependent on the temperature of the phase shifting element. Thus, in a preferred embodiment, the temperature of the phase shifting element can be derived from the second signal. This derived temperature can then, for example, be used for computational compensation of a temperature dependence of the measured signals and hence for a computational compensation of the temperature dependence of the derived voltage between the first and the second terminal. Thus, a better accuracy can be provided.

In an embodiment, the two signals are based on electric field-dependent changes of a physical property of the light beams, for example, the phase of two orthogonal linearly polarized light waves per electro-optical light transmitting element. Then, e.g. after interference of these light waves at a polarizer at the end of each electro-optical light transmitting element, the resulting light intensity signals are converted to an electrical signal per crystal, e.g., by photodiodes.

In an embodiment, the electro-optical light transmitting elements are arranged in series, i.e. electrically in series (i.e. one after another along the z -axis in a longitudinal or axial direction) between the

terminals. Thus, the electric field is distributed over the single electro-optical light transmitting elements, which leads to simpler insulation and cheaper implementation.

5 The to-be-measured voltage between the terminals is in particular an AC voltage and/or in the high-voltage range, in particular in the range between 75 kV and 800 kV or even more. Thus, voltages in substations of power transmission networks can be measured.

10 After a first time interval $[t1; t2]$ with voltage ranges leading to a periodicity of the measured signals as functions of the voltage (i.e. the whole period of the measured signals is covered, or, in other words, the measured signals as periodic functions of the
15 voltage reach their maximum and minimum values), an advantageous embodiment of the disclosed method and/or device is also suitable for measuring small voltages during a second time interval $[t3; t4]$. The term "small voltage" refers to a range of voltages that is too small for the
20 measured signals to reach their maximum and minimum values (i.e. to cover the full period of the measured signals). The capability of measuring small voltages is advantageous in the case of a voltage-drop due to, e.g., a malfunction in the power transmission network. The time
25 gap $(t3-t2)$ between the first time interval and the second time interval is larger than one voltage signal period to enable "small voltage" detection. Then, scale and/or offset parameters that has or have been derived during the first time interval $[t1; t2]$ is or are kept
30 constant for deriving the voltage V between the terminals during the second time interval $[t3; t4]$. Thus, an accurate deriving of the voltage is possible even for voltage ranges that do not cover the full period of the measured signals.

35 In an embodiment, only one signal per electro-optical light transmitting element is measured. This results in simpler optics.

In another embodiment, at least one internal parameter α_n , e.g. the fraction of the total voltage V that is applied to a single electro-optical light transmitting element (or another value descriptive of a distribution of the voltage over the electro-optical light transmitting elements), is recursively derived based on its most common value. Due to a recursive tracking of the internal parameter α_n , its exact values are not needed during a first initialization.

In another preferred embodiment, at least three electro-optical light transmitting elements are arranged in series in the electric field between the terminals and at least three signals indicative of the electric fields over the respective electro-optical light transmitting elements are measured. By combining all signals, the voltage between the first and the second terminal can be derived. In this process, ambiguities in all signals can be resolved.

Furthermore, a device which is adapted to carry out a voltage measurement by means of a method according to the invention is provided.

In summary, in the invention, the step of resolving the ambiguity in the first signal comprises a step of taking a binary decision between two hypotheses. These hypotheses correspond to different possible voltage values given the measured value of the first signal. The binary decision further comprises a derivation of an expected value of the second signal for each of the hypotheses and a comparison of the expected value to a measured value of the second signal. Thus, an unambiguous solution can be found.

Brief Description of the Drawings

The invention will be better understood and objectives other than those set forth above will become apparent when consideration is given to the following de-

tailed description of the invention. This description makes reference to the annexed drawings, wherein:

Fig. 1 (prior art) shows a schematic representation of an optic voltage sensor,

5 Fig. 2a, 2b, 2c, 2d show different configurations for electro-optical voltage sensors,

Fig. 3 shows an arrangement of two electro-optical light transmitting elements in the electric field between two terminals,

10 Fig. 4a, 4b show flowcharts of a method for measuring a voltage between a first and second terminal with a plurality of electro-optical light transmitting elements and with a single electro-optical light transmitting element, respectively,

15 Fig. 5 shows a signal with period numbers, or more precisely a count k of zero crossings,

Fig. 6a, 6b, 6c show disambiguation procedures using a reference or quadrature signal,

20 Fig. 7 shows a first procedure to measure a phase between a base signal and a reference signal,

Fig. 8 shows a second procedure to measure a phase between a base signal and a reference signal,

25 Fig. 9 shows an arrangement of three electro-optical light transmitting elements in the electric field between two terminals, and

Fig. 10a, 10b, 10c show a method for an improved reconstructing of a voltage waveform from a base signal and reference signal.

30 Modes for Carrying Out the Invention

A method and device for measuring a voltage between two terminals, in particular an AC voltage in the high-voltage regime, is disclosed. Advantageously, the method and/or device relies on an electro-optic effect in
35 an electro-optical element. This electro-optic effect introduces, e.g., a different optical phase shift in two perpendicularly polarized light waves that travel through

the electro-optical element. Thus, a signal indicative of the electric field at the position or over the length of the electro-optical element can be measured. Ambiguities in the signals are resolved by an additional quadrature
5 signal. By arranging a plurality of these electro-optical elements in series between the terminals, advantages in terms of cost efficiency and insulation are achieved, but resolving the ambiguities of the signals becomes more challenging, particularly for unequal and/or varying
10 voltages over the single electro-optical elements (and consequently unequal periodicity of the measured signals) as well as for varying relative phases of signals.

The invention relates to a method for accurately reconstructing the waveform of the applied voltage
15 between the terminals, may it be the full voltage or a partial voltage or both, using a base signal S_n , for example S_1 , indicative of the electric field over the first electro-optical light transmitting element and a reference signal S_n' , for example S_2 , for resolving the ambiguity in the deriving of the voltage. The method comprises:
20 determining from the first signal S_n at least two hypotheses h^+ , h^- corresponding to different possible voltage values v^{h^+} , v^{h^-} or $V_n^{h^+}$, $V_n^{h^-}$, for example $V_1^{h^+}$, $V_1^{h^-}$, of the voltage V or V_n , deriving an expected value
25 $S_n^{h^+}$, $S_n^{h^-}$, for example $S_2^{h^+}$, $S_2^{h^-}$, of the second signal S_n' for each of the hypotheses h^+ , h^- , comparing the expected values $S_n^{h^+}$, $S_n^{h^-}$ to a measured value of the second signal S_n' , and taking a binary decision between the hypotheses h^+ , h^- by validating that hypothesis h^+ or h^-
30 for which the expected value $S_n^{h^+}$ or $S_n^{h^-}$ is closest to the measured value of the second signal S_n' .

In an embodiment, exactly one electro-optical light transmitting element 2 is used, and the hypotheses h^+ , h^- correspond to different possible voltage values
35 $V_1^{h^+}$, $V_1^{h^-}$ of the full voltage V between the first terminal 1a and the second terminal 1b.

Embodiments disclose a method for accurately reconstructing the waveform of the applied voltage between the terminals using a plurality of electro-optical elements but not requiring a quadrature signal for each electro-optical element. Furthermore, the temperature of the system can be derived from the phase of the quadrature signal and it can be used to compensate for the temperature dependence of the electro-optic effect itself. Furthermore, a method for deriving a small voltage (i.e. the voltage being much smaller than the rated voltage and the electro-optic phase shift being within $\pm 180^\circ$) is disclosed. Furthermore, a device for measuring a high-voltage is disclosed.

Definitions:

The term "high voltage" designates AC voltages exceeding 1 kV or DC voltages exceeding 1.5 kV and, in particular, voltages exceeding 75 kV.

The terms "radial" and "axial" are understood with respect to the axial direction (parallel to the axis of the light beam $h\nu$, z-axis) of the sensor, with "radial" designating a direction r perpendicular to the axial direction and "axial" designating a direction parallel to the axial direction z .

25

Description of the invention:

As shown in Fig. 1 (prior art), an electro-optical light transmitting element 2 comprises an optical sensor 21 (e.g. an electro-optic crystal) introducing a field-dependent phase shift between a first polarization or mode and a second polarization or mode of light passing through it. This light can, e.g., be guided to the optical sensor 21 through an optical fiber 27 and a coupling lens 26. Ideally, an electro-optical light transmitting element 2 measures the line integral $\int E \cdot ds$ of the electric field between two electric potentials 1a, 1b, e.g. ground 1b and high voltage potential 1a. This con-

cept is particularly suited for outdoor installations, e.g. substations in power transmission networks, because the measurement accuracy is not deteriorated by field perturbations, e.g. due to rain or ice or crosstalk from neighboring phases. Electro-optic crystals 21 of certain symmetry are well suited to implement this concept.

An electric field applied to an electro-optical crystal 21 induces an anisotropic change in the refractive index of the material (birefringence). This birefringence (or change of birefringence) causes a phase shift between two orthogonally linear polarized light waves traversing the crystal 21 (Pockels effect). By measuring this phase shift, the applied voltage can be derived. One configuration of an electro-optical light transmitting element 2, which implements line integration of the electric field, is shown in Fig. 1: The voltage V is applied to the end faces of a crystal 21 with the light also entering and leaving the crystal through the end faces. The crystal material and its axis orientation are chosen such that only electric field components E_z (pointing along the cylinder) contribute to the electro-optic phase shift. One suitable material is $\text{Bi}_4\text{Ge}_3\text{O}_{12}$ (BGO) in a [001] configuration, corresponding to the 4-fold crystal axis being parallel to the direction of light propagation. The input light $h\nu$ (broad arrow) is linearly polarized by a first polarizer 22 (thinner arrows indicating the direction of a transmitted polarization; the first polarizer 22 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 Γ between the components of the light with polarizations parallel to x' and y' is caused by the electric field in the crystal 21 and is converted to an amplitude modulation of the transmitted light by a second polarizer 23 arranged at the output end of the crystal 21. To bias the phase shift Γ , an additional

phase shifting element 3 (adding a phase ϕ) may be placed in the optical path (between the two polarizers 22, 23). The principal retarder axes e_1 and e_2 are aligned parallel to the electro-optic axes x' and y' of the crystal 21. In general, the intensity I of the transmitted light after the second polarizer 23 is of the form $I \sim \cos^2(V)$. The retarder 3 is advantageously a $\lambda/4$ waveplate.

For typical voltages V at high-voltage substations, an ambiguous sensor response is usually achieved. This ambiguity is classically resolved by working with two optical output paths per crystal that are substantially $\pi/2$ (90°) out of phase, i.e. that are in quadrature, or that have any other relative phase shift that is not a multiple of π .

Fig. 2a - 2d show optical sensor arrangements that can be used in the measuring method of the present invention.

In Fig. 2a, the sensor crystal 21 is used in reflection using a reflecting prism 28, and in Fig. 2d in transmission. The light is transmitted via optical 27, coupling lens 26 and first polarizer 26 into the crystal 21. After the crystal 21, the light is split via beam splitter 24 into two optical paths, namely one path comprising, e.g., a deflection prism 25 and a second polarizer 23 and photodetector 4a (shown in Fig. 3) coupled to the optoelectronic unit, and another path comprising a phase shifting element 3 and a further second polarizer 23 and a further photodetector coupled to the optoelectronic unit 4. Thus, the 90° -phase shift may be generated by splitting the light that leaves the crystal 21 into two paths by means of the beam splitter 24 and the deflection prism 25 and arranging the phase shifting element 3 in one of the paths.

In a voltage sensor comprising at least a first and a second electro-optical light transmitting element 2a and 2b (Fig. 3), a base signal S_1 or in general S_n and a quadrature signal $S_1' = S_2$ or in general S_n' may

be generated by inserting a phase retarder 3 into the optical path at one of the electro-optical light transmitting elements (here: electro-optical light transmitting element 2b as in Fig. 2c) and operating the other electro-optical light transmitting element(s) (here: electro-optical light transmitting element 2a as in Fig. 2b) without a retarder. As a consequence, there is only one output path per crystal (as in Figs. 2b and 2c). Extra beam splitters 24 and deflection prisms 25 for a quadrature path per crystal 21 (as in Fig. 2a) are thus avoided. As a result the device becomes significantly smaller (and cheaper), which allows to mount the sensing elements in a relatively narrow bore.

In the shown embodiment, light is guided to and from the electro-optical light transmitting elements 2a, 2b through optical fibers 27. The light is usually produced by a light source 4c (e.g. an LED or a laser) inside a light processing module 4 or optoelectronic unit 4. Transmitted light is detected inside the optoelectronic unit 4 by a photodetector 4a, 4b, such as a photodiode, per channel, which means here, e.g., per electro-optical light transmitting element 2a, 2b due to a single path being present per element. Alternatively, the photodetectors 4a, 4b could be integrated into the electro-optical light transmitting elements 2a, 2b themselves. A first and a second signal S_1 and S_2 , i.e. S_n with $n=1$ and $n=2$, which are indicative of the electric field over the respective electro-optical light transmitting element 2a and 2b are thus measured. A control unit 41 (consisting of a CPU 41a and a memory 41b) derives the voltage V between the terminals 1a and 1b based on the signals S_1 and S_2 . During the derivation, ambiguities in a single signal - or, in the case of more than two signals, ambiguities in a subset of the signals - are resolved by the quadrature signal $S_1'=S_2$. In other words, all pairs of measured signals produce an unambiguous output, in particular if one of, preferably exactly one of, the signals

is phase-shifted with respect to the other. Therefore, it is possible to measure only one signal S_1 and S_2 per electro-optical light transmitting element 2a and 2b and nevertheless to arrive at an unambiguous voltage signal V.

The voltage sensor shown in Fig. 9 is very similar to the voltage sensor discussed above, with the exception that it comprises an additional, e.g. a third, electro-optical light transmitting element 2c from which a third signal S_3 is measured via a third photodetector 4d.

The procedure for accurately reconstructing the waveform of the applied voltage V (even under unequal and varying partial crystal voltages V_n , and consequently under unequal periodicity of the optical signals S_n) as well as under varying relative signal phases is summarized in Fig. 4a for plural electro-optical light transmitting elements and in Fig. 4b for exactly one such element.

The procedure starts with an initialization stage, where (not necessarily accurate) initial values α_n^{init} and Δ_n^{init} are set for each electro-optical light transmitting element (see below). These parameters might be determined in a (semi-)automated way or provided manually by the operator. Then, for each measured signal S_n (e.g. from photodiodes 4a, 4b, ...) representing a light intensity level I from each n-th electro-optical light transmitting element 2a, 2b, ..., it is verified whether the applied voltage is "large", i.e. whether the signal(s) S_n reaches a minimum and a maximum, or whether the voltage is equal to or exceeds the half wave voltage or is smaller than the half wave voltage, for example whether an electro-optic phase shift $>\pm 180^\circ$ is induced or, in other words, the absolute value of the electro-optic phase shift exceeds 180° , or "small", i.e. whether the signal(s) S_n does not reach a minimum and a maximum, for example whether the electro-optic phase shift remains

within $\pm 180^\circ$ or, in other words, the absolute value of the electro-optic phase shift is smaller than or equal to 180° . When the voltage is "large", the amplitude of the acquired signal S_n is normalized to a given interval, e.g. to the interval $[-1;1]$, in order to eliminate gain and offset differences amongst the channels or paths due to the measurement chain (here e.g. photodiode - amplifier). When the voltage is "small", the signal S_n is not normalized in order to preserve the correct information about amplitude, and thus about the applied voltage (see below). In other words, when the voltage is "small", updating of the normalization parameters, such as gain, offset, etc., is disabled. Therefore, the most recent normalization parameters that had been obtained, i.e. updated, with "large" voltage are used.

Fig. 4b shows a largely similar procedure for the case of exactly one electro-optical light transmitting element 2, with the same or similar steps being applied as described above. The base signal is designated as S and the reference signal as S' . In particular, α_n are not needed, the initial phase shifts Δ_{init} , Δ'_{init} of the base signal and reference signal, or their relative initial phase shift $\Delta_{init} - \Delta'_{init}$, are used, and the full voltage V can be directly determined without summation over n . In addition, an auxiliary control loop can comprise updating or refining of the phase shifts Δ and Δ' , or $\Delta - \Delta'$, by separating the ac and dc voltage components from each other and calculating Δ and Δ' , or $\Delta - \Delta'$, from the dc component (see Fig. 8). Such updating or refining can be applied both in Fig. 4a and Fig. 4b.

Now continuing with Fig. 4a, the partial voltage V_n applied to each n -th electro-optical light transmitting element 2a, 2b, ... is determined from S_n in two steps: The first step is to count the zero-crossings in S_n , as it is illustrated in Fig. 5. This is used to determine the period K of the cosinusoidal response and provides a first, coarse approximation of the applied

voltage V_n . This approximation can then (if necessary) be refined by computing the remainder or approximation error, which is given by the inverse response (usually the arccosine function) of the sensor. The sum of the zero-crossings approximation and of the remainder gives the applied voltage V_n .

The total voltage V between the terminals 1a and 1b is finally given by the sum of all partial voltages V_n : In the embodiment of the invention from Fig. 3, the high-voltage sensor is composed of several electro-optical light transmitting elements 2a, 2b. Each electro-optical light transmitting element 2a, 2b can be inserted in an insulator with a central bore containing, e.g., a BGO crystal 21. The total voltage between terminals 1a and 1b is denoted by V . The partial voltage applied to a given electro-optical light transmitting element 2a, 2b, ... is denoted by V_n . The total voltage V is then the sum of all partial voltages: $V = \sum V_n$. Conversely, partial voltages V_n are defined by the fraction α_n of the total voltage V that is applied to the corresponding module: $V_n = \alpha_n \cdot V$. As mentioned earlier, partial voltages might differ and vary in time. Therefore, $\alpha_n \neq \alpha_m$ if $n \neq m$ and $\alpha_n = \alpha_n(t)$ may occur. The intensity I_n of the light beam exiting each electro-optical light transmitting element 2a, 2b, ... is given by the following expression:

$$I_n = I_{n,0} \cdot \cos^2(\pi(\Gamma_n + \Delta_n)) \quad (1)$$

$$\Gamma_n = \frac{V_n}{2V_{h,n}} \quad (2)$$

where $I_{n,0}$ is the intensity of the exiting beam with zero retardation, Γ_n expresses the voltage-dependent retardation (field-dependent phase shift) between the two polarized light components when they exit the crystal 21, and Δ_n is the relative phase of the n -th signal with respect to the applied voltage. $V_{h,n}$ is the half-wave voltage of the BGO crystal 21 in optical channel n . This is the

voltage that leads to the retardation of $\Gamma_n=1/2$. In equation (1), it is assumed that the modulation depth of the optical signal is equal to unity. The relative phases Δ_n of the signals can differ and vary in time depending on temperature, as mentioned earlier. Therefore, $\Delta_n \neq \Delta_m$ if $n \neq m$ and $\Delta_n = \Delta_n(t)$ may occur.

The electrical signals S_n produced by the measurement chain (photodiode - amplifier) is then given by

10

$$S_n = G_n \cdot I_n + b_n + e_n \quad (3)$$

where G_n is the cumulated gain of all components in the measurement chain, and b_n is an offset. The term e_n is a noise term.

15

Measurement of the applied voltage

As mentioned above, in the first signal processing stage (Fig. 4a, 4b), the amplitude of each electrical signal can be normalized to the interval $[-1; 1]$. This operation eliminates the gain and offset parameters from equation (3) (the noise term e_n has been neglected here):

20

25

$$S_n^{Norm} = 2 \cdot \cos^2(\pi(\Gamma_n + \Delta_n)) - 1 \quad (4)$$

Signal normalization is simply achieved by applying the scale and offset factors that map the minimum or maximum of the actual response to the desired, normalized minimum or maximum (i.e., -1 and 1):

30

$$scale = 0.5 \cdot (max - min) \quad (5)$$

$$offset = min + scale \quad (6)$$

35

$$S_n^{Norm} = \frac{S_n - offset}{scale} \quad (7)$$

To solve the above equations, both response extrema min (=minimum) and max (=maximum) shall be determined. This means in turn that response normalization can only be done when the electro-optic phase shift induced by applied voltage between the terminals 1a and 1b is above $\pm 180^\circ$, i.e. a "large" voltage is measured. Otherwise, the scale and offset factors must be kept constant until the above condition is fulfilled again (see "Measurement of small voltages" below). In the second stage, all partial voltages V_n are determined by solving equations (1)-(4) for V_n . This leads to

$$V_n = \frac{V_{h,n}}{\pi} \left(\left(\pm \arccos \left(\frac{2(S_n - b_n)}{G_n \cdot I_{n,0}} - 1 \right) + K \cdot 2\pi \right) - 2\pi \Delta_n \right) \quad (8)$$

Note that after signal normalization, $G_n=1$ and $b_n=0$. In equation (8), it is apparent that due to the periodicity of the (arc-)cosine, V_n can only be resolved up to the factor $2 \cdot K \cdot V_{h,n}$ when K = number of periods is unknown. In order to determine K , i.e. the period of the sinusoidal response of the electro-optical light transmitting element that corresponds to the applied voltage V_n , a bidirectional count k of the number of zero crossings of the measured signal S_n is used. In fact, the number k of zero crossings changes twice per period K . The zero-crossings counting procedure is derived from US 5'001'419, which in its entirety is herewith made part of the disclosure by reference. Two optical signals at quadrature are considered: The count k is incremented as the voltage waveform represented by the base signal is becoming more positive and is decremented as the magnitude of the represented waveform is becoming more negative. The base signal is the signal for which the parameter of interest, e.g. here the number of zero crossings, is determined. The quadrature signal is another signal - in our case from a different electro-optical light transmitting element 2a, 2b,

... - that has been delayed with respect to the base signal, e.g. by using a phase shifting element 3. The direction in which the waveform is moving is determined by which of the signals (base signal or quadrature signal) is leading. Reversal of the direction of the voltage waveform results in a switch in which one signal is leading and can therefore be detected by two consecutive zero crossings in the same signal.

In order to avoid random indexing of the bidirectional cumulative count k of zero crossings, which could occur with small signals, a dead band is created around the zero axis. Zero crossings are not counted while the signal is in this dead band. Instead, a determination is made when the signal again leaves the dead band as to whether the zero crossings should be indexed:

- If the signal exits the dead band on the same side that it entered, then the target signal has changed direction and k should not be indexed;
- if the signal exits the dead band on the opposite side from which it entered, then there has been a zero crossing and k is indexed.

Note that if the zero crossings counter k can be set to zero when the voltage is zero, then subsequent voltage measurements will be correct. In general, however, the voltage at startup (during the initialization) is not known and therefore k is arbitrary. Under the assumption that the applied voltage is purely AC, k can be adjusted in integer steps until the average value of the calculated voltage over one cycle is zero. After k has been properly adjusted, the calculated voltages will be correct until the program is interrupted.

It is apparent in equation (8) that measured voltage V_n is given by the sum of two distinct terms. The first term, $K \cdot 2\pi$, is approximated using cumulative zero crossings counting as discussed above. Computation of the second term, $\arccos(2(S_n - b_n)/(G_n \cdot I_{n,0}) - 1)$, will be dis-

cussed next: Fundamentally, equation (8) must be solved for V_n given the signal S_n , with period number K known from zero-crossings counting k . The sign of the arccosine cannot be determined from S_n alone. Therefore, the quadrature signal is additionally used in order to disambiguate the sign. The corresponding procedure is illustrated in Fig. 6a, and in even more detail in Fig. 6b and 6c. Fig. 6a shows the base signal S_1 , or more general S_n , with zero phase shift $\Delta=0$ and the reference signal S_1' , or more general S_n' , with ideal quadrature phase shift $\Delta'=90^\circ$, both normalized to a range $[-1; +1]$, as a function of the high voltage in kilovolt. Fig. 6b and 6c show the corresponding raw base signal S_1 and raw reference signal S_1' oscillating between zero and maximum light intensity I_0 , or optical power respectively, around a medium light power $I_0/2$. As a remark, in this case, the count k of zero crossings, or equivalently periods, would correspond to counting crossings of the medium light power $I_0/2$.

Fig. 6b shows the case of two identical crystals 21 or identical electro-optical light transmitting elements 2a, 2b exposed to the same partial voltages $V_1 = V_2 = V/2$ and the base signal S_1 derived from one of them and the reference signal S_1' from the other, or equivalently the case of one crystal 21 or one electro-optical light transmitting element 2 with both base signal S_1 and reference signal S_1' derived therefrom. The x-axis shows the voltage V normalized to the half wave voltage V_π . The signal S_1 is basis for two hypothetical reference voltages V_1^{h-} and V_1^{h+} , of which V_1^{h-} is validated by finding most similarity of closeness of the corresponding hypothetical reference signal S_2^{h-} with the measured reference signal $S_1'=S_2$.

Fig. 6c shows the case of two crystals 21 or electro-optical light transmitting elements 2a, 2b exposed to different partial voltages V_1, V_2 , i.e. with different α_1 and α_2 . The base signal S_1 is derived from one of them

and the reference signal S_1' from the other. The x-axis shows the voltage V normalized to the (common) half wave voltage V_π . The broadened signal S_1 is basis for two hypthetic reference voltages V_1^{h-} and V_1^{h+} , derived from the relevant S_1 values (full dots) by multiplying with the ratio α_2/α_1 , of which V_1^{h-} is validated by finding most similarity or closeness of the corresponding hypothetical reference signal S_2^{h-} with the measured reference signal $S_1'=S_2$.

In more detail, two hypotheses h^+ and h^- are generated:

$$h^+ : V_n^{h+} \propto +\arccos(\cdot)$$

$$h^- : V_n^{h-} \propto -\arccos(\cdot)$$

The voltage V_n under both hypotheses, V_n^{h+} and V_n^{h-} , is then calculated using equation (8). Subsequently, the quadrature signal response under both hypotheses, S_n^{h+} and S_n^{h-} , is computed. This is done by inserting V_n^{h+} and V_n^{h-} into the following expression, derived from equations (1)-(4):

$$S_n^h = G_{n'} \cdot I_{n',0} \cdot \cos^2 \left(\pi \left(\frac{V_{n'}^h}{2V_{h,n'}} + \Delta_{n'} \right) \right) + b_{n'} \quad (9)$$

Note that in equation (9), n' is the index of the quadrature signal (e.g., $n'=2$) that is used to disambiguate the sign, not the index n of the signal whose voltage is computed: $n' \neq n$. Finally, the hypothesis with the calculated quadrature signal response S_n^{h-} (expected value) that is closest (in terms of Euclidean distance) to the measured quadrature signal response S_n' is validated.

As mentioned above, the sign of the arccosine is disambiguated by "projecting" both voltages V_n^{h+} and V_n^{h-} onto the quadrature response in order to verify which hypothesis produces an image that matches the measured quadrature signal most closely. Since it is possible

that the voltage fractions applied to the base path and to the quadrature path differ ($\alpha_n \in [0;1]$), it is necessary to convert from the voltage over one element to the voltage over the other element prior to comparison.
 5 This is achieved by expressing one response as a function of the other one:

$$\begin{aligned} V_n &= \alpha_n \cdot V \\ V_{n'} &= \alpha_{n'} \cdot V \\ \Rightarrow V_{n'} &= \frac{\alpha_{n'}}{\alpha_n} \cdot V_n \end{aligned} \quad (10)$$

Determination of the alphas

It has been mentioned earlier that partial
 15 voltages might be unequal and varying in time. I.e., $\alpha_n \neq \alpha_m$ if $n \neq m$ and $\alpha_n = \alpha_n(t)$. The partial voltage applied to each electro-optical light transmitting element 2a, 2b, ... can be determined by rewriting the definition of α_n :

$$\alpha_n = \frac{V_n}{V} \quad (11)$$

In equation (11), α_n is calculated using the measured partial voltages V_n and the total voltage V . On the other hand, the α_n must be known in order to compute
 25 V_n , and thus V , using equation (8). This means that in general, α_n must be known in order to compute V_n and V , and the voltages are required to compute α_n .

However, this apparent contradiction is loosened by observing that in the measurement of the applied
 30 voltage, the purpose of α_n is only to disambiguate the sign of the arccosine. Specifically, compensation for different α_n is done prior to the data association step illustrated in Figs. 6a, 6b, 6c. Since the outcome of this step is a binary decision, i.e. positive or negative
 35 sign, the decision will be correct even with slightly erroneous α_n as long as the measured quadrature signal re-

sponse S_n , is "much closer" to one calculated signal response S_n^h than to the other one.

With AC voltage, the above observation implies that most of the time (or equivalently, for most voltages V_n), the $\alpha_n = f(V_n(t))$ calculated using equation (8) will be correct. α_n will only be erroneous when V_n , and thus V , is wrong due to an incorrect hypothesis selection. Therefore, α_n is correct "most of the time" or, equivalently, the correct α_n is given by most common value or mode of α_n .

α_n tracking control loop

Normally, the exact α_n are not known during initialization. In fact, they are usually not known at any time because α_n depend on stray fields, mechanical variations of the sensor, etc. Therefore, the auxiliary control loop should be initialized with an estimate of α_n for all optical channels n . Then, a first series of measurements is taken and based on the resulting V_n , more exact α_n are calculated using equation (11) and the mode of the α_n . These new estimates of α_n are used for the following calculations of V_n , which are in turn used to refine α_n , etc. Thus, α_n are converging.

The above describes an auxiliary control loop that tracks the α_n based on incoming voltage measurements. The optimal refresh rate of the control loop must be determined experimentally; however, it is expected to correspond to a few periods of the applied (AC) voltage.

Measurement of delta and extraction of the retarder temperature

The actual retardation introduced by the phase shifting element 3 varies (approximately linearly) with temperature, whereas the temperature dependence of the phase of the optical channels without retarder is weak. Therefore, the temperature of the retarder can be extracted from the phase difference between the quadrature

signal S_n' (with phase shifting element 3) and the base signal S_1 (without retarder). This information will in turn be used to compensate the sensor output for the temperature dependence of the electro-optic effect.

5 In order to measure the relative signal phase Δ_n for any channel n , equation (8) is solved for Δ_n when $V_n=0$ (therefore, $k=0$), as illustrated e.g. in Fig. 7, or alternatively in Fig. 8 (see below). With the normalized signal ($G_n=1$ and $b_n=0$), this leads to the following expression:
10

$$\Delta_n = \pm \frac{V_{h,n}}{2\pi^2} \arccos\left(\frac{2(S_n)}{I_{n,0}} - 1\right) \quad (12)$$

Solving equation (8) when $V_n=0$ is useful because at this
15 specific point, the response is dependent on the relative phase Δ_n , but not on the applied voltage fraction α_n . However, this implies that the right time instant (sample) must be determined when $V_n=0$.

The procedure to find this time instant when
20 $V_n=0$ is summarized next: First, the returning points R1 and R2 of the applied voltage can be located under the assumption that the excitation signal is purely AC (i.e. mean value=0). This is a reasonable assumption under normal operating conditions; whenever the assumption does
25 not hold, computation of Δ_n is temporarily disabled. DC components in the applied voltage can be detected by computing the mean value of the reconstructed voltage V over one or several periods.

An easy way to locate R1 and R2 is to scan the
30 response signal for two successive extrema which are equal to neither 0.5 nor -0.5. However, this does not work for certain values of input signal amplitudes.

An alternative method to locate the returning
points R1 and R2 is to use the zero crossings count output k . The returning points R1 and R2 are located on the
35 extrema (either minimum or maximum, determined, e.g., by second derivative) of the measured signal (base or quad-

rature) that are located within the time period where the counter output k is maximal or minimal. These extrema of k indicate the returning points of the applied voltage V , since k is an approximation of V .

5 In Fig. 8 an alternative method to measure a relative phase Δ between a base signal and the applied voltage V is shown. In an ideal optical voltage sensor, the two optical signals that are produced by the sensor are in exact quadrature. Usually, the base signal S has a
10 phase shift $\Delta=0^\circ$, whereas the reference signal S' is given a phase shift $\Delta'=90^\circ$ by inserting a quarter-wave retarder in the corresponding optical path. In real systems, the phase shifts are generally not equal to their ideal values $\Delta=0$ and $\Delta'=90^\circ$. This is due to temperature
15 dependencies and inaccuracies of the quarter-wave retarder as well as other physical effects. Thus in order to insure accurate reconstruction of the applied voltage, the real phase shifts Δ and Δ' must be determined.

The proposed procedure for determining phase
20 shifts is based on the following observation: the effect on the intensity signal S of a non-zero phase shift $\Delta \neq 0$ is identical to the effect of an applied voltage with non-zero DC component $DC \neq 0$. This is illustrated in Fig. 8. A pure AC voltage ($DC=0$) is applied to both optical
25 paths with $\Delta=0$ and with $\Delta \neq 0$. The resulting intensity signal S is shown in black for $\Delta=0$ and in grey for $\Delta \neq 0$, respectively. Furthermore, the intensity signal with $\Delta=0$ for an applied voltage is not pure AC ($DC \neq 0$) is plotted in grey. Clearly, the grey signal due to the non-zero
30 phase shift and the grey signal due to the DC component in the applied voltage are identical.

If it is now assume that the actual applied voltage is purely AC, then any DC offset that is apparent in the reconstructed voltage must be entirely due to the
35 phase shift $\Delta \neq 0$. Therefore, the phase shift can be determined by:

Determining the apparent DC offset in the reconstructed voltage V by computing $DC = \text{mean}(V_{\text{reconstructed}})$, and

Calculating the corresponding phase shift Δ :

$$\Delta = \frac{DC * \pi}{V_h}$$

5

with V_h = half wave voltage. The same procedure can be applied to determine the phase shift Δ' of the reference signal S' with respect to the applied voltage V .

10

Measurement of small voltages

The invention also provides a mechanism for determining the applied voltage V between the terminals 1a and 1b in cases where the voltage V is much smaller than the rated voltage and the electro-optic phase shift is therefore within $\pm 180^\circ$. Specifically, the measurement of voltages that lead to phase shifts smaller than or within $\pm 180^\circ$ is identical to large voltages (as described above), but with two differences:

- No signal normalization. Phase shifts smaller than or within $\pm 180^\circ$ lead to signals that do not cover the entire possible output amplitude range. I.e., the intensity I of the light beam exiting the electro-optical light transmitting element 2a, 2b, ... as given by equation (1) does not cover the entire admissible range $[0; I_n, 0]$. Therefore, updating of signal normalization must be disabled in order to preserve the correct information about signal amplitude, and thus about the applied voltage.

- No measurement of delta. Since the estimation of Δ_n , and thus of the temperature, relies on zero-crossings in the response signal, this cannot be performed when the electro-optic phase shift is within $\pm 180^\circ$.

To detect voltages V with phase shift below or within $\pm 180^\circ$, one cannot rely on the voltage measurement

35

itself, because this is obviously only available after signal normalization has been done. Instead, one relies on the scale and offset factors produced by the normalization procedure in equations (5)-(6) when the voltage was still "large". In fact, in a first time period [t1; t2] with t2>t1 the phase shift must be above or outside $\pm 180^\circ$ (i.e., full output amplitude range covered, "large" range of voltages applied to the terminals 1a and 1b). Then, scale and offset remain approximately constant. When in a second time period [t3; t4] (with t4>t3), the phase shift drops below or within $\pm 180^\circ$, at least one of these factors would change rapidly (i.e., within one period of the voltage V), because the signal S_n needs to be rescaled.

Therefore, the voltage V or V_n is considered "small" (phase shift $< \pm 180^\circ$) when either

$$scale(t) - scale(t - \Delta) > \delta_{scale} \quad (14) \text{ or}$$

$$offset(t) - offset(t - \Delta) > \delta_{offset} \quad (15)$$

Here, δ_{scale} and δ_{offset} are threshold values that are used to detect significant or rapid changes in the corresponding parameters. Δ is the time interval that separates two consecutive evaluations of scale and/or offset. (Note: time interval Δ does not refer to a phase shift here!). For proper operation of the method, this time interval Δ must be small enough to ensure proper reaction time (no slowly changing voltages), but larger than one signal period (i.e. 20 ms at 50 Hz or 16.6 ms at 60 Hz).

Fig. 10a, 10b, 10c show in another aspect of the invention a method to improve the voltage waveform reconstructed from a base signal and reference signal.

Fig. 10a shows the sensor response (solid line: base signal S_n , dotted line: reference quadrature signal S_n') normalized to [-1, 1] for the ideal case where the phase shift between the two signals is $\lambda/4$.

If only one of the two signals is used for the voltage reconstruction, one ends up with regions of high sensor sensitivity, e.g. around $\pm V_n/2$ for the base signal S_1 , and regions where the sensitivity is low, e.g. near 0 V or $\pm V_n$. If the sensitivity of the sensor is low, even a small measurement error of the light intensity, e.g. due to noise or any error in signal normalization, will translate to a large error in the reconstructed voltage. It is thus of advantage to avoid using these regions of low sensitivity for voltage reconstruction.

The bold lines in Fig. 10a show the signal which has a higher sensitivity in a certain voltage region. Due to the nature of the signal response it is always that signal which is smaller in magnitude and thus closer to the linear region of the cosine function.

- Improved reconstruction using the more linear signal

Therefore, one embodiment is to reconstruct the voltage using always the "more linear" signal, i.e. the bold signal in Fig. 10a. The formula shown in Fig. 10b can be used. The parameter β_n can be chosen to be either 0 or 1, depending on which signal has the smaller magnitude. Thus, either the voltage reconstructed by the base signal S_n alone ($\beta_n = 1$) or by the quadrature signal S_n' alone ($\beta_n = 0$). This significantly improves the quality and accuracy of the reconstructed voltage waveform as the regions of low sensor sensitivity are avoided.

The method also works for cases where the phase shift between the two signals S_n , S_n' differs significantly from $\lambda/4$. Note that the voltage is still reconstructed using an arccosine function, and hence no approximations are used in contrast to the prior art.

- Improved reconstruction using a weighted average for two signals

In the improved reconstruction method using the more linear signal described above we end up with a sudden switch between the base and reference signals S_n , S_n' used for reconstruction. This can cause discontinuities

in the reconstructed voltage waveform. In particular, the errors caused for example by an erroneous normalization tend to have an opposite sign for the two signals S_n , S_n' near the location where one switches from one to the other signal.

By mixing the results from the reconstruction of both of the channels, such discontinuities can thus be removed and, in addition, such errors of opposite sign can be compensated for. For this purpose, the formula in Fig. 10c can be used by replacing the square function for the parameter β_n with a function, which continuously oscillates between 0 and 1, in particular $\beta_n = \cos^2(S_n * \pi/2) / (\cos^2(S_n * \pi/2) + \sin^2(S_n' * \pi/2))$. In Fig. 10c this parameter β_n is correspondingly represented exemplarily by a $\sin^2(V_n * \pi/V_{\Pi})$ function of the applied voltage, but it could also be a triangular curve or a more complex curve with steeper edges and flatter minima and maxima as a function of voltage. Herein, V_n = voltage over the n-th electro-optical light transmitting element and V_{Π} = half-wave voltage, for example $V_{\Pi} = V_{h,n}$ = half-wave voltage of the crystal in the nth electro-optic light transmitting element.

Notes:

Figs. 2a - 2c show arrangements where the electro-optical light transmitting elements 2, 2a, 2b are operated in reflection mode using a reflector 28, i.e., the light passes the optical sensor 21 twice. Alternatively, the electro-optical light transmitting element 2 may also be operated in transmission mode as in Fig. 1 or Fig. 2d, i.e. the light passes the crystal 21 only once.

Another option to remove the ambiguity instead of or additionally to using a quadrature signal is to operate the sensor with light of two different wavelengths.

The embodiments described here refer to one, two or three electro-optical light transmitting elements.

It should be noted, however, that the method and/or device according to the invention is or are suitable for any number of electro-optical light transmitting elements greater than one or two and/or more than two measured
5 signals. The measured signal from any electro-optical light transmitting element can be used to disambiguate the signal(s) from any other electro-optical light-transmitting element(s), in particular if at least one measured signal is phase-shifted with respect to the other
10 measured signal(s) (e.g., one element has a phase shifting element, the other one(s) not).

The role of "base" and "quadrature" signals in this invention is interchangeable, i.e., the quadrature signal can be used to resolve ambiguities in the
15 derivation of the voltage from the base signal, and/or the base signal can be used to resolve ambiguities in the derivation of the voltage from the quadrature signal.

It should be noted that the described hypotheses-method in the "Measurement of the applied voltage"-
20 section is in principle also suitable for disambiguating a "base" signal with a "quadrature" signal in a sensor in which both signals originate from the same electro-optical light-transmitting element, e.g. a classical sensor in which two paths (one without and one with a quarter-wave retarder) are read out from the same electro-
25 optical light-transmitting element.

Throughout this application, the index n shall designate the numbering of the electro-optical light transmitting elements. The index n is an integer
30 that runs from $n=1, 2, 3, \dots$.

Optical channel n corresponds to the n -th electro-optical light transmitting element 2, 2a, 2b, 2c, ... of the voltage sensor. The n -th element 2, 2a, 2b, 2c, ... or, e.g., n -th crystal 21 is subject to and is measuring
35 the n -th partial voltage V_n , and in the case of exactly one element 2, the full voltage $V=V_1$.

Splitting into two optical paths corresponds to creating a base signal S_1 and a reference signal S_1' . In general for n optical channels, splitting into two optical paths for the n -th channel corresponds to creating
5 a base signal S_n and a reference signal S_n' . These base signal S_1 or generally S_n and reference signal S_1' or generally S_n' may be generated from the same electro-optic light transmitting element 2, 2a, 2b, 2c or same crystal 21, or from different light light transmitting elements
10 2, 2a, 2b, 2c or crystals 21. For example, one may generate base signal S_1 from the first element and reference signal $S_1'=S_2$ from the second element, or base signal S_2 from the second element and reference signal $S_2'=S_1$ from the first element, or both base signal S_1 or generally S_n
15 and reference signal S_1' or generally S_n' from the same element $n=1$ or generally n . The base signal S_1 or generally S_n is the one that is disambiguated with the help of the reference signal S_1' or generally S_n' using the hypothesis tests according to the invention. The n -th base
20 signal S_n is indicative of the voltage V or partial voltage V_n over the n -th electro-optical light transmitting element. However, in particular when both base signal S_1 or generally S_n and reference signal S_1' or generally S_n' are derived from the same electro-optical light transmitting
25 element, both the base signal S_1 or generally S_n and the reference signal S_1' or generally S_n' may be used in reconstructing an improved waveform of the full voltage V or partial voltage V_n .

Please note, that the naming of the electro-optic light transmitting element 2, 2a, 2b, 2c as
30 "first", "second" etc. need not correspond to the index "n" being 1 or 2 etc, because at least one "first" element may be present. As well, the naming of the signals as "first", "second" etc. need not correspond to the index
35 "n" being 1 or 2 etc, because at least one "first" signal may be present.

Furthermore, the mentioned base signals S_n and reference signals S_n' shall be raw signals or partially normalized signals (e.g. offset to be symmetric relative to a zero line, or scaled in amplitude) or fully
5 normalized signals (e.g. offset and scaled to a value range $[-1; +1]$), as it may be needed or appropriate for the method step under consideration.

Reference numbers

	1a, 1b:	terminals
	2, 2a, 2b, 2c:	electro-optical light transmitting ele-
5		ment (sensor module)
	3:	phase shifting element
	4:	light processing module, optoelectronic
		unit
	4a, 4b, 4d:	photodetector
10	4c:	light source
	21:	optical sensor, e.g. electro-optic crys-
		tal
	22:	first polarizer
	23:	second polarizer
15	24:	beam splitter
	25:	deflection prism
	26:	coupling lens
	27:	optical fiber
	28:	reflector
20	41:	control unit
	41a:	central processing unit (CPU)
	41b:	memory
	S_1, S_2, S_3, S_n :	signals
	S_n :	base signal of n-th element or channel
25	S_n' :	reference signals of n-th element or
		channel
	V:	voltage
	I:	intensity

Claims

1. A method for measuring a voltage (V , V_n), in particular a full voltage (V) and/or a partial voltage (V_n) between a first terminal (1a) and a second terminal (1b),
5 wherein the first terminal (1a) is spatially separated from the second terminal (1b) and wherein the voltage (V , V_n) creates an electric field between the terminals (1a, 1b), the method comprising the steps of
- 10 arranging at least one first electro-optical light transmitting element (2, 2a) in the electric field between the first (1a) and the second terminal (1b),
passing light through the first electro-optical light transmitting element (2, 2a),
- 15 measuring at least one first signal (S_n) from the first electro-optical light transmitting element (2, 2a) and further measuring a second signal (S_n') from the first or a second electro-optical light transmitting element (2, 2a, 2b, 2c), wherein both signals (S_n , S_n') are periodic
20 functions of the voltage (V) and have a relative phase shift other than zero,
- deriving the voltage (V , V_n) and resolving an ambiguity in the deriving of the voltage (V , V_n) from the first (S_n) and the second signal (S_n'), characterized by the
25 steps of:
- (i) using the first signal (S_n) as a base signal (S_n) indicative of the electric field over the first electro-optical light transmitting element (2, 2a),
- (ii) using the second signal (S_n') as a reference signal
30 (S_n') for resolving the ambiguity in the deriving of the voltage (V , V_n),
- (iii) determining from the first signal (S_n) at least two hypotheses (h^+ , h^-) corresponding to different possible voltage values ($V_n^{h^+}$, $V_n^{h^-}$) of the voltage (V , V_n),
- 35 (iv) deriving an expected value ($S_n^{h^+}$, $S_n^{h^-}$) of the second signal (S_n') for each of the hypotheses (h^+ , h^-),

(v) comparing the expected values (S_n^{h+} , S_n^{h-}) to a measured value of the second signal (S_2), and
(vi) taking a binary decision between the hypotheses (h^+ , h^-) by validating that hypothesis (h^+ , h^-) for which
5 the expected value (S_n^{h+} , S_n^{h-}) is closest to the measured value of the second signal (S_n').

2. The method of claim 1, wherein exactly two hypotheses (h^+ , h^-) are determined and exactly one reference signal
10 (S_n') per base signal (S_n) is used, and/or wherein closeness of the expected values (S_n^{h+} , S_n^{h-}) to the measured value (S_n') is determined using Euclidean distance.

3. The method of any of the preceding claims, wherein the
15 base signal (S_n) is a cosinusoidal function of the voltage (V , V_n), and the voltage (V_n^{h+}) under the first hypothesis (h^+) is assumed to be proportional to $+\arccos$, and the voltage (V_n^{h-}) under the second hypothesis (h^-) is assumed to be proportional to $-\arccos$.

20

4. The method of any of the preceding claims, wherein during the derivation, ambiguities in a single signal or, in the case of more than two signals, in a subset of signals of the at least one first signal (S_n) and at least
25 one second signal (S_n') are resolved by at least one, in particular exactly one, of the signals being phase-shifted with respect to the other signals.

5. The method of any of the preceding claims, wherein a
30 waveform of the applied voltage (V) between the first terminal (1a) and the second terminal (1b) is reconstructed using a plurality of the electro-optical light transmitting elements (2a, 2b) without requiring a quadrature signal for each electro-optical light transmitting
35 element (2a, 2b).

6. The method of any of the preceding claims, wherein the first signal (S_n) and the second signal (S_n') have the same periodicity of the voltage (V).

5 7. The method of any of the preceding claims, wherein the phase shift between the first signal (S_n) and the second signal (S_n') is at least partly introduced by a phase shifting element (3) that is arranged in an optical path in the second electro-optical light transmitting element
10 (2b), in particular wherein the phase shifting element (3) is a $\lambda/4$ retarder, and/or

wherein the phase shift between the first signal (S_n) and the second signal (S_n') is a function of temperature of the phase shifting element (3), and the temperature of
15 the phase shifting element (3) is derived from the second signal (S_n'), and/or

wherein the phase shift between the first signal (S_n) and the second signal (S_n') is different from 90° .

20 8. The method of any of the preceding claims, in particular wherein the voltage is in the high-voltage range and/or the voltage is an AC-voltage, wherein the first signal (S_n) and the second signal (S_n') are based on an electric field-dependent change of a physical property of
25 the light, that is passed through the electro-optical light transmitting element or elements (2a, 2b), which change is induced by the electro-optical light transmitting element or elements (2a, 2b).

30 9. The method of claims 7 and 8, wherein the electric field-dependent change is a function of the temperature of the electro-optical light transmitting element (2, 2a, 2b) and the derived temperature of the phase shifting element (3) is used in deriving the voltage (V).

10. The method of any of the preceding claims, wherein in a first time interval $[t_1; t_2]$ between a first time t_1 and a second time $t_2 > t_1$ a range of the voltages (V) over the terminals (1a, 1b) is large enough for the signals
5 (S_n) to reach their maximum and minimum values as functions of the voltages (V) and

wherein in a second time interval $[t_3; t_4]$ between a third time $t_3 > t_2$ and a fourth time $t_4 > t_3$ the range of the voltages (V) is not large enough for the signals (S_n) to
10 reach their maximum and minimum values as functions of the voltages (V) and

wherein at least a scale and/or an offset of the signals (S_n) that was or were derived in the first time interval $[t_1; t_2]$ is or are used in deriving the voltage (V) in
15 the second time interval $[t_3; t_4]$.

11. The method of any of the preceding claims, wherein the electro-optical light transmitting element (2, 2a, 2b) comprises an optical sensor (21) introducing a field-
20 dependent phase shift between a first polarization or mode and a second polarization or mode of light passing through the electro-optical light transmitting element (2, 2a, 2b), and in particular wherein the optical sensor (21) comprises

25 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 piezo-electric device, in particular of crystalline
30 quartz or a piezoelectric ceramic, and a waveguide carrying at least two modes, wherein the waveguide is connected to the piezo-electric device thus that a length of the waveguide is field-dependent.

35 12. The method of any of the preceding claims, wherein during the derivation, the ambiguity is removed instead

of or additionally to using a quadrature signal by using light of two different wavelengths.

13. The method of any of the preceding claims, wherein
5 the signals (S_n , S_n'), in particular the base signal (S_n) and/or the reference signal (S_n'), is or are normalized to a symmetric value range around zero, in particular is or are scaled and offset to a value range $[+1, -1]$.

10 14. The method of claim 13, wherein a bidirectional cumulative count k of the number of zero crossings is determined for the base signal (S_n) and is used in the deriving of the voltage (V , V_n).

15 15. The method of any of the preceding claims, wherein the deriving of the voltage (V , V_n) comprises reconstructing an improved waveform (V , V_n) of the voltage (V , V_n) with the steps of:

determining first voltage values (V_1, V_{1n}) of the voltage
20 (V , V_n) from the base signal (S_n), in particular by calculating an arccosine,

determining second voltage values (V_2, V_{2n}) of the voltage (V , V_n) from the reference signal (S_n'), in particular by calculating an arccosine, and

25 determining the improved voltage waveform (V) from the first voltage values (V_1) and the second voltage values (V_2), and

in particular wherein the base signal (S_n) and the reference signal (S_n') are derived from the same light transmitting element (2).
30

16. The method of claim 15, comprising the steps of: for each n -th electro-optical light transmitting element (2, 2a), in particular for exactly one electro-optical
35 light transmitting element (2, 2a), normalizing the base

signal (S_n) and the reference signal (S_n') to the same maximum and minimum amplitude, in particular to a value range $[+1, -1]$,

selecting a weighting parameter β_n with $0 \leq \beta_n \leq 1$, and

5 determining the improved voltage waveform (V, V_n) by calculating a weighted sum $V = \sum V_n = \sum \{ \beta_n * V_{1n} + (1 - \beta_n) * V_{2n} \}$, with V_{1n}, V_{2n} = first and second voltage values of the n -th electro-optical light transmitting element (2).

10 17. The method of claim 16, comprising the steps of:

selecting the weighting parameter β_n such that the more linear of the base signal (S_n) and the reference signal (S_n') as a function of the voltage (V, V_n) is given a bigger weight.

15

18. The method of any of the claims 16-17, comprising the steps of:

selecting the weighting parameter $\beta_n = 1$ when an absolute value of the base signal (S_n) is smaller than an absolute value of the reference signal (S_n'), and

20

selecting the weighting parameter $\beta_n = 0$ when an absolute value of the reference signal (S_n') is smaller than an absolute value of the base signal (S_n).

25 19. The method of any of the claims 16-17, comprising the steps of:

selecting the weighting parameter β_n as a continuous function of the voltage (V, V_n), in particular according to $\beta_n = \cos^2(S_n * \pi/2) / (\cos^2(S_n * \pi/2) + \sin^2(S_n' * \pi/2))$.

30

20. The method of any of the claims 1-14, wherein only one signal (S_n) per electro-optical light transmitting element (2, 2a, 2b) is measured, and/or wherein the first electro-optical light transmitting element (2a) is operated without a retarder.

35

21. The method of any of the preceding claims, wherein the second electro-optical light transmitting element (2b) is used, and the second signal (S_n') is measured
5 from the second electro-optical light transmitting element (2b), and the hypotheses (h^+ , h^-) corresponds to different possible voltage values ($V_1^{h^-}$, $V_1^{h^+}$) of the partial voltage (V_n) applied to the first electro-optical light transmitting element (2a).

10

22. The method of any of the preceding claims, wherein at least two electro-optical light transmitting elements (2, 2a, 2b) are used and are subject to individual partial voltages (V_n),
15 measuring the first signal (S_n) for each n-th electro-optical light transmitting element (2, 2a, 2b) and using it as the n-th base signal (S_n) indicative of the electric field over that n-th electro-optical light transmitting element (2a),
20 determining the second signal (S_n') for each n-th electro-optical light transmitting element (2, 2a, 2b) and using it as the n-th reference signal (S_n') for resolving the ambiguity in the deriving of the n-th partial voltage (V_n) over that n-th electro-optical light transmitting
25 element (2, 2a, 2b), and
for each n-th electro-optical light transmitting element (2, 2a, 2b) performing the method steps (iii), (iv), (v) and (vi) to disambiguate the partial voltage (V_n) over that n-th electro-optical light transmitting element (2,
30 2a, 2b), and
determining the full voltage (V) between the first (1a) and second terminal (1b) from the partial voltages (V_n).

23. The method of any of the preceding claims, wherein
35 the electro-optical light transmitting elements (2a, 2b) are arranged electrically in series, and/or wherein the

electro-optical light transmitting elements (2a, 2b) are arranged in series for distributing the electric field over the electro-optical light transmitting elements (2a, 2b), and/or wherein the light transmitting elements (2a, 2b) are arranged in series in an axial direction between the terminals (1a, 1b).

24. The method of any of the preceding claims, wherein the electro-optical light transmitting elements (2a, 2b) are optically read out in parallel.

25. The method of any of the preceding claims, comprising:
applying to each electro-optical light transmitting element (2a, 2b) a partial voltage (V_n),
determining from the first and second signals (S_n , S_n') the partial voltage (V_n) for each electro-optical light transmitting element (2a, 2b), and
determining the total voltage (V) between the first terminal (1a) and the second terminal (1b) by calculating the sum ($V = \sum V_n$) of all partial voltages (V_n).

26. The method of any of the preceding claims, further comprising the steps of:
defining at least one internal parameter $\alpha_n = V_n/V$, wherein V_n = partial voltage applied to the n th electro-optic light transmitting element (2a, 2b) and V = total voltage between the first terminal (1a) and the second terminal (1b),
determining an estimate of α_n for all electro-optical light transmitting elements (2a, 2b), and
using the α_n for resolving the ambiguity in the deriving of the voltage (V , V_n) from the first signal (S_n).

27. The method of claim 26, further comprising the steps of:

measuring electrical signals S_n as a function of the intensities of the light beam exiting each electro-optical light transmitting element (2a, 2b),

determining all partial voltages V_n according to

$$V_n = \frac{V_{h,n}}{\pi} \left(\left(\pm \arccos \left(\frac{2(S_n - b_n)}{G_n \cdot I_{n,0}} - 1 \right) + K \cdot 2\pi \right) - 2\pi \Delta_n \right)$$

with $V_{h,n}$ = half-wave voltage of the crystal (21) in the nth electro-optic light transmitting element (2a, 2b), b_n = signal offset, G_n = cumulated gain of all components in the measurement chain from photodiode to amplifier, $I_{n,0}$ = intensity of the exiting beam with zero retardation, K = count of periods of the cosinusoidal response, and Δ_n = relative phase of the signal with respect to the voltage (V, V_n), and

using the α_n , in particular an estimate of the α_n for all optical channels, for disambiguating the sign of the arc-cosine.

20

28. The method of any of the claims 26-27, wherein the step of taking a binary decision to disambiguate the first signal (S_n) of the first electro-optical element (2a) with applied partial voltage (V_1) comprises using the α_n to compute from the at least two hypotheses (V_1^{h+} , V_1^{h-}) the corresponding voltage hypotheses (V_2^{h+} , V_2^{h-}) for the second electro-optical element (2b) with applied partial voltage (V_2), and selecting that expected value (S_2^{h+} , S_2^{h-}) of the second signal (S_2) which is closer to the measured value of the second signal (S_2).

30

29. The method of any of the claims 26-28, wherein strongly erroneous α_n are detected from an incorrect hypothesis selection, in particular from a discontinuity in

the measured voltage (V), and the most common values of α_n which are used most of the time are determined to be the correct α_n .

5 30. The method of any of the preceding claims 26-29, further comprising the step of recursively deriving at least one of the internal parameters (α_n) by:

initializing an auxiliary control loop with the estimate of α_n for all optical channels, wherein the internal parameter (α_n) is descriptive of a distribution of the
10 voltage (V) over the electro-optical light transmitting elements (2a, 2b),

taking a first series of measurements, and
based on the resulting V_n , calculating more exact α_n using equation $\alpha_n = V_n/V$ and the most common values of α_n .
15

31. The method of claim 30, further comprising the steps of:

using the more exact α_n as new estimated of α_n , and
20 converging the α_n , and/or tracking a time dependence $\alpha_n(t)$ of the α_n .

32. The method of any of the claims 1-19, wherein exactly one electro-optical light transmitting element (2) is
25 used, and the hypotheses (h^+ , h^-) correspond to different possible voltage values ($V_1^{h^+}$, $V_1^{h^-}$) of the full voltage (V) between the first terminal (1a) and the second terminal (1b).

30 33. The method of any of the preceding claims, further comprising the steps of
arranging at least a third electro-optical light transmitting element (2c) in the electric field between the first (1a) and the second terminal (1b),

passing light through the third electro-optical light transmitting element (2c),

measuring at least a third signal (S_3) from the third electro-optical light transmitting element (2c) wherein
5 the third signal (S_3) is indicative of the electric field over the third electro-optical light transmitting element (2c), and wherein the third signal (S_3) is a periodic function of the voltage (V),

deriving the voltage (V) from the first signal (S_n), the
10 second signal (S_n'), and the third signal (S_3), wherein the second signal (S_n') is used to resolve an ambiguity in the deriving of the voltage (V) using the first (S_n) and the third signal (S_3).

15 34. The method of any of the preceding claims, for each n -th electro-optic light transmitting element (2a, 2b) and its corresponding base signal (S_n) and/or reference signal (S_n') performing the steps of:

reconstructing a waveform of the measured voltage (V ,
20 V_n), in particular the full voltage (V) and/or partial voltage (V_n) between the first terminal (1a) and the second terminal (1b),

calculating a time average over a number of periods of the reconstructed waveform,

25 determining from the time average an apparent DC offset voltage V_{DC} , and

calculating a relative phase Δ_n of the base signal (S_n) and/or reference signal (S_n') with respect to the applied voltage according to $\Delta_n = V_{DC} * \pi / V_{h,n}$, with $V_{h,n}$ = half-wave voltage of the n th electro-optic light transmitting
30 element (2a, 2b).

35 35. Method for measuring a voltage (V , V_n) according to the preamble of claim 1, in particular according to any of the preceding claims, characterized by the steps of:

- (i) using the first signal (S_n) as a base signal (S_n) indicative of the electric field over the first electro-optical light transmitting element (2a),
- (ii) using the second signal (S_n') as a reference signal (S_n') for resolving the ambiguity in the deriving of the voltage (V , V_n),
- (iii) determining from the first signal (S_n) two hypotheses (h^+ , h^-) corresponding to different possible voltage values ($V_n^{h^+}$, $V_n^{h^-}$) of the voltage (V , V_n),
- (iv) determining the actual relative phase shift (Δ) between the base signal (S_n) and the reference signal (S_n'),
- (v) determining from the base signal (S_n), the reference signal (S_n') and the actual relative phase shift (Δ) a synthetic quadrature signal ($S_n'^{\text{quad}}$) having an ideal relative phase shift of 90° , and
- (vi) taking a binary decision between the hypotheses (h^+ , h^-) based on the sign of the synthetic quadrature signal ($S_n'^{\text{quad}}$).

20

36. The method according to any of the claims 34-35, wherein step (v) comprises:

calculating the synthetic quadrature signal ($S_n'^{\text{quad}}$) according to the formula

$$S_n'^{\text{quad}} = \cos^{-1}(2 * \pi * \Delta) * S_n' + \tan(2 * \pi * \Delta) * S_n$$

25

37. A device for measuring the voltage (V) comprising means for carrying out the steps of the method according to any of the preceding claims.

30

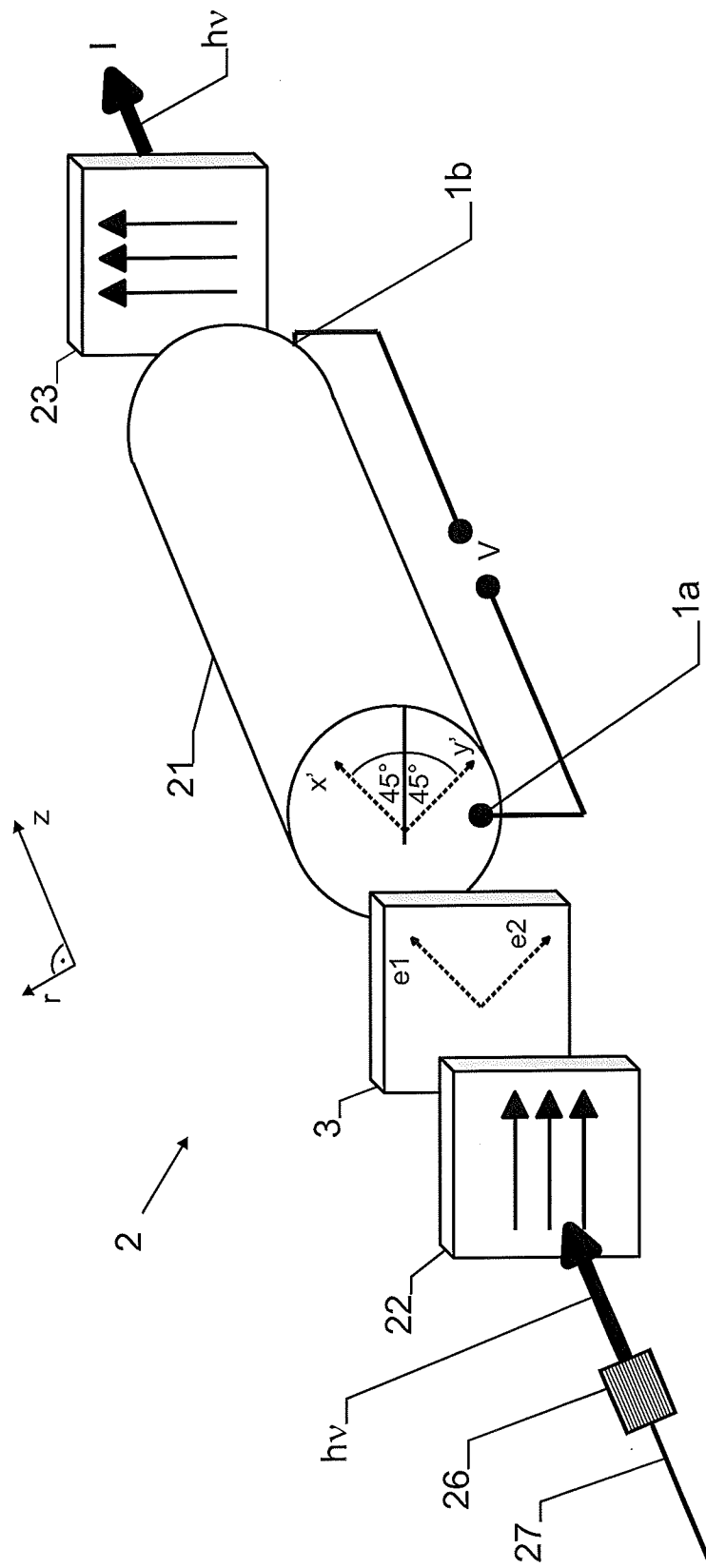
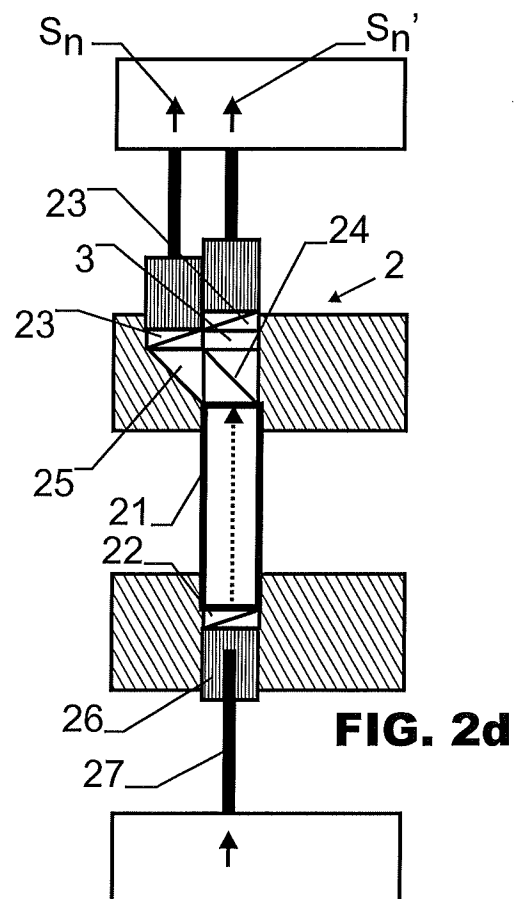
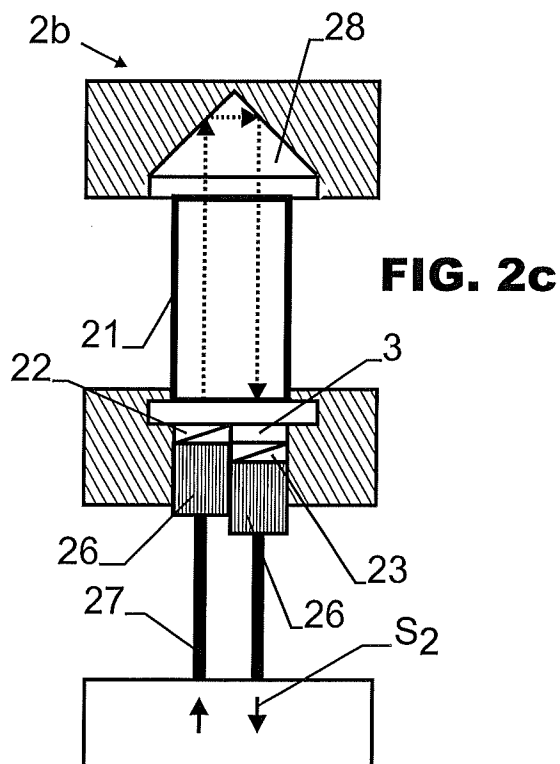
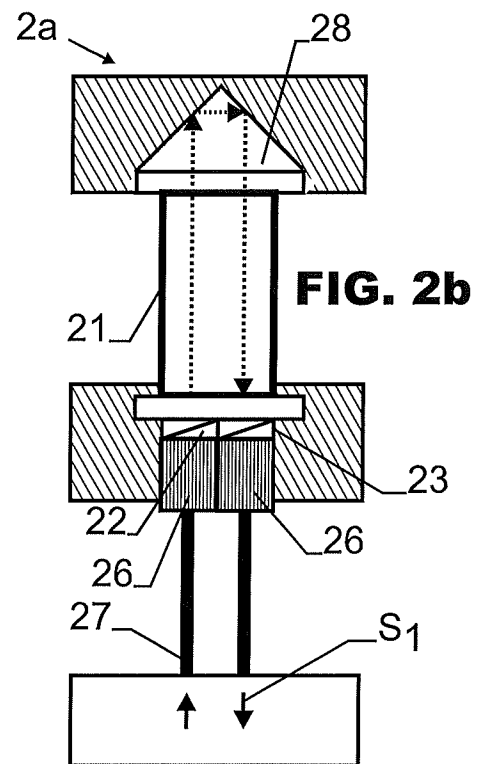
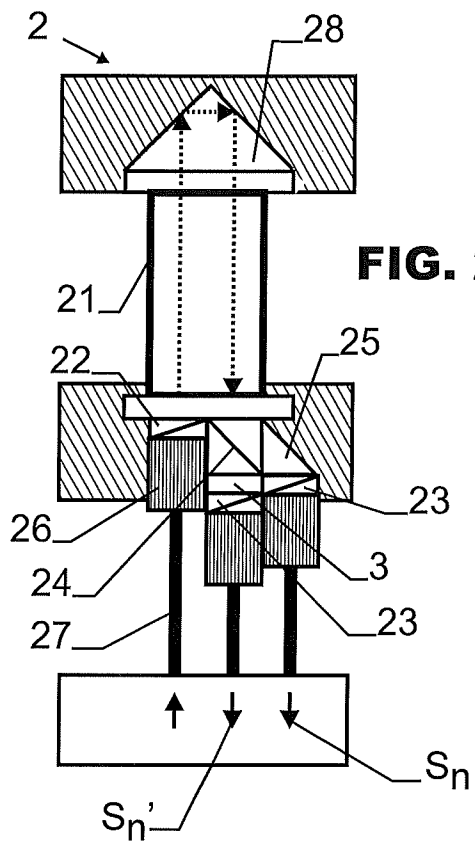
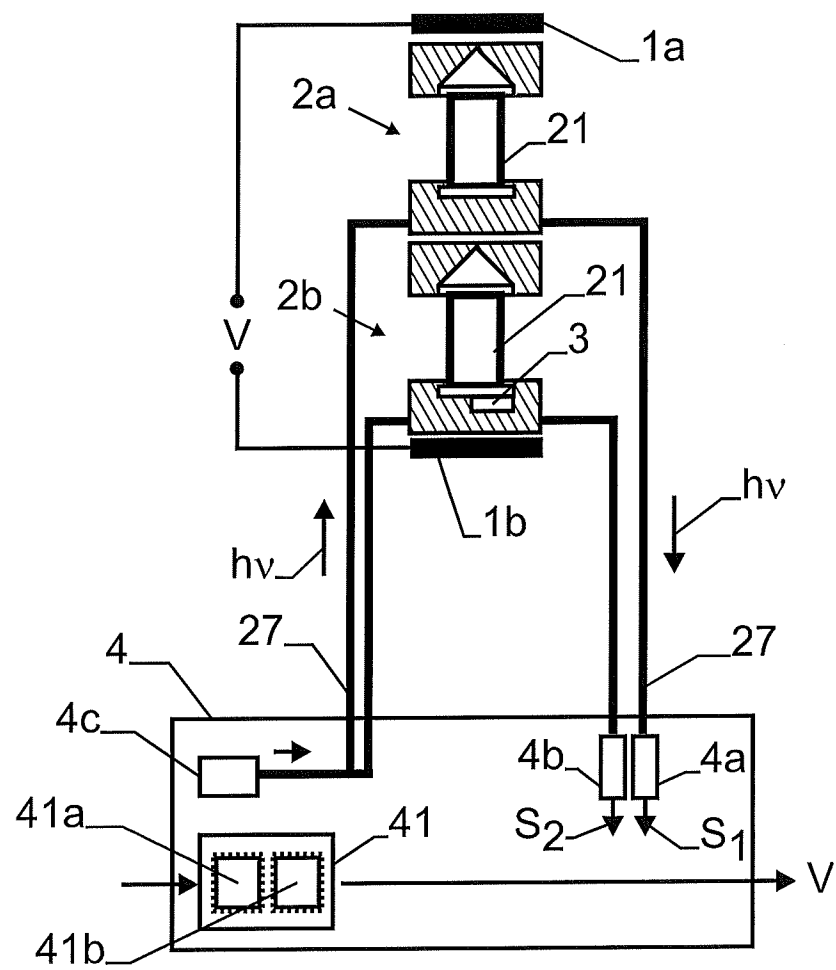


FIG. 1



3 / 10

**FIG. 3**

4 / 10

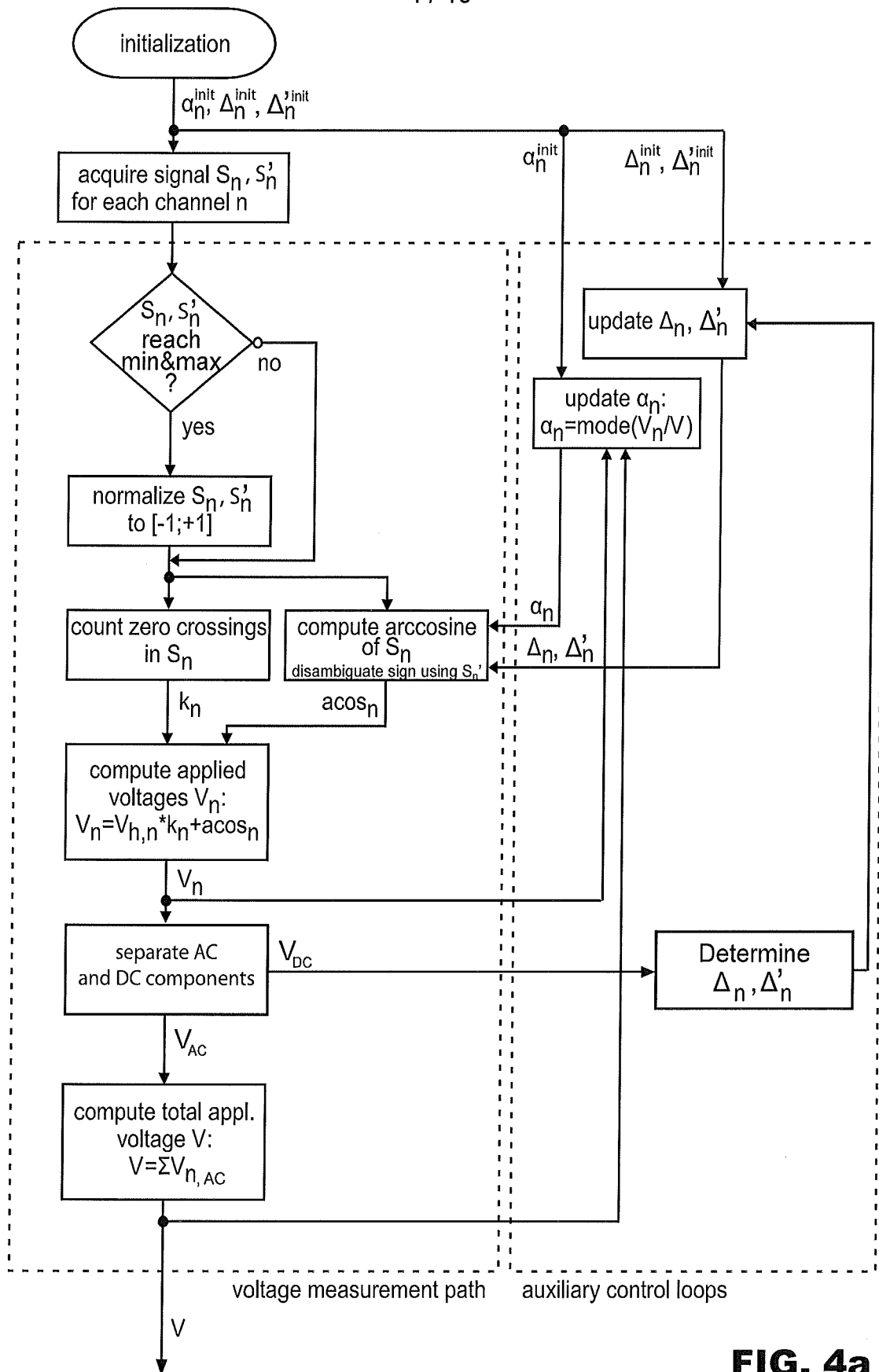
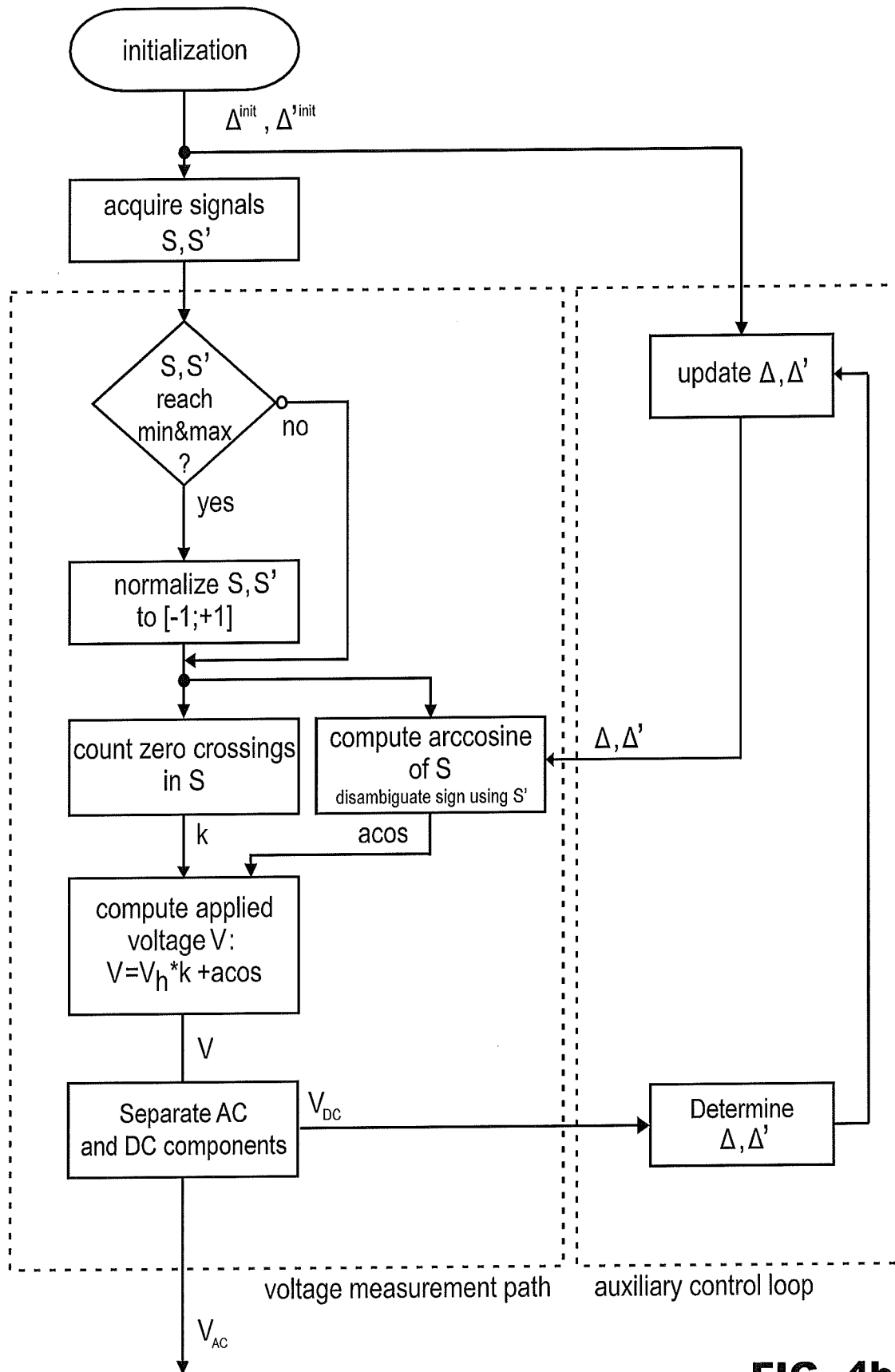


FIG. 4a

5 / 10

**FIG. 4b**

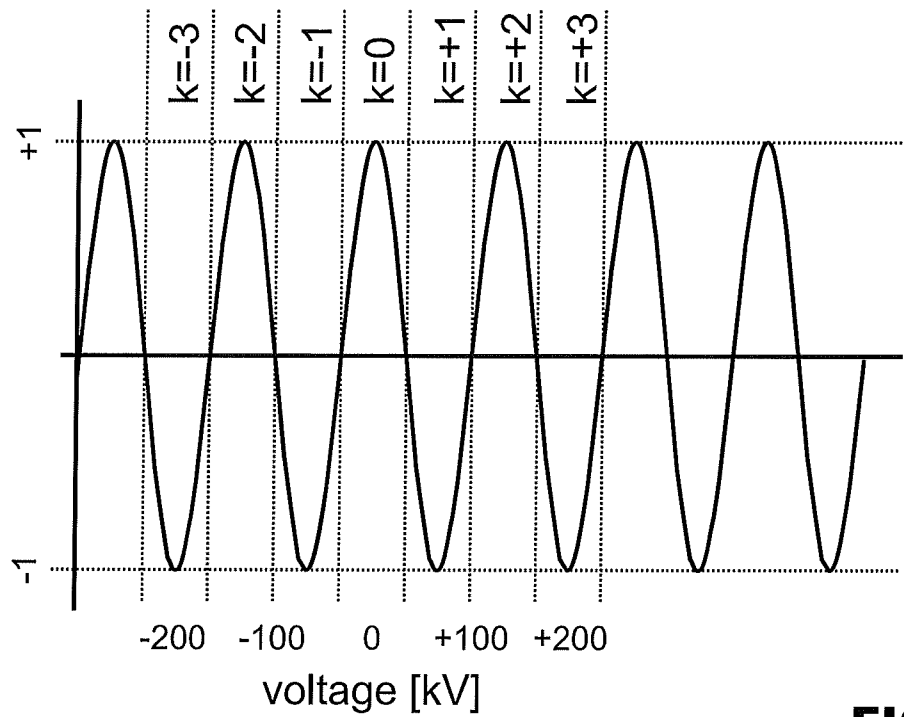


FIG. 5

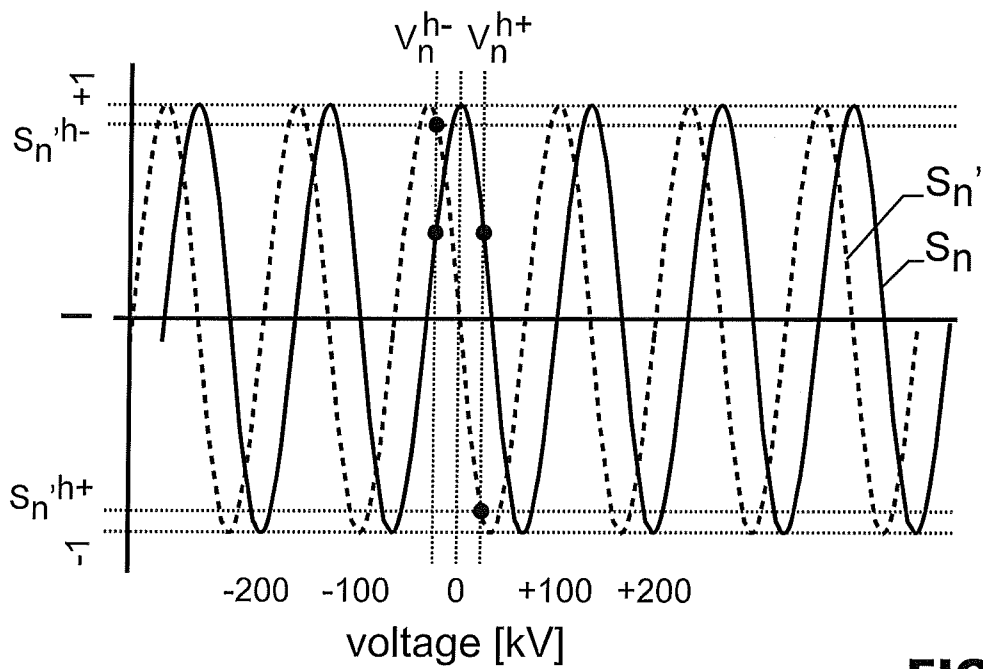
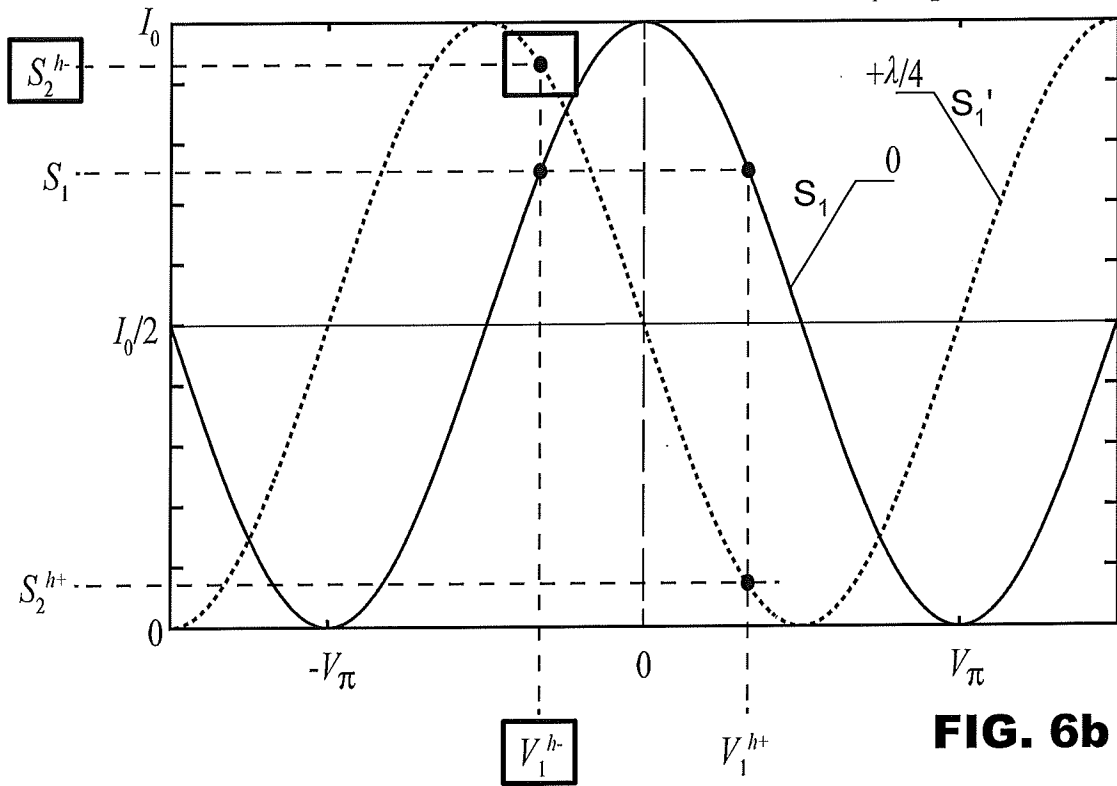


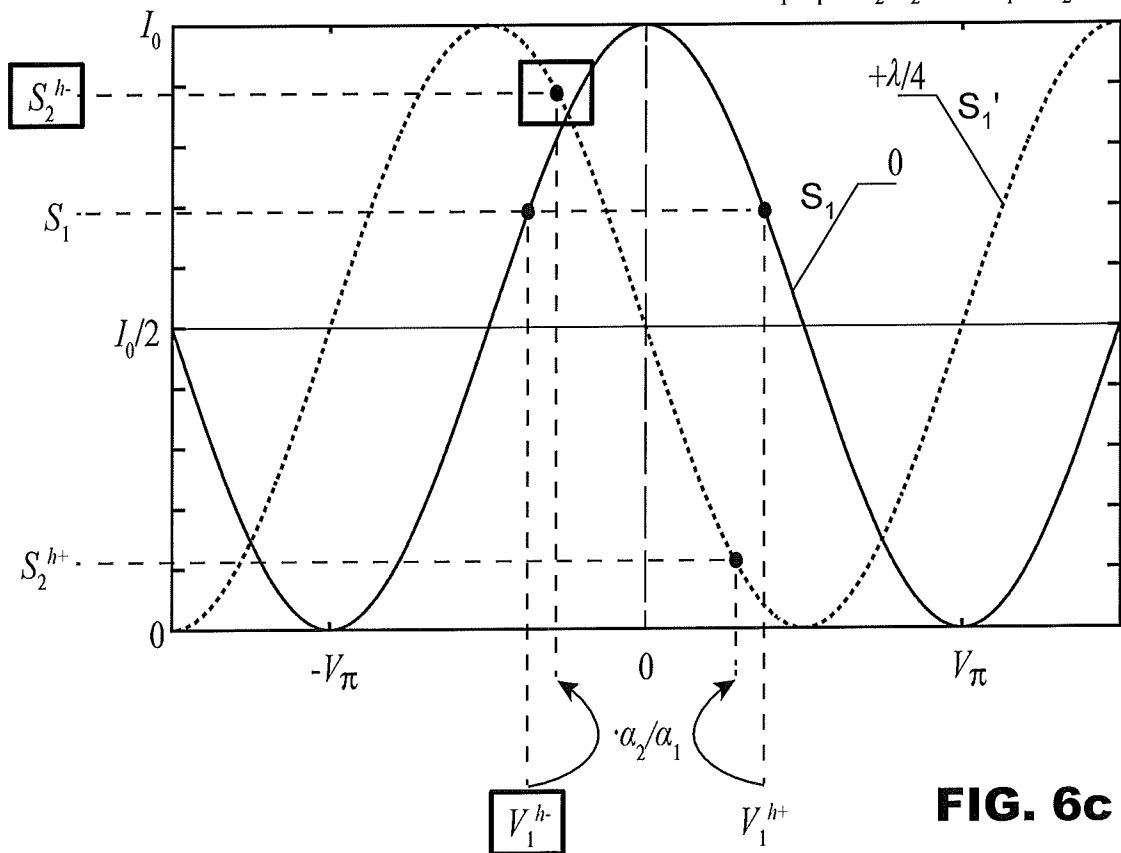
FIG. 6a

7 / 10

case: $V_1 = V_2 = \alpha V, \alpha = 0.5$



case: $V_1/\alpha_1 = V_2/\alpha_2 = V, \alpha_1 > \alpha_2 > 0$



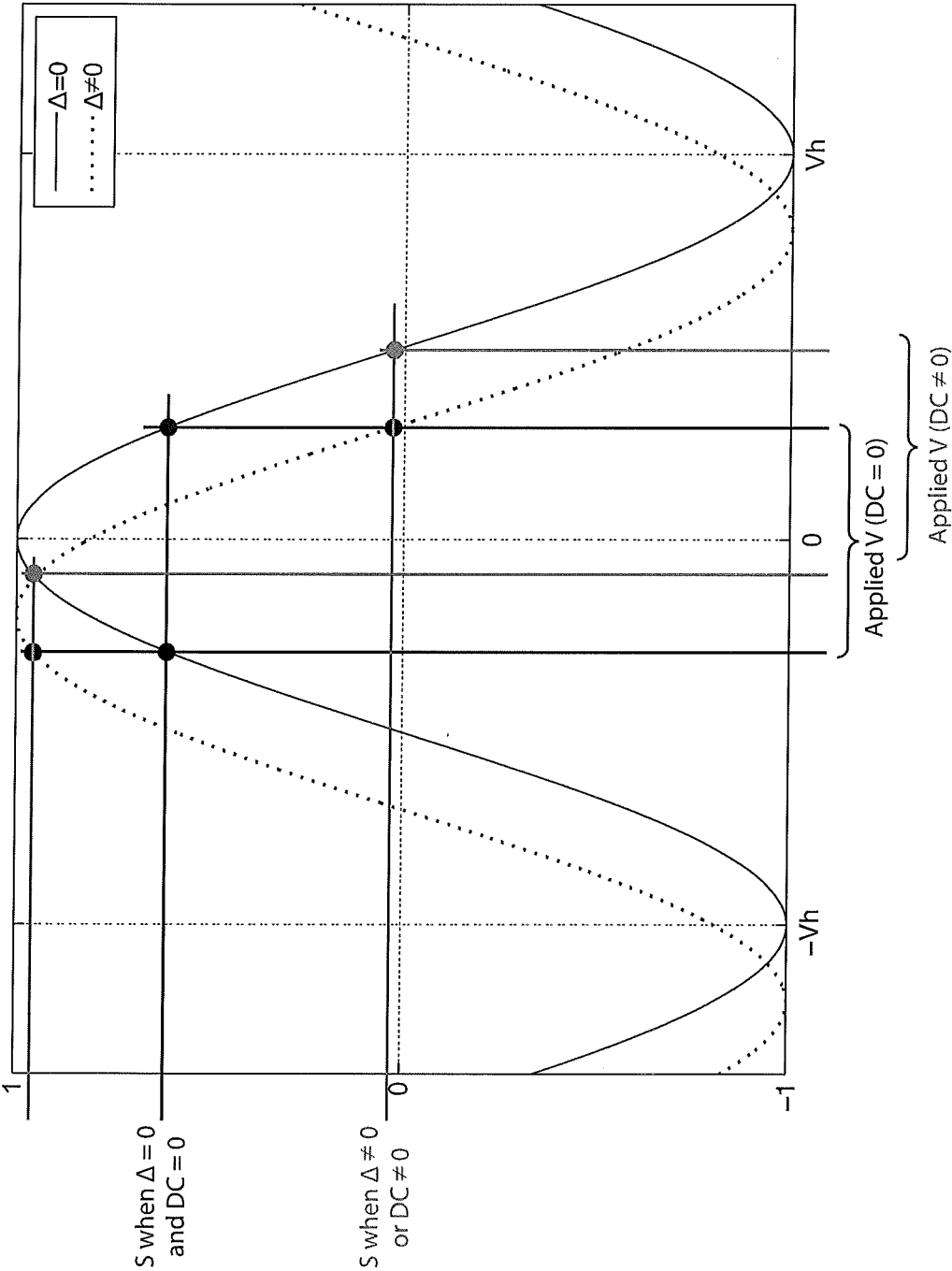


FIG. 8

9 / 10

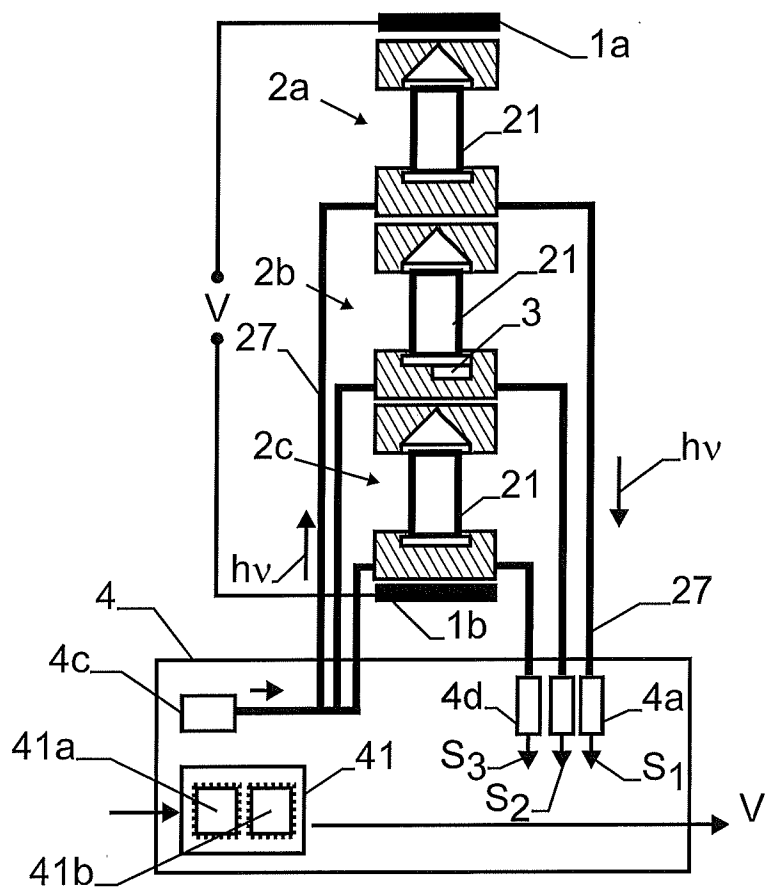
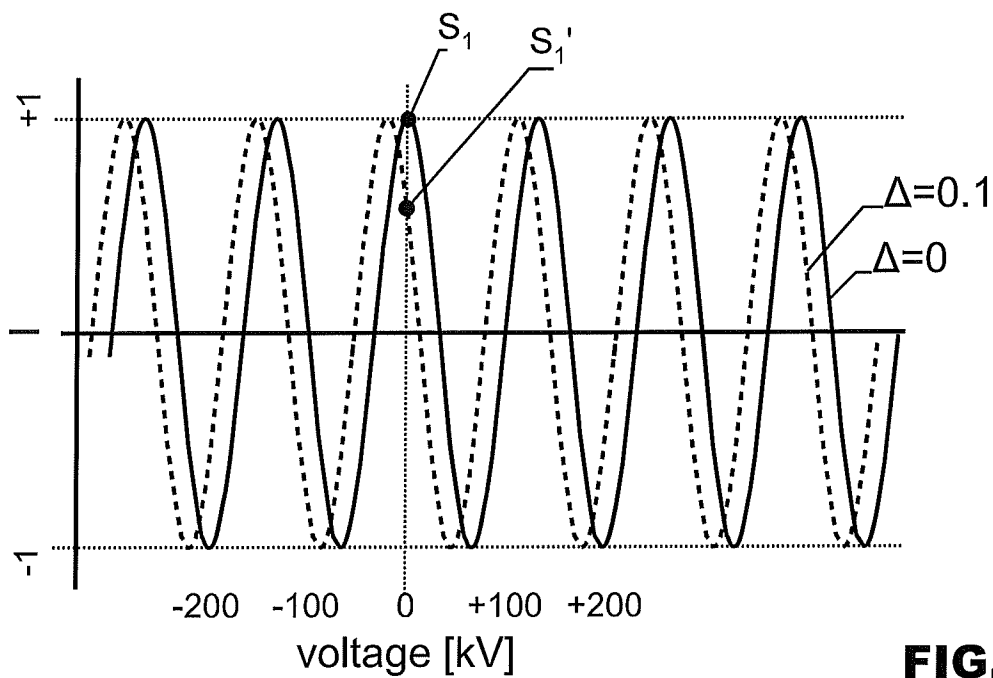


Fig. 9

10 / 10

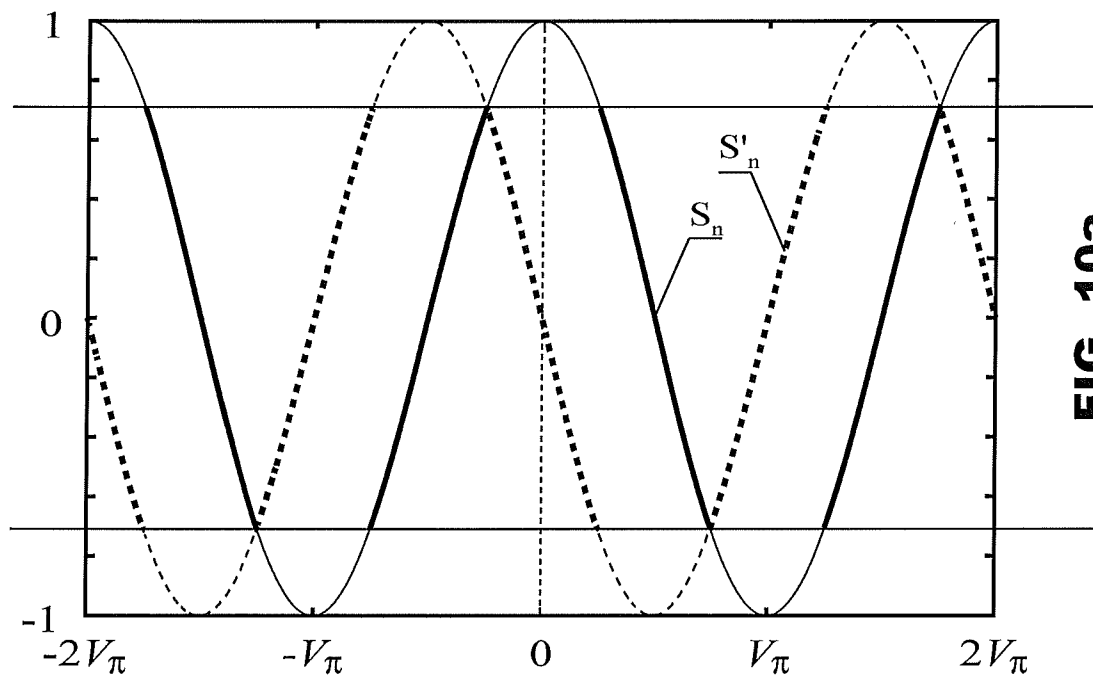


FIG. 10a

$$V_n = \beta_n \cdot V_{1n} + (1 - \beta_n) \cdot V_{2n}$$

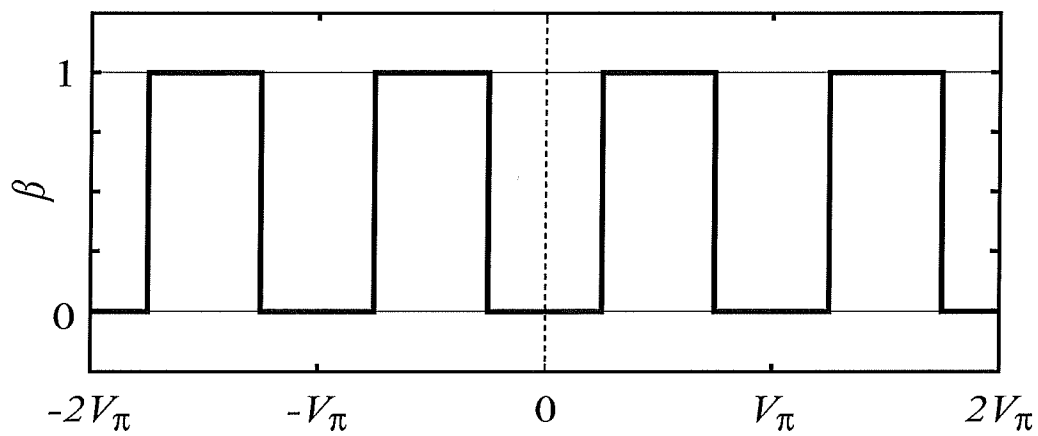


FIG. 10b

$$V_n = \beta_n \cdot V_{1n} + (1 - \beta_n) \cdot V_{2n}$$

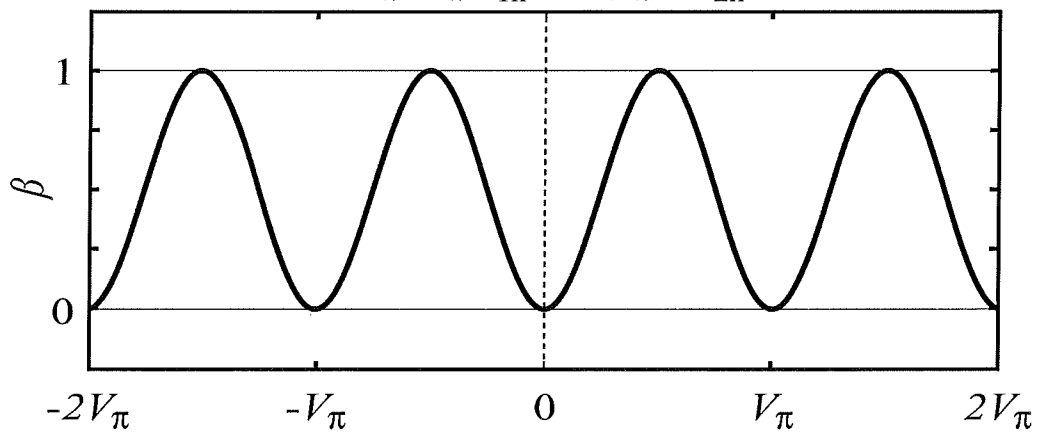


FIG. 10c

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2012/060065

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 practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 1 179 735 A1 (ABB RESEARCH LTD [CH]) 13 February 2002 (2002-02-13)	1-4, 7-12, 15, 20, 24, 32, 34, 37
Y	abstract; claim 1; figure 1 paragraph [0013] - paragraph [0030] paragraph [0002] - paragraph [0005] -----	5, 21-23, 25-31, 33
X	US 4 904 931 A (MILLER ROBERT C [US]) 27 February 1990 (1990-02-27) cited in the application	1-4, 6-11, 13-15, 24, 34, 37
Y	abstract; figures 1-3, 6-8 column 4, line 7 - column 8, line 19 column 11, line 49 - column 12, line 31 ----- -/-	5, 21-23, 25-31, 33



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

4 October 2012

Date of mailing of the international search report

16/10/2012

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Ernst, Monika

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2012/060065

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X,P	J. PASCAL, S. ADAM, O. STEIGER, W.R. WERBANETS: "Optimization of an Electro-Optic Voltage Transducer using a VHDL-AMS model", PROCEDIA ENGINEERING, EUROSENSORS XXV, vol. 25, 7 September 2011 (2011-09-07), pages 59-62, XP002684622, the whole document	16-19
A	----- US 6 252 388 B1 (JAEGER NICOLAS AUGUST FLEMING [CA] ET AL) 26 June 2001 (2001-06-26) cited in the application abstract; figures 1,2	1-34,37
A	----- SHIWU XIAO ET AL: "Novel Optic High Voltage Transducer Based on Gaussian Quadrature Method", POWER AND ENERGY ENGINEERING CONFERENCE (APPEEC), 2010 ASIA-PACIFIC, IEEE, PISCATAWAY, NJ, USA, 28 March 2010 (2010-03-28), pages 1-5, XP031658381, ISBN: 978-1-4244-4812-8 abstract; figure 1	1-34,37
A	----- PATRICK P CHAVEZ ET AL: "Accurate Voltage Measurement by the Quadrature Method", IEEE TRANSACTIONS ON POWER DELIVERY, IEEE SERVICE CENTER, NEW YORK, NY, US, vol. 18, no. 1, 1 January 2003 (2003-01-01), XP011078907, ISSN: 0885-8977 the whole document	1-34,37
A	----- DE 197 16 477 A1 (SCHWARZ HARALD PROF DR ING [DE]; JENAU FRANK [DE] AREVA T & D SA [FR]) 24 September 1998 (1998-09-24) abstract; figures 3-6	1-34,37
A	----- US 5 715 058 A (BOHNERT KLAUS [CH] ET AL) 3 February 1998 (1998-02-03) abstract; figures 6a,6b column 1, line 14 - column 2, line 14 column 10, line 3 - line 28	1-34,37
A	----- US 5 113 131 A (COOPER DAVID E [US] ET AL) 12 May 1992 (1992-05-12) abstract; figures 6,7	1-34,37

INTERNATIONAL SEARCH REPORT

International application No.
PCT/EP2012/060065

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☒ Claims Nos.: 35, 36
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
see FURTHER INFORMATION sheet PCT/ISA/210
3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

Continuation of Box II.2

Claims Nos.: 35, 36

Claim 35 defines a method for measuring a voltage according to the preamble of claim 1. However, it is not clear which part of claim 1 constitutes the preamble and therefore, which features the method of claim 35 comprises. As such, the International Searching Authority would be left with an undue burden of searching for a variety of possible combinations of features. Moreover, claim 35 is also not supported by the description and the figures as no disclosure or embodiments with regard to the subject-matter as defined in claim 35 is present. As such, it is unclear, what the underlying problem leading to the features of claim 35 should be and what features really are required for solving it. The features in claim 35 are therefore anyway either obvious to the skilled person or not sufficiently disclosed. For the sake of completeness of arguments it is added, that even if claim 35 would have been drawn up by clearly defining all features which have to be present in the method, it appears at present that such a claim might have lacked the requirements of Rule 13 PCT with regard to unity. Claim 36 is dependent on claim 35 and therefore the reasoning above applies *mutatis mutandis*.

The applicant's attention is drawn to the fact that claims relating to inventions in respect of which no international search report has been established need not be the subject of an international preliminary examination (Rule 66.1(e) PCT). The applicant is advised that the EPO policy when acting as an International Preliminary Examining Authority is normally not to carry out a preliminary examination on matter which has not been searched. This is the case irrespective of whether or not the claims are amended following receipt of the search report or during any Chapter II procedure. If the application proceeds into the regional phase before the EPO, the applicant is reminded that a search may be carried out during examination before the EPO (see EPO Guideline C-VI, 8.2), should the problems which led to the Article 17(2) declaration be overcome.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2012/060065

Patent document cited in search report		Publication date		Patent family member(s)		Publication date
EP 1179735	A1	13-02-2002	DE	10039455 A1		21-02-2002
			EP	1179735 A1		13-02-2002

US 4904931	A	27-02-1990	AR	247791 A1		31-03-1995
			AU	616303 B2		24-10-1991
			AU	4127089 A		05-04-1990
			BR	8904866 A		08-05-1990
			CA	1328482 C		12-04-1994
			DE	68922951 D1		13-07-1995
			DE	68922951 T2		11-01-1996
			DE	68928916 D1		04-03-1999
			DE	68928916 T2		02-09-1999
			EP	0361832 A2		04-04-1990
			EP	0613015 A1		31-08-1994
			JP	2120673 A		08-05-1990
			JP	3189840 B2		16-07-2001
			US	4904931 A		27-02-1990

US 6252388	B1	26-06-2001	AT	302417 T		15-09-2005
			AU	5613799 A		26-06-2000
			CA	2351573 A1		15-06-2000
			DE	69926792 D1		22-09-2005
			DE	69926792 T2		08-06-2006
			EP	1137950 A1		04-10-2001
			JP	2002532688 A		02-10-2002
			US	6252388 B1		26-06-2001
			WO	0034793 A1		15-06-2000

DE 19716477	A1	24-09-1998	CA	2289736 A1		11-09-1998
			DE	19716477 A1		24-09-1998
			EP	0965046 A1		22-12-1999
			JP	4127413 B2		30-07-2008
			JP	2001513893 A		04-09-2001
			US	7084616 B1		01-08-2006
			WO	9839662 A1		11-09-1998

US 5715058	A	03-02-1998	BR	9501973 A		12-12-1995
			CA	2148310 A1		10-11-1995
			CN	1128862 A		14-08-1996
			DE	4416298 A1		16-11-1995
			EP	0682261 A2		15-11-1995
			JP	3677314 B2		27-07-2005
			JP	8005462 A		12-01-1996
			US	5715058 A		03-02-1998
			ZA	9503289 A		11-01-1996

US 5113131	A	12-05-1992	NONE			
