Optical high voltage measurement transformer using white light interferometry

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Abstract

A new approach to perform measurement of potentials in high voltage levels using electrooptical Pockels sensors is presented here. This paper describes an application of the White Light Interferometry technique to a high voltage optical fiber measurement system. In this system the information is encoded in the spectrum of the light, allowing the measurement to be independent of the optical power transmitted by the optical fiber link. A prototype was built and tested under excitation of a.c. voltages up to 60 kV in 60 Hz showing good response and demonstrating the feasibility of this method.

Introduction

High voltage measurements have been made using electromagnetic voltage transformers (VTs) and, in some cases, capacitive or resistive dividers. The application of recently developed new technologies provides alternatives to the conventional VTs having improved performances of insensitivity to electromagnetic interference (EMI), wider frequency response, etc.

Electrooptic techniques combined with optical fiber links can be used in optical voltage sensors (OVTs) which have many advantages in replacing the conventional VTs, such as: the possibility of a totally dielectric construction, electromagnetic noise immunity, complete electric insulation, wide frequency bandwidth, small size, light weight, etc.

The optical sensor using a Pockels micro single crystal, which is a crystal with a long and thin rod shape, was developed to overcome the effect of oscillatory signals and to realize an ideal high voltage optical sensor having the wide bandwidth of dc to high frequency. However, the maximum voltage that is measurable in such a kind of sensor is limited to less than 80 kV, which is approximately the half-wave voltage ($V\pi$) of this sensor. Additionally, since the Pockels cell used can be seem as a polarimetric interferometer, the voltage measured is traduced in the optical intensity at its output. Therefore, the measurement becomes dependent on the losses in the link, which can change unpredictably in time.

In the present work an application of White Light Interferometry (WLI) to the Pockels cell used to built OVTs is proposed as an option to overcome such problem. Since in a system based on the WLI method the information is encoded in the spectrum of the light, it can provides a measurement which is independent of the optical power present in the optical fiber link output.

Experimental Setup

The linear electro-optic effect, known as Pockels effect, has been extensively used to built modulators that are the core of high voltage optical sensors. The authors have developed a polarimetric Pockels sensor operating in a longitudinal configuration which is able to measure high voltages up to about 70 kV. In a latter development, this high voltage sensor is used as birefringent sensor interferometer in a WLI sensor system which is the main part of an optical high voltage transformer. These developments, together with their fundamentals, are following described.

The refractive index of some materials changes when an electric field is applied to them. This is the electro-optic effect. A refractive index can be expressed using a power series with respect to an applied electric field E as [1]:

$$n = n_O + rE + sE^2 + \dots\dots\dots \quad (1)$$

where n_O is the ordinary refractive index exhibited by the material in case of no applied field and r and s are the coefficients for the electro-optic effect. The second term in the right hand side of (1) shows a linear dependence on the electric field, corresponding to the Pockels effect, and the third term shows a square dependence, corresponding to the Kerr effect. In optical modulators the applied electric field and the light beam directions can be parallel or perpendicular to each other. These two cases are called longitudinal and transverse modulators, respectively.

For a polarimetric modulator in longitudinal configuration, as shown in Fig. 1, with polarizer and analyzer whose polarization directions are crossed to each other, between the two orthogonal light components is induced a phase retardation Γ.

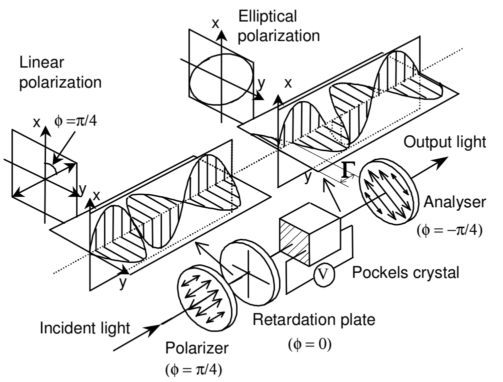

Fig. 1. Principle of electro-optic effect and longitudinal electro-optic modulator

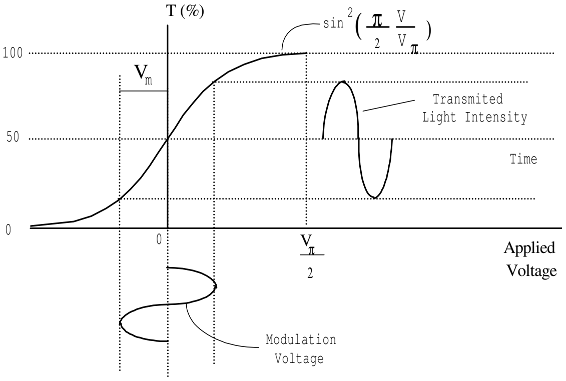

Fig. 2. Pockels modulator response curve for sinusoidal voltage applied to the crystal.

For a cubic crystal ($\bar{4}3m$ symmetry group) in a longitudinal modulator, and considering that $V = EL$, the induced birefringence becomes:

$$\Delta n = n_o^3 \, r_{41} \frac{V}{L} \tag{2}$$

where n_o is the ordinary refractive index and r_{41} is the only relevant electro-optic coefficient of the crystal.

The total phase retardation, Γ_t, is the summation of the electrically induced phase retardation, Γ, with an additional part, ϕ_r, introduced by the retardation plate, and can be written as:

$$\Gamma_t = \phi_r + \pi \frac{V}{V_\pi} \tag{3}$$

where the half-wave voltage is defined [2] as the value of V at which Γ reaches to π (V_π). The response curve (applied voltage versus outgoing light intensity) for this kind of modulator is shown in Fig. 2.

A high voltage optical sensor was formerly developed to be used as the main part of an optical voltage transformer (OVT). The schematic diagram of such sensor is shown in Fig. 3.

The high voltage sensor consists in an arrangement of a long piece of electro-optic Pockels crystal inserted between two aluminium electrodes, which are separated and supported by an acrylic tube. The electro-optic crystal used was a piece of $Bi_3Ge_4O_{12}$ (BGO) in parallelepiped shape. In order to provide easier manipulation and mechanical protection, this crystal is encapsulated in an acrylic cylinder. Using a BGO crystal, which has $n_o = 2.098$ and $r_{41} = 1.03\text{x}10^{-12}$ (m/V), and a superluminescent diode (SLD) operating in $\lambda = 1.321$ µm as light source in the high voltage sensor described, the half-wave voltage is $V_\pi \cong 69.4$ kV.

The polarimetric Pockels sensor described before has the inconvenience of showing a dependence of the output light signal on the attenuation in the optical fiber communication link. There are some already reported methods trying to avoid such dependence using electronic post-processing of the signal [3, 4, 5]. In the present work a new method is proposed in which the WLI technique plays the main role.

In a white light interferometer the light emitted from a wide spectrum source is divided in two parts, which are led to propagate in optical paths of different length. After left these two paths, the two light components are recombined to interfere but, if the optical path difference (OPD) is greater then the coherence length (L_c) of the light source, the two components are said to be not correlated and the visibility of the interference is too week to be detected. At this point the information of the Interferometry is encoded only in the spectrum of the light [6]. If an interferometer built in this way (having OPD >> L_c) is used as a sensor, in order to recover the information introduced in the spectrum of the light it is necessary to make its output light propagate trough a second interferometer. In such recover interferometer the OPD must be equal (or, at least, similar) to the OPD present at the sensor interferometer.

In this case, the Pockels high voltage sensor can be seen as a birefringence interferometer, with a total OPD is $\Delta L_{s.}$ Since the BGO crystal has no natural birefringence, the electrically induced OPD introduced between the two polarization components is equal zero when the applied voltage is also zero. To obtain a WLI configuration, a Litium Niobate ($LiNbO_3$) plate is used as the retardation plate in the high voltage sensor. Such plate has 1 mm in thickness and is oriented with the x-axis parallel to the light propagation direction and the y and z axes oriented parallel to the x and y axes of the BGO crystal. The retardation plate introduces a fix additional

OPD, $\Delta L_{RPs,}$ much bigger than the L_c of SLD source, between the two orthogonal polarized components of the propagating light.

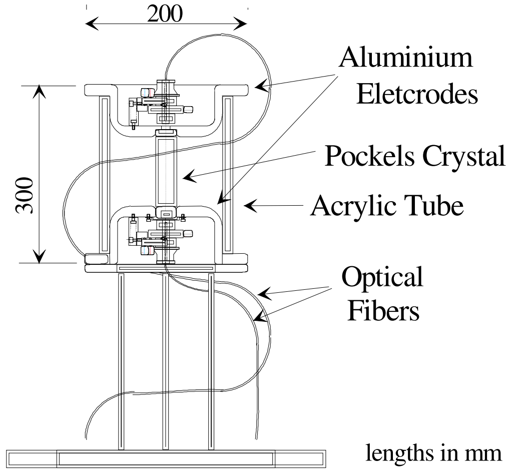

Fig. 3. High voltage electro-optical Pockels sensor.

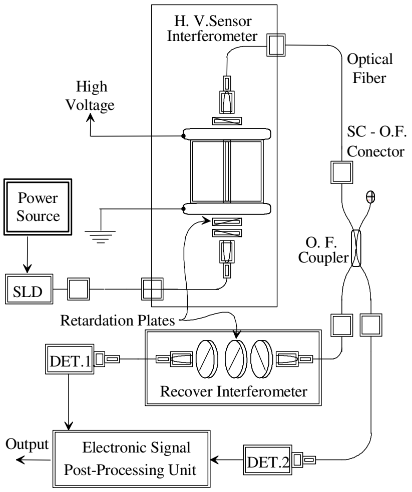

Fig. 4. Optical high voltage transformer using WLI Configuration.

To recover the interferometric signal, a simple recover interferometer is placed in series with the optical fiber in the return path of the sensing system. The recover interferometer is composed of a retardation plate inserted between two aligned polarizers. The optical power at the output of the recover interferometer I_o is given by [7]:

$$I_o = \frac{1}{4}\alpha_S.\alpha_R.I_i\left\{1+\frac{1}{2}e^{-(\pi\Delta L/L_c)^2}\cos 2\pi\frac{\Delta L}{\lambda_0}\right\} \tag{4}$$

where I_i is the optical power at the input of the system (output of the SLD), α_S is the attenuation of light from the SLD source to the output of sensor interferometer, α_R is the attenuation of light from the output of sensor interferometer the output of recover interferometer, λ_0 is the central wavelength of the light source and ΔL is the total OPD in the sensor system, given by: $\Delta L = \Delta L_s - \Delta L_{RPr}$.

The retardation plate used in the recover interferometer is identical to the one used in the sensor interferometer, however, it is hold by a special positioner witch can rotate around two axes to allow a fine tuning of the OPD introduced. Using this two axes rotation capability, it is possible to set the OPD in the recover interferometer in such way that: $\Delta L_{RPr} = \Delta L_{RPs} - \lambda_0/4$. In such condition, from (4), I_o becomes:

$$I_o = \frac{1}{4}\alpha_S\alpha_R I_i\left\{1+\frac{1}{2}e^{-\left[\frac{\lambda_0}{2}\left(\pi\frac{V}{V_\pi}-\frac{\pi}{2}\right)\Big/L_c\right]^2}\cos\left(\pi\frac{V}{V_\pi}-\frac{\pi}{2}\right)\right\} \tag{5}$$

Since in practical applications L_c is much larger than λ_0, the exponential term in (5) remains close to the unity when $|V| < V_\pi$. Therefore, I_o can be approximated by:

$$I_o = \bar{I}_o\left(1+\frac{1}{2}sin\,\pi\frac{V}{V_\pi}\right) \tag{6}$$

where $\bar{I}_o = \frac{1}{4}\alpha_S\alpha_R I_i$, is the average of output light intensity.

The response curve for this kind of sensor system, is similar to the response curve of a polarimetric Pockels modulator, shown in Fig. 2.

As in the polarimetric Pockels sensor described before, also in the WLI sensor system just described there is a dependency of the output light intensity, I_o (which carries out the measurement of the applied voltage), on the total attenuation of the system, α_t.

To take advantage of WLI technique and eliminate such dependency, an optical high voltage tranformer was developed as shown in Fig.4. The light intensity at output of sensor interferometer, I_{os}, is given by:

$$I_{os} = \frac{1}{2}\alpha_s . I_i \left\{ 1 + e^{-(\pi \Delta L_s / L_c)^2} \cos 2\pi \frac{\Delta L_s}{\lambda_0} \right\} \tag{7}$$

Since $\Delta L_s >> L_c$, the exponential term in (7) approaches to zero. Therefore, I_{os} reduces to

$$I_{os} = \frac{1}{2}\alpha_s . I_i = \frac{2}{\alpha_R} I_o^- \tag{8}$$

Results and Discussions

The optical high voltage transformer described before was built and tested for a.c. applied voltages up to 60 kV_{ef}. Such level of voltage was obtained from the secondary of a 138 kV class conventional voltage transformer. This VT was supplied in its primary by an adjustable-ratio output transformer (Variac) allowing the voltage to be adjusted continuously from zero to maximum.

A typical signal observed in the output of the system, $V_{out}(t)$, compared to the applied voltage, V(t), is shown in Fig. 5.

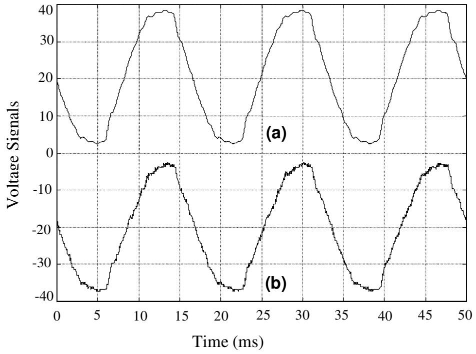

Fig. 5 - Typical voltage signals experimentally observed: (a) Applied Voltage V(t), (b) Optical transformer output voltage signal $V_{out}(t)$.

Conclusions

This work presented an application of WLI method to interrogate an optical voltage transformer, built with a Pockels high voltage sensor, which can successfully reduce the dependency of the measured voltage with the light intensity in the optical fiber link. The transmission of information in the spectrum of the light makes possible to reduce this dependency in at least 50 times. Additionally, it is expected that optical noises introduced in the optical fiber link, for instance intensity noise or polarization noise, may be also reduced due to a filter action of the applied signal processing technique.

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