Proceedings of The Korea-Russia Joint Conference on
Advanced Sciences and Technologies. *June, 1998, Korea*

Improvements to the stability of electric field sensors

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The measurement of the amplitude and phase of electric fields on high voltage transmission lines is important for several reasons including a) Metering and determination of power flow, b) protective relaying, and c) fault sensing. The work reported here is directed toward a major improvement to optically based, electric-field sensors. This is a signal processing based technique for overcoming the instabilities of conventional, optically-based, electric-field sensors to changes in optical power or temperature.

The earliest demonstrations of optically based electric field sensors employed bulk crystals. More recent instruments have employed integrated, optical waveguide versions of Mach-Zehnder interferometers on lithium niobate substrates[1-4]. In either type of device the phase difference between two interfering beams is modulated by an ac, low frequency electric field. In the absence of an ac electric field the phase difference between interfering beams is determined solely by propagation distances and material properties. If the field-independent phase difference can be chosen to be exacdy 90 degrees, then the intensity of the recombined beam will vary linearly with the magnitude of the ac electric field. Unfortunately in nearly all electrooptical based field measurement techniques it is nearly impossible to maintain a field-independent phase difference of exactly 90 degrees. Changes in temperature, as well as pyroelectric and photorefractive effects have all been reported to be major contributors to drift of the field-independent phase difference. These changes destroy the linear relationship between ac field amplitude and the output optical intensity.[5-10]

The technique that we have demonstrated does not attempt to set the phase difference between the two beams to 90 degrees and overcomes the limitations of previous electric field sensors by using signal processing techniques to calculate the size of both the ac field and the field-independent phase difference.

The output intensity from an electrooptical electric field sensor contains all harmonics (Bessel function J_n amplitudes) of the ac electric field. A measurement of the amplitude and phase of the first three harmonics of the optical intensity can be used to calculate the field-independent phase difference as well as the ac field amplitude. If the input optical intensity to the electric field sensor is I_0, then the ratio of output intensity I to input intensity is given by:

$$
\begin{aligned}
I / I_0 &= \sin^2(\theta_0 + KE_m \sin\omega t) \\
&= 1/2 - 1/2\cos(\theta_0)J_0(KE_m) \quad \text{(DC)} \\
&+ \sin(\theta_0)J_1(KE_m)\sin\omega t \ \text{(fundamental frequency)} \\
&- \cos(\theta_0)J_2(KE_m)\cos 2\omega t \ \text{(2nd frequency)} \\
&+ \sin(\theta\ )J_3(KE_m)\sin 3\omega t \ \text{(3rd frequency)} \\
&+ \ldots
\end{aligned}
$$

The parameter K depends on material parameters, $E_m \sin \omega t$ is the ac electric field, and θ_0 is the field-independent phase shift between the two propagation paths. For small values of KE_m (the usual case) we can use series expansions for the Bessel functions and determine the electric amplitude from $(KE_m)^2$ = (Magnitude of 3rd harmonic/Magnitude of fundamental) and the field-independent phase shift can be found from

$\theta_0 = \tan^{-1}$ {0.25 K E_m (Magnitude of fundamental/Magnitude of 2nd harmonic)}.

In preliminary work we have used a bulk lithium niobate field sensor to measure the size of a low frequency (80 Hz) field. In two experiments we measured nearly constant ac fields (1250 and 1750 volts/m) even as the field-independent phase difference was intentionally scanned from approximately 54-87 degrees in the first experiment and 30-85 degrees in the second. Some of these results shown in Figure 1. Our preliminary work looked only at the amplitudes of the various harmonics. Our continuing work looks at both amplitude and phase. Questions that we are addressing include: a) How reliably can the phase of the output signal be used to infer the phase of the ac electric field? b) What is the effect of the small harmonic content that is typically present on an ac transmission lines?

A fast Fourier transform of the sensor's voltage output is performed to determine the magnitude and phase of the harmonics relative to the fundamental component's magnitude and phase. Phase measurements are complicated by the need for compensation for finite duration signal samples (windowing). Windowing introduces a phase shift associated with the window function. The effects of different types of data windows (e.g., Hamming) are determined analytically, so that the influence of window functions can be minimized. Harmonic content in the input electrical signal introduces error in the calculation of both field amplitudes and in calculation of the field-independent phase shift.

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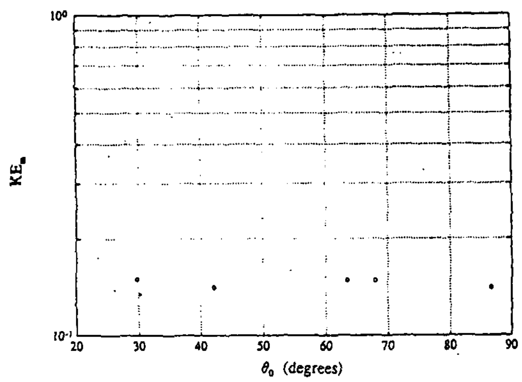

Figure 1.

KE_m versus field-independent phase shift θ_0 for an applied field of 1750 V/m. The theoretical value of KE_m is 0.11.