A laboratory investigation of electro-optic Kerr effect for detection of electric transmission line faults

Badrul H. Chowdhury
Missouri University of Science and Technology, bchow@mst.edu

E. Grigsby

T. J. Englert

Follow this and additional works at: http://scholarsmine.mst.edu/faculty_work

Part of the Electrical and Computer Engineering Commons

Recommended Citation
http://scholarsmine.mst.edu/faculty_work/1222

This Article is brought to you for free and open access by Scholars' Mine. It has been accepted for inclusion in Faculty Research & Creative Works by an authorized administrator of Scholars' Mine. For more information, please contact weaverjr@mst.edu.
ABSTRACT

A prototype Kerr cell has been constructed and tested for detecting and identifying faults by monitoring high voltages such as are found in electric power delivery systems. Simulated faults have been generated under laboratory conditions, monitored by the Kerr cell, and preliminary analysis done using analog-to-digital conversion of the detected waveforms with a single board microprocessor serially interfaced with a personal computer. The occurrence of faults is readily observed and results indicate that identification of fault types can be accomplished within less than one cycle of a standard sixty-cycle-per-second delivery system such as that found in the United States. With a dedicated analysis system such a technique may prove timely and economical in fault identification and location.

Keywords Kerr cell, voltage monitoring, synchronous generator, nitrobenzene.

1. INTRODUCTION

A primary objective of public utility electrical power systems is to maintain a high level of continuity of service. It is impossible to avoid accidental failure or misoperation due to human error and inadvertent connections or "flashover" of wires or from wires to ground along the delivery systems. Detection and analysis of the occurrence of such faults in these systems are critical to the timely maintenance of service.

Detection apparatus, prior to approximately the last decade, depended on inductive devices such as current transformers which consist of a simple coil surrounding the power line. These are susceptible to induced signals from other sources not necessarily associated with the power delivery system and are prone to give false indications of fault occurrences. With the advent of highly transparent optical waveguides (optical fibers) the possibility of fault sensing without electromagnetic interference became more feasible. A variety of methods using optical techniques and the linear Pockels effect have since been reported which exhibit relatively good success in fault detection [1,2,3,4]. The analysis schemes of many of the techniques seem unnecessarily complicated however. The linear electro-optic effect has also been used in field distribution measurements in transformer applications [5].

In this paper we describe a prototype cell, which uses the non-linear Kerr effect in nitrobenzene, for detection of fault occurrences, and show the resulting waveforms and associated frequency spectra of the optical intensity modulated by the monitored electric potentials including steady-state and laboratory-generated voltage faults. Non-linear or Kerr effect electro-optic techniques have been used for a variety of applications in sensing electric fields but have been primarily aimed at field mapping. These field mapping studies make use of the repetitive behavior, sometimes called fringing, of the phase retardation of lightwaves whose electric fields are polarized in the direction of the external electric field imposed on the electro-optic material. "Fringing" in this context is not to be confused with fringing due to lightwave interference or diffraction patterns.

Rather, the fringing alluded to is caused by the external electric field passing through multiples of the field value which yields the first maximum optical response [6-13]. The experiments described here are designed to monitor simulated line voltages at or below electric field magnitudes yielding the first maximum optical response.

2. KERR CELL DETECTION

2.1 Principle of Operation

The Kerr effect differs from the Pockels effect in that the birefringence in the Kerr material depends on the square of the electric field in the material rather than a linear dependence found in the Pockels effect. Birefringence induced by the presence of an electric potential applied to electrodes separated by the Kerr material causes the orthogonal components of polarization of the electric field of light passing through the material to travel at different speeds. As such, when the light passing through the cell reaches the exit the two components of polarization are out of phase causing varying degrees of elliptic polarization, depending on the applied potential. A polarizer placed at the optical output end of the cell then transmits light whose intensity depends upon the alignment of the axes of the elliptically polarized light incident on the polarizer.

Voltages applied across the Kerr cell are the line-to-line voltages of a balanced three-phase system. In Fig. 1 the voltage across lines b and c are shown applied to the cell which is the configuration throughout the series of tests reported herein. Functional descriptions of the data acquisition system at the output side of the Kerr cell are given in later sections of this paper. The difference in the indices of refraction for the two components of lightwave polarization for the Kerr effect, is given by

\[ n_+ - n_0 = K \lambda E^2 \]  

where \( n_0 \) is the index of refraction of light whose electric field is polarized parallel to the direction of the externally applied electric field, \( n_0 \) is the index for the polarization component perpendicular to the field, \( \lambda \) is the vacuum wavelength of the light passing through the cell, \( E \) is the electric field applied to the Kerr material, and \( K \) is the Kerr coefficient. It should be noted here that the electric field, \( E \), includes that of the light whose electric field is assumed to be small compared to the externally applied field. With relatively low intensity light, this field may be taken to be only that due to the high voltage field being measured. Light linearly polarized at an angle of 45° to the direction of the electric field applied to the cell gives equal polarization components parallel to and perpendicular to the externally applied field. This light is launched into the Kerr cell and becomes elliptically polarized, due to relative phase differences suffered by the two propagating components of polarization, with the degree of ellipticity dependent upon the strength of the field. Figure 1 depicts a sketch of the Kerr cell along with polarizing elements. If the electric field of the incident lightwave is given by

\[ E = E_0 \cos (kz - \omega t) \]  

with the direction of the field at 45° to the input polarizer axis, then the components of the field as the light propagates through the medium is found to be

\[ E_x = \frac{E_0}{\sqrt{2}} \cos \left( \frac{2\pi n_x z}{\lambda_0} - \omega t \right) \]  

and

\[ E_y = \frac{E_0}{\sqrt{2}} \cos \left( \frac{2\pi n_y z}{\lambda_0} - \omega t \right) \]  


0885-8977/91/0700-0979$01.00 ©1991 IEEE
As the lightwave propagates through the Kerr medium a phase difference results between the orthogonal components of polarization resulting in an elliptically polarized state. If, after traveling through a length $L$ of the Kerr medium the light is passed through a second polarizer which is oriented orthogonally to the input polarizer, the output optical intensity is found to be

$$I = I_0 \sin^2 \left( \frac{K_0 V_0^2 L}{2} \right)$$

(5)

where $I_0$ is the maximum transmitted light intensity, $V$ is the electric potential difference between the Kerr cell electrodes, $L$ is the effective length of the light path through the cell, and $d$ is the effective dimension of the cell in the direction of the externally applied field. Equation 5 is often written as

$$I = I_0 \sin^2 \left( \frac{E_0 V_0}{2V_m} \right)$$

(6)

where $V_m$ is given by [10]

$$V_m = \frac{2L}{2K_0}$$

(7)

Taking the source of the externally applied potential to be a line-to-line voltage, in these experiments, of the electrical power delivery system measured, we may write this potential as

$$V = V_0 \sin (\omega t)$$

(8)

where $V_0$ is the maximum voltage of the power line. The potential of Eq. 8 is allowed to appear across the Kerr cell giving rise to a time varying field within the cell, thus yielding a variation in output light intensity exiting the cell according to Eq. 6. The experimental work described in this paper restricts the applied potential to $V \leq V_m$ and the Kerr cell is designed accordingly.

### 2.2 Design of the Prototype Kerr Cell

The coefficients for electro-optic modulation of light, such as those found in the Kerr effect are typically small. For nitrobenzene, the material chosen for this work since the Kerr coefficient is relatively large, $K$ is approximately $3.16 \times 10^{-10} \text{ m/V}^2$. Small applied potentials therefore make the cell dimensions prohibitively small. A power laboratory three phase, 2-pole synchronous generator rated at 120 volts and 5 kVA is used to drive a transformer to yield a maximum potential of 3,500 volts at 60 Hz. The Kerr cell is therefore designed for a voltage of 3,500 volts. A rectangular cross section glass tubing having an inner dimension, $d$, of 0.6 mm, cut to a length of 43.2 cm, is filled with nitrobenzene and copper electrodes placed above and below the tube. The thickness of the glass tubing must be accounted for in calculation of the electric field in the nitrobenzene. A straightforward calculation using electric field continuity conditions across dielectric boundaries gives the electric field $E$ which appears in Eq. 1, within the nitrobenzene as

$$E = \frac{V}{d - \epsilon_0 \epsilon_r}$$

(9)

where $V$ is the voltage appearing across the Kerr cell, $d$ is the thickness of the nitrobenzene, $\epsilon$ is the dielectric constant of the nitrobenzene, $\epsilon_0$ is the thickness of the glass tubing wall, and $\epsilon_r$ is the dielectric constant of the glass. Field fringing has been ignored. The 60 Hz, 3,500 volt peak output of the transformer is used to drive the laser to the Kerr cell giving rise to a maximum potential of 3,500 volts thereby avoiding fringing orders greater than 1.

Figure 2 shows the Kerr cell and Figure 3 shows a typical output of measured light intensity for the system in the steady state (no faults). It should be noted that the output optical intensity represents a rectified version of the voltage applied to the Kerr cell, however the rectified wave is not that found in the usual sense because of the square of the sine functions found in the intensity described by Eqs. 5 and 6. Some optical noise is evident in the curve of Figure 3 which was found to be due to variation in the light intensity from the laser. This variation is caused by ripple in the rectified power supply driving the laser and has a frequency of 120 Hz. Laser versions of this system will use a more constant intensity source of light such as a laser diode or light-emitting diode.

### 2.3 Detection and Conversion of the Optical Output

The data acquisition system consists of a master-slave type interface of a single board, 8086 microprocessor (slave) and a Texas Instrument (TI) personal computer (master). Appropriate code routines are routed through a serial interface from the TI to the microprocessor allowing A/D conversion and data storage.

A PIN photo-diode is used to detect the optical signal with the amplified output fed into a sample and hold for the A/D conversion. The conversion rate is set at 1800 samples per second by the master and a total of 4096 samples (22.7 seconds) accumulated, corresponding to 30 samples for each cycle of 60 Hz signal, and stored in RAM of the slave board. According to principles of digital signal processing, a signal is uniquely represented if (Nyquist criteria) [14]

$$f_s \geq 2f$$

(10)

where $f_s$ is the sampling frequency and $f$ is the frequency component in the sampled signal. At 1800 samples per second corresponding to 30 samples per cycle, zero mean square error is anticipated for signal frequency components as large as 900 Hz [14]. Frequencies due to fault conditions introduced into the signal may then be reliably sampled up to 900 Hz. The reader is reminded that the steady-state optical signal being monitored has a frequency of 120 Hz, as discussed earlier. Any frequency components greater than 900 Hz will lead to "aliasing" in the signal processing. To avoid aliasing, a simple low-pass R-C filter with a 3-dB point at 795 Hz and a 20-DB per decade slope after the corner frequency, is used. This anti-aliasing filter effectively reduces frequency component contributions above 900 Hz to a negligible level. The likelihood of fault induced frequencies above this frequency is assumed to be remote.

Start of conversion is controlled by the master and monitored with a LED to indicate to the operator that conversion is taking place. After conclusion of the conversion, the data stored in RAM of the slave is transmitted to the master via the serial port and stored on hard disk by the master. A block diagram of the electronics and computer controlled data acquisition system is shown in Fig. 4.

### 2.4 Signal Conditioning and Processing

Voltage data, transduced by the Kerr cell, for the steady state was found to vary somewhat in amplitude due to light intensity variation from the laser source as noted earlier. To alleviate this minor effect, the data are normalized to yield maxima and minima of +1 and -1 respectively. Normalization was accomplished by determining the maximum and minimum amplitudes within a given data set, dividing every data point by the maximum after subtraction of the minimum from every data point. The final step in normalization subtracted the mean value determined from the steady-state signal, which preceded the fault, in the data set from all other points of the set. This normalization then allows easy comparison of relative amplitudes and spectral energy of various frequency components, including dc components, during successive fault tests.

Data sequences produced by the normalization routine are then analyzed for spectral energy density by using the Discrete Fourier technique (DFT). A rectangular window function is used, the original data sequence being blocked into 32-point sections, each section overlapping by 16 data points. This window width represents approximately one full cycle of the original 60 Hz high-voltage signal while moving the window 16 data points for successive analyses will represent a DFT during each half cycle of the 60 Hz signal. Each block, or window, is then padded with 96 zeros to increase the output resolution of the spectral estimation routine which produces estimations with a fundamental of 14 Hz and 64 discrete frequency components. This padding has been added to reduce "leaking" which typically occurs in DFT calculations using rectangular windows [15]. Remnants of leakage effects are evident in the data presented below, however these effects are not so large as to mask the data of interest. In principle it would be possible to include more data points but computation time increases accordingly for each DFT, which defeats the ultimate aim of real-time analysis. The integral power of two data points within the analysis window has been chosen for computational convenience in the DFT algorithm used.

### 3. TEST RESULTS

Several tests were conducted on a power laboratory, three-phase synchronous generator to investigate the behavior of the optical fault detector under different fault conditions. The generator was configured as a wye-connected, 120V line-to-line generation system transformed to 2475V (3300 peak) as described earlier, with its neutral solidly grounded. The experimental set-up for conducting faults on a loaded generator is shown in Fig. 1, in Section 2 of this paper. The simulation of power line faults is accomplished by causing line-to-ground or line-to-line contacts in electrical power delivery to be performed.
The following is a list of the fault studies conducted:

- a) Single line to ground fault on the loaded generator.
- b) Line-to-line fault on the loaded generator.
- c) Double line-to-ground fault on the loaded generator.
- d) Three phase fault on the loaded generator.

The objectives of the tests are the identification of certain distinctive characteristics from the output of the Kerr cell for all the different fault conditions. As noted earlier, the Kerr cell is connected across the b and c phases.

A graph of the light intensity output during the time of an introduced line-to-ground fault, and until recovery after removal of the fault, is shown in Figure 5. Three successive DFT analysis windows, described earlier, are outlined within the figure. Window 1 is the pre-fault zone, window 2 contains the point of application of the fault and window 3 is the post-fault zone. Each window is 2 cycles (of 120 Hz) wide and the windows overlap a half cycle. Shifting the windows across the acquired samples allows investigation of the evolution of the spectral content. Due to the large temporal variations in the samples at the point of application of the fault and beyond, the spectral contents of the three windows, pre-fault, during fault, and post-fault windows, will show different spectral characteristics. In the following analysis, we attempt to demonstrate the susceptibility of fault identification to the spectral information contained within such windows.
A graph such as Fig. 5 is obtained for each fault type. A 2-cycle window is then traversed across the entire graph. Using the signal conditioning procedure as described in Section 2.4, the discrete points inside each window are subjected to a Discrete Fourier Transform (DFT). This information is plotted on a three-dimensional diagram as shown in Figure 6a for a single line-to-ground fault on the system. In this figure, each of the smallest marks on the "Time Window" axis corresponds to 8.33 msec. Figure 6a clearly shows the identification of a fault in the power system after 0.5 secs from the origin of the plot.

Figure 6b, c and d show the frequency spectrum as a result of the application of DFT to each of the three windows 1, 2 and 3 respectively for the same fault as portrayed in Fig. 6a. To repeat, these windows correspond to pre-fault, during-fault and post-fault conditions respectively. Figures 7 through 9 show the same set of information for other types of faults. Marked differences in frequency components and/or amplitudes can be observed in each of the figures. The salient points are tabulated in Table 1. Care was taken so that each test was conducted repeatedly under similar conditions, which included performance of the laser gun, frequency of the generator, load on the generator, voltage generated by the generator, the faulting device, etc. Due to degradation of the performance of the laser gun, one of the tests, namely fault between lines a and b, could be conducted only once and hence no conclusion could be drawn on that particular fault.

From the table, it is evident that the type of fault, meaning whether it is a phase fault or a ground fault can be differentiated by observing certain characteristics. Of course, the characteristic should be investigated with regard to the location of the Kerr cell across specific lines. It appears that, since the cell was connected across lines b and c, any fault involving these two phases will have a relatively large impact on the 120-Hz component. In other words, this component will shrink considerably in both the fault and post-fault windows. This particular effect is sharply noticeable when the two phases are faulted alone either to each other or to ground. Also from the table, the double line-to-ground faults consistently produce a second frequency component higher than the 120-Hz and the latter is reduced to almost nil in the post-fault window. On the other hand, the three-phase fault produces a rather clean 120-Hz frequency component in the fault and post-fault windows. Presence of dc component in any of the spectra is due to the fact that the datum of the sampled data is shifted either during or after fault. It should be pointed out that in all fault cases, voltage collapse is maintained consistently in the post-fault window, which means that a significant amount of time is available to allow distinction between a fault and a transient on the system.

4. CONCLUSIONS AND DISCUSSION

A prototype Kerr cell has been constructed and tested for monitoring high voltages and identifying faults in power systems. Simulated faults were generated under laboratory conditions using a power laboratory synchronous generator and monitored by the Kerr cell. Results can be extended to any larger systems such as are found in typical electric power delivery systems in the U.S.

The occurrence of faults is readily observed by inspection of light intensity outputs during the time of an introduced fault, however it is evident from the spectral analyses that fault types are identifiable which may not be immediately evident in the time domain data. Discrete Fourier techniques were used to analyze the spectral energy density in the data sequence produced by the Kerr cell before the fault, during the fault and after the fault. Investigation of the results produced by various types of faults in the system reveals the fact that the Kerr cell identifies significant differences between the phase faults and the ground faults. The position of the Kerr cell between two particular phases, is very important in the analysis. During the investigations, the Kerr cell was connected between phases b and c. As a result, the b-to-c line-to-ground fault and the b-to-c line fault appear to have similar frequency components. This might be expected because in both cases the Kerr cell apparently looks at a collapsed voltage across its terminals. On the other hand, the line a-to-ground and line b-to-ground faults are quite different, each having distinctive features. The ground faults, in general produce large dc components during and after the faults. In any case, the spectral components of various fault types exhibit marked differences. The test spectra show general consistency when experiments are repeated under identical laboratory conditions.

<table>
<thead>
<tr>
<th>Fault</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line a-to-ground</td>
<td>The 120-Hz component reduces to 89% of the pre-fault condition during fault and to 64% in the post-fault window. No significant dc component is present in the three windows. Presence of two humps at 600-Hz and 700-Hz. It is believed that these two frequency components are due to the non-linear excitation of the transformer across the other two phases. The two high frequency components are absent in the other two line-to-ground faults.</td>
</tr>
<tr>
<td>Line b-to-ground</td>
<td>The 120-Hz component reduces to 83% of the pre-fault condition during fault and to 43% in the post-fault window. Presence of large dc component in post-fault window signifying that there is a shift of datum after the voltage starts to recover.</td>
</tr>
<tr>
<td>Line c-to-ground</td>
<td>The 120-Hz component reduces to 22% of the pre-fault condition during fault and maintains this magnitude in the post-fault window. Presence of large dc component in both fault and post fault windows signifying that there is a shift of datum during and after the voltage recovery.</td>
</tr>
<tr>
<td>Lines a &amp; b-to-ground</td>
<td>The 120-Hz component reduces to 65% of the pre-fault condition during fault and to 50% in the post-fault window. This component is predominant in all windows. No significant dc component is present in the three windows.</td>
</tr>
<tr>
<td>Lines b &amp; c-to-ground</td>
<td>The 120-Hz component reduces to 53% of the pre-fault condition during fault and to an undetectable level in the post-fault. Presence of a large dc component in the post-fault window is due to the same reason as noted earlier. The 120-Hz component is not predominant. A frequency component higher than 120-Hz is present in window 2.</td>
</tr>
<tr>
<td>Lines a &amp; c-to-ground</td>
<td>The 120-Hz component reduces to 47% of the pre-fault condition during fault and to 8% in the post-fault window. Presence of a large dc component in window 3. The 120-Hz component is not predominant. A frequency component higher than 120-Hz is present in window 2.</td>
</tr>
<tr>
<td>Three-phase fault</td>
<td>The 120-Hz component reduces to 38% of the pre-fault condition during fault and to 5% in the post-fault window. Presence of a large dc component in window 3. The 120-Hz component is not predominant. A frequency component higher than 120-Hz is present in window 2.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fault</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line a-to-c</td>
<td>The 120-Hz component reduces to 47% of the pre-fault condition during fault and to 8% in the post-fault window. Presence of a large dc component in window 3. The 120-Hz component is not predominant. A frequency component higher than 120-Hz is present in window 2.</td>
</tr>
<tr>
<td>Lines a &amp; c-to-ground</td>
<td>The 120-Hz component reduces to 38% of the pre-fault condition during fault and to 5% in the post-fault window. Presence of a large dc component in window 3. The 120-Hz component is not predominant. A frequency component higher than 120-Hz is present in window 2.</td>
</tr>
<tr>
<td>Three-phase fault</td>
<td>The 120-Hz component reduces to 63% of the pre-fault condition during fault and to 16% in the post-fault window. Presence of a large dc component in window 3. The 120-Hz component is predominant in all windows.</td>
</tr>
</tbody>
</table>
Figure 6. Line a-to-ground fault

Figure 7. Double line b-to-c fault
Figure 8. Double line b-and-c-to-ground fault

Figure 9. Three-phase fault
The use of nitrobenzene in these experiments was dictated primarily by availability, economics, and the relatively large Kerr coefficient. Off-the-shelf research quality nitrobenzene having a purity of 99% or greater and available at a reasonable price, economics, and the relatively large Kerr coefficient. Off-the-shelf nitrobenzene was used for approximately six months. This may in part be attributable to the use of borosilicate glass and teflon, although no special precautions other than ordinary laboratory cleanliness were taken. If the nitrobenzene is not exposed to contaminants, such as air and water, and dielectric breakdown is avoided, one would anticipate a relatively long lifetime expectancy. A year old cooling was used in another application to find that the electrical conductivity of 2.5 x 10^-7 mhos/cm^3 compared to 7 x 10^-7 mhos/cm^3 for pure nitrobenzene. A detrimental timing effect has been noted in previous work when sodium silicate (water glass) was used for confinement of nitrobenzene used in fast (5.7°C) melting point measurements. Here, thermal dependence of the refractive index of nitrobenzene was shown to be about 5 parts in 10^4/°C. Under these conditions, temperature effects do not present any undue complications, and the melting point of the film is significantly higher than the operating temperature. The use of sodium silicate for this application is thus recommended. The melting points of the glass and teflon, although no special precautions other than ordinary laboratory cleanliness were taken. If the nitrobenzene is not exposed to contaminants, such as air and water, and dielectric breakdown is avoided, one would anticipate a relatively long lifetime expectancy.

Future experiments and computer simulations are planned which will incorporate simultaneous voltage and current measurements using electro-optic and magneto-optic effects. It is expected that more specific identification of faults will be possible as well as fault location, based on spectral information gleaned from fault data.

Acknowledgements
This research work was made possible by a grant from the University of Wyoming research office.

5. REFERENCES


Thad J. Englert was born in Garden City, Kansas on November 14, 1934. He received his B.S. degree in Physics from the University of Northern Colorado in 1962, M.S. in Physics from Iowa State University in 1965, and Ph.D. in Physics from the University of Wyoming in 1983. Between the master's and doctoral degrees, he worked for four years at the Iowa State Synchrotron facility and for six years teaching at Colorado Mountain College at Glenwood Springs, CO. He is currently an Assistant Professor of Electrical Engineering at the University of Wyoming. His research interests include electro-optics, non-linear optics and optical waveguides.

Dr. Englert is a member of IEEE, SPIE, ASEE and AAPT.

Badral H. Chowdhury(M87) received his Bachelor of Science degree in Electrical Engineering from the Bangladesh University of Engineering and Technology in 1981. He obtained his M.S. in Physics from Iowa State University in 1983 and his Ph.D. in Physics from the University of Wyoming in 1985. Between the master's and doctoral degrees, he worked for four years at the Iowa State Synchrotron facility and for six years teaching at Colorado Mountain College at Glenwood Springs, CO. He is currently an Assistant Professor.

Dr. Chowdhury has been actively involved in research in the area of Power Engineering for a number of years. His major areas of research interests are in power system planning, and operation, expert systems and alternate energy systems. He is the author of several technical papers in these areas.

Dr. Chowdhury is a member of IEEE and ASEE.

Ed Grigsby (S’86) was born in New Castle, Wyoming on August 1, 1964. He received his B.S. and M.S. degree in Electrical Engineering in 1988 and 1990 respectively, from the University of Wyoming. He is currently working at the Edwards Air Force Base in California. His present research interest is in electro-optics.

Mr. Grigsby is a member of IEEE and a member of LEOS.