Nonintrusive Sensing Techniques for the Discrimination of Energized Electric Cables

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***Abstract*—The implementation of a piezoelectric acoustic sensor for nonintrusive detection of the energization status of 3-ϕ electric power cables is presented. Simultaneous excitation of a piezoelectric crystal by acoustic vibrations and electric field may occur. The Fourier spectral analysis of the sensor's output signal is used to determine the current loading status of the cable. Test results are included for both shielded and nonshielded 3-ϕ cables. Also, the possible use of an optical fiber interferometer for acoustic wave detection is discussed.**

I. Introduction

The detection of underground energized cables poses a serious problem for urban electric utilities [1]. As power networks continue to expand and become more interconnected, the task of maintaining an accurate topological representation of the power grid is often sacrificed. Consequently, maintenance personnel are constantly required to determine the energization status of underground cables for routine maintenance and service restoration.

The predominant detection method practiced today is intrusive in nature, requiring the maintenance personnel either to puncture or remove the protective conducting sheath surrounding the cable [1]. This approach not only exposes the worker to a potentially hazardous situation, but it causes irreversible damage to the integrity of the cable. A passive, nonintrusive detection method is ideal from both the perspective of safety and infrastructural preservation. The evaluation of the energization status of nonshielded cables may be accomplished more safely and more easily by sensing the induced electric field surrounding an energized cable. The suitability and performance of several nonintrusive measurement techniques for energized cable detection are studied in this paper.

Acoustic vibrations, characteristic only of energized cables, may also be used in the determination of the cable's energization status [2]. This method involves the detection of second-harmonic (120 Hz) acoustic surface waves generated by an energized, current-carrying 3-ϕ cable. This paper focuses specifically on the implementation of a piezoelectric accelerometer for this purpose. A piezoelectric crystal, which constitutes the sensing element of commonly used miniature accelerometers, responds both to the surface acoustic waves and the power-frequency electric fields of an energized conductor. Fourier analysis of the frequency spectral content of the sensor's output is required to discriminate between these two effects.

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II. Theoretical Background

The theoretical models used to describe the acoustic vibrations induced in an energized conductor are presented. Additionally, a mathematical model used to describe the relationship of the spatial displacements caused by an electric field gradient across a piezoelectric ceramic crystal is given.

A. Magnetically Induced Vibrations

By Faraday's law of induction, magnetically induced forces are generated in a 3-ϕ cable that is carrying current [2]. These surface acoustic vibrations are caused not only by the current traveling though the individual phase conductors, but also by the geometrical configuration of the cable. In utilizing cylindrical coordinates with the conductor serving as the z axis, a currrent i_1 in a conductor induces a magnetic field $\vec{B}$ around that conductor which is a function of the azimuthal vector $\vec{\theta_0}$ extending from the conductor's center,

$$\vec{B} = \frac{\mu_0 i_1}{2\pi r}\vec{\theta_0}. \tag{1}$$

This magnetic field induces a force $\vec{F_i}$,

$$\vec{F_i} = \vec{i_2} \times \vec{B} = \frac{\mu_0 i_1 i_2}{2\pi r}\vec{r_0} \tag{2}$$

where r is the distance between the conductor carrying current i_1 and, for our application, another conductor carrying current i_2.

If we take the currents in the two conductors to both be modulated at frequency ω with some arbitrary phase difference θ we get the resultant force

$$\vec{F_i} = \frac{\mu_0 I_1 I_2}{4\pi r}[\cos\theta + \cos(2\omega t - \theta)] \tag{3}$$

where I_1 and I_2 are the amplitudes of the currents i_1 and i_2 in the two conductors. For our specific application, we studied a 3-ϕ cable containing three embedded conductors. Ideally, for a symmetrically loaded 3-ϕ cable, carrying phase currents i_1, i_2 and i_3 all having the same amplitude I, i.e., $I_1 = I_2 = I$, the three phase currents would follow the well-known 3-ϕ representation as

$$i_1 = I\cos\omega t \tag{4}$$
$$i_2 = I\cos(\omega t - 120°) \tag{5}$$
$$i_3 = I\cos(\omega t + 120°). \tag{6}$$

If the three conductors are geometrically spaced in an equilateral triangular arrangement with distance r separating each conductor, then by (3), a force is exerted on each conductor from the currents in the remaining two.

B. Electrically Induced Vibrations

A time-varying electric field encompassing an energized cable also induces acoustic surface waves. In a 3-ϕ system, the relationship between the phase voltages is

$$v_1 = V\cos\omega t \tag{7}$$
$$v_2 = V\cos(\omega t - 120°) \tag{8}$$
$$v_3 = V\cos(\omega t + 120°). \tag{9}$$

The surface charges of the individual conductors in the 3-ϕ cable also modulate sinusoidally and in phase with their individual phase excitation voltages. Their interaction results in second-harmonic frequency (120 Hz) vibrations. The resultant, electrically induced force applied to the conductors $\vec{F}_v$ is a function of the 3-ϕ voltages with frequency ω [2],

$$\vec{F}_v = \frac{1}{2}V^2\frac{dC}{dx}[\cos\theta + \cos(2\omega t - \theta)] \tag{10}$$

where C is the capacitance per unit length of the two insulated parallel conductors, and x is the distance between them.

C. Piezoelectric Transducer

As a voltage is applied across the thickness of a flat slab, rectangular piezoelectric transducer (PZT), the induced electric field forces contraction and expansion along the longest axis, as illustrated in Fig. 1. Likewise, an applied force induces an internal electric field in the piezoelectric crystal (i.e., our accelerometer) which is detected with the assistance of an amplifier and bandpass filter. The physical relationships governing the incremental spatial modulation of the PZT $(\Delta W, \Delta L, \Delta thk)$ as a function of the applied voltage V, are given in (11)–(13). For our specific application, the surface acoustic waves generated by a loaded (3) and energized (10) cable are detected through the induced voltage in the accelerometer,

$$\Delta W = \frac{d_{31}VW}{thk} \tag{11}$$
$$\Delta L = \frac{d_{31}VL}{thk} \tag{12}$$
$$\Delta thk = d_{33}V \tag{13}$$

where

- W, L, thk are the width, length, and thickness of the PZT (m),
- d_{31} is the PZT strain coefficient, along L and W (m/V), and
- d_{33} is the PZT strain coefficient, along thickness (m/V).

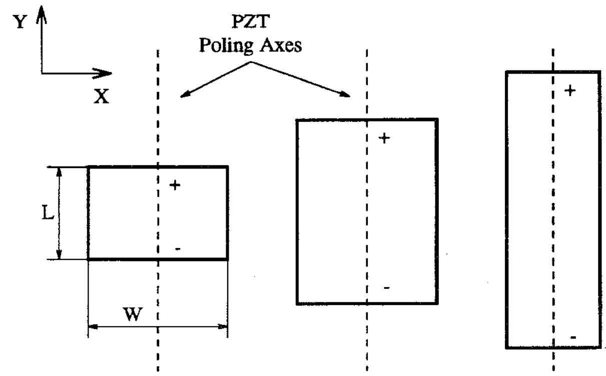

Fig. 1. PZT Expansion and Contraction.

The mechanical response of commercially available PZT's can easily match electric field modulation for low-frequency applications (i.e., 60 Hz).

III. Experimental Arrangement

The 3-ϕ power cable utilized in the test configuration was energized by a 120/208 V, 3-ϕ power supply and terminated by a variable 3-ϕ load rack to allow testing under load ($i \neq 0$) and no-load ($i = 0$) conditions. A piezoelectric accelerometer was attached to the 3-ϕ power cable to quantify the current loading effects of magnetically induced acoustic vibrations. Fig. 2 shows the experimental test configuration.

The variable-load rack consisted of three 1.5 kW bulbs Δ-connected to provide a sufficient cable load current ($\sim$12 A per phase). There were two 3-ϕ cables used in the testing: a COLLYER LSTSGU-23-M24643/16-05UN and an SO P-123-70-MSHA. The second, smaller cable was loaded close to its maximum current-carrying capacity in an effort to characterize this effect on magnetically induced vibrations.

The acoustic sensor was a type 6062 piezoelectric accelerometer produced by Columbia Research, Inc. A Stanford Research Systems amplifier/filter was used to condition the output signal from the sensor. For high-frequency or power-frequency noise suppression, an appropriate band-pass was chosen, depending on the specific orientation of the sensor and the current loading of the cable. After passing through this amplifier and filter, the signal was patched to an oscilloscope for visual display purposes and to an analog instrumentation data recorder for Fourier spectral and other off-line data analyses.

A RACAL V-Store instrumentation data recorder was used to record the sensor signal on a standard VHS tape. For data analyses, including Fourier spectral analysis, Global Lab Software by Data Translation, Inc., was used.

IV. Analysis of Experimental Data

As previously mentioned, the output of the sensor is a function of two parameters. The first is the ambient electric field, and the second is the magnetically induced acoustic vibra-

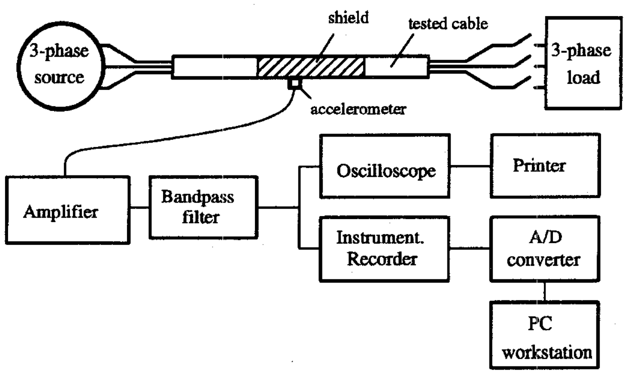

Fig. 2. Test Configuration.

tions. Both signals contain the fundamental power-frequency component and its harmonics. The sum of several sinusoidal signals with frequency ω of various phases is also a sinusoid of frequency ω. Consequently, the frequency spectrum of the output signal itself is insufficient for discrimination between the two phenomena.

In order to separate the electric field and acoustic wave contribution to the output signal, a sequence of tests has been performed. The sensor was attached to the surface of the cable in two different orientations. The first orientation, as prescribed by the manufacturer, fixed the flat surface of the accelerometer on the cable with an adhesive (i.e., beeswax). For the second orientation, the sensor is rotated by 90°, so that the acoustic excitation is applied to the two orthogonal axes of the accelerometer. A shielded cable was emulated by placing aluminum foil around the cable surface. Measurements were taken for three specific test cases: 1) when the tested cable was de-energized, 2) when it was energized with no load current, and 3) when it was energized and loaded.

A. Shielded Cable

The frequency spectral content of the output signal is shown in Fig. 3 for the three cable test conditions. In Fig. 3(a), when the cable is not energized, there is a significant background electric field, mostly of the fundamental (60 Hz) and third-harmonic (180 Hz). Energization of the cable does not significantly change the sensor output signal, as seen in Fig. 3(b). This suggests that the additional electric field, created by the cable energization, is effectively shielded. The electrically induced acoustic vibrations given by (10) are virtually negligible and cannot be used to determine the energization status of the cable.

However, when current flows through the conductors, the output signal changes significantly. Most importantly, there is a significant second-harmonic content (120 Hz), as predicted by (2). In Fig. 3, the second-harmonic contribution is smaller than that of the fundamental and third harmonics; however, the relative magnitude of these frequencies is mostly defined by the properties of a particular sensor. An increase in the fundamental and third harmonics should be attributed mostly to imperfect shielding. Thus, without prior knowledge of a nonenergized cable's background signal level, the discrimination on the basis of the fundamental frequency power spectrum is almost impossible.

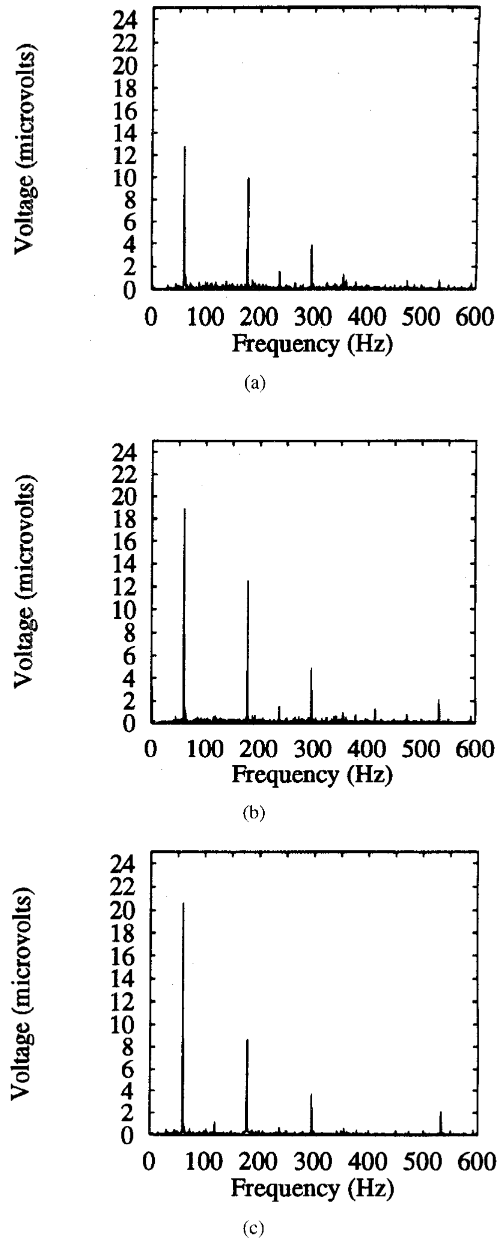

Fig. 3. Frequency spectrum of the sensor output signal when a shielded cable is (a) nonenergized, (b) energized, and (c) energized and loaded.

B. Nonshielded Cable

When no shield is present on the cable surface, the ambient electric field can easily be detected with various electric field sensors [3]. In most cases, the difference between the background fields and the fields near the surface of the cable can serve as an indicator of energization. However, while the absence of the electric field gradient around a nonshielded cable serves as a reliable indicator of a nonenergized status,

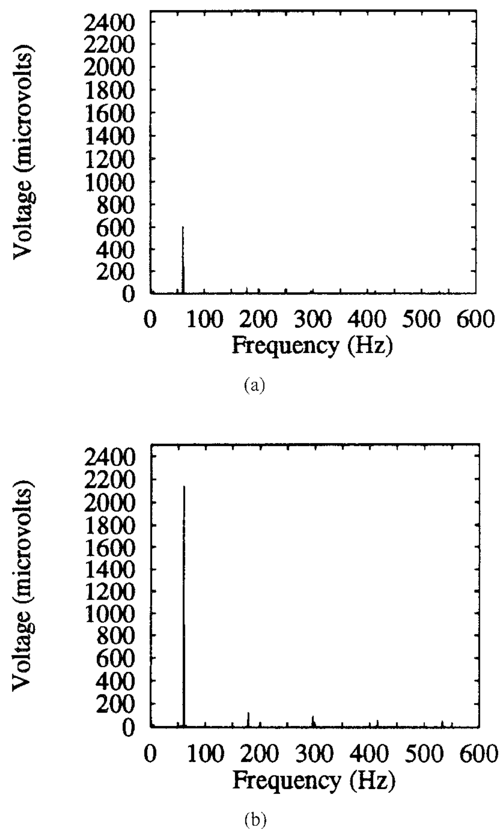

Fig. 4. Frequency spectrum of the sensor output signal when a nonshielded cable is (a) nonenergized, and (b) energized with and without load.

the converse is not always true. In other words, an electric field gradient may exist around nonenergized cables as well as around energized ones. This is caused by longitudinally induced voltages in mutually coupled lines. Although this apparent field, from mutual coupling, is weaker than a field from an energized cable, it may be strong enough to give a false test result.

An example of this situation is given in Fig. 4. The electric field lines are virtually perpendicular to the cable surface. In this experiment, the test arrangement remained the same, except the cable shielding was removed from the cable surface. With the same sensor orientation as described in the previous section, the output signal is practically the same as in Fig. 4. This suggests that the electric field caused by energization of the cable does not affect the sensor's response. Rotating the sensor by 90° changes the output signal dramatically, since in this orientation, the sensor's PZT element responds to the electric field surrounding the conductor.

When the tested cable is not energized, but still connected to the electric network, charges are induced on the phase conductors of the cable, and the sensor spectral output is shown in Fig. 4(a). When the cable is energized, its output increases, as shown in Fig. 4(b). Since the sensor's response to the ambient electric field is two orders of magnitude greater than for a shielded cable, current loading has virtually no effect on the output signal, as shown in Fig. 3. Fig. 4(b) is very similar for both loaded and nonloaded conditions.

V. Discussion

A. Sensor Implementation for Power Applications

The significant subject to note is the fact that the second-harmonic frequency content is nonexistent when a cable is not loaded. By using an acoustic wave sensor (i.e., an accelerometer) in conjunction with a lock-in amplifier tuned to 120 Hz, the current loading status of a shielded cable may easily be determined. The discrimination of the energization status of an unloaded shielded cable is more difficult. Relatively, it is easy to discriminate the status if the fundamental and third-harmonic power-frequency noise is quantified. However, the background noise spectral density is usually unavailable, and a sensor suitable for field application (i.e., underground cable discrimination) should be immune to such background effects. Clearly, some noise suppression design must be integrated to provide an adequate sensor for acoustic wave detection of shielded cables.

B. Optical Sensor Implementation

The dielectric characteristics of optical fiber are ideal for power system applications (i.e., immunity to electromagnetic and radio-frequency interference) [4]. The implementation of an electrically isolated, optical acoustic sensor could be used for detection of the current loading status of a power cable.

The intensity-modulated, back-reflected light signal for a fiber Fabry-Perot interferometer (FFPI) is well understood [5]. Specifically, it is the length-changing characteristic of the interferometer cavity that drives this signal modulation.

An acoustic-to-optical transducer, coupled to the FFPI cavity, could spatially modulate the FFPI as a function of the magnetically induced surface acoustic waves in a current-carrying conductor. This particular application is presently being investigated at Texas A&M University.

VI. Conclusions

A commercially available accelerometer employing a PZT as the sensing element has successfully indicated the energization and current loading status of a 3-ϕ power cable. By Fourier spectral data analysis of the voltage signal output from the accelerometer, the current loading status of a shielded or nonshielded cable is easily determined. Because the sensing element of the accelerometer, a PZT, is sensitive to both cable surface acoustic vibrations and ambient electric fields, the power spectral density provides key information in determining the energization and current loading status from the same output signal.

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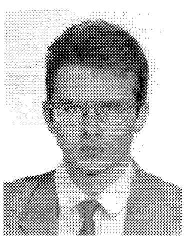

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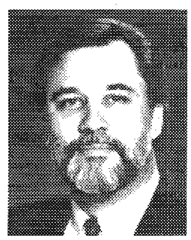

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