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(54) **Title:** SYSTEM AND METHOD FOR MONITORING OF ELECTRICAL CABLES
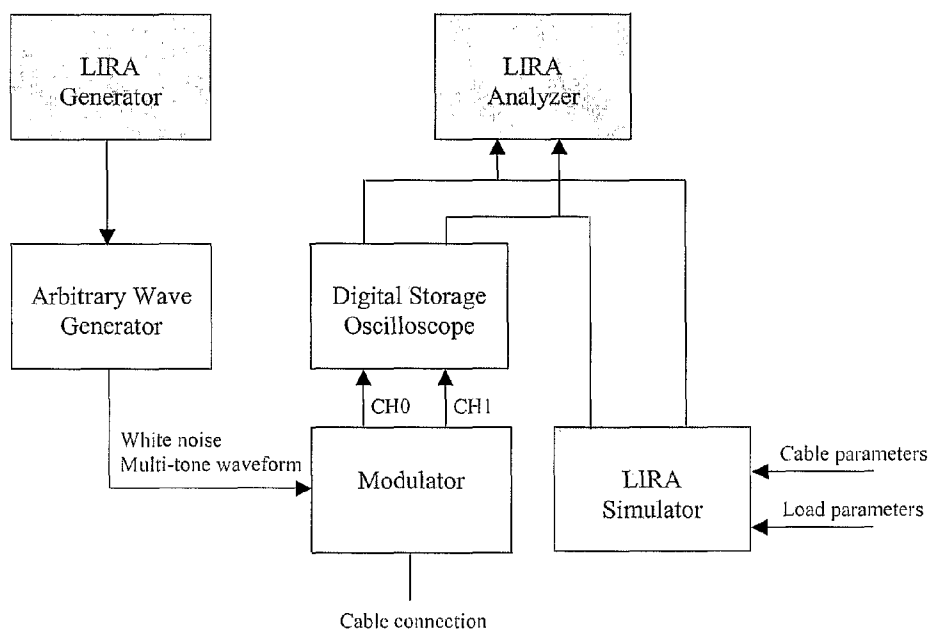
(57) **Abstract:** The present invention provides a method for monitoring a condition of an electrical cable, the method comprising providing a reference signal CH0 and a signal CH1, said signal CH1 being the reference signal CH0 after amplitude and phase modulation by a cable impedance Z_{DUT} of the electrical cable; calculating the cable impedance Z_{DUT} as a function of the applied signal frequency based on the reference signal CH0 and the signal CH1; and analyzing said cable impedance providing an assessment of the cable condition. A system performing the method is also disclosed.

SYSTEM AND METHOD FOR MONITORING OF ELECTRICAL CABLES

INTRODUCTION

The present invention provides a system and a method for monitoring of installed

5   electrical cables based on line resonance analysis. Monitoring comprises e.g.

condition monitoring and real-time diagnosis of the electric cables. Throughout the

present description the system is also referred to as LIRA (Line Resonance

Analysis System). The cables have lengths ranging from a few meters to several

hundred kilometers, depending on the cable structure and attenuation.

10

BACKGROUND

LIRA (Line Resonance Analysis System) is based on transmission line theory, an

established and well documented theory that is at the base of two other existing

15   cable fail detection techniques known as "Time Domain Reflectometry" (TDR) and

"Frequency Domain Reflectometry" (FDR). Differences and limitations of these two

existing techniques are explained in the following.

A transmission line is the part of an electrical circuit providing a link between a

20   generator and a load. The behavior of a transmission line depends by its length in

comparison with the wavelength λ of the electrical signal traveling into it. The

wavelength is defined as:

$$\lambda = \frac{v}{f} \qquad\qquad (1)$$

25

where v is the speed of the electric signal in the wire (also called the *phase

velocity*) and f the frequency of the signal.

When the transmission line length is much lower than the wavelength, as it

30   happens when the cable is short (i.e. few meters) and the signal frequency is low

(i.e. few KHz), the line has no influence on the circuit behavior. Then the circuit

impedance (Z_{in}), as seen from the generator side, is equal to the load impedance at any time.

However, if the line length is higher than the signal wavelength, ($L \geq \lambda$), the line characteristics take an important role and the circuit impedance seen from the generator does not match the load, except for some very particular cases.

The voltage V and the current I along the cable are governed by the following differential equations, known as the *telephonists equations*:

$$\frac{d^2V}{dz^2} = (R + j\omega L)(G + j\omega C)V \qquad (2)$$

$$\frac{d^2I}{dz^2} = (R + j\omega L)(G + j\omega C)I \qquad (3)$$

where ω is the signal radial frequency, R is the conductor resistance, L is the inductance, C the capacitance and G the insulation conductivity, all relative to a unit of cable length.

These four parameters completely characterize the behavior of a cable when a high frequency signal is passing through it. In transmission line theory, the line behavior is normally studied as a function of two complex parameters. The first is the *propagation function*

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} \qquad (4)$$

often written as

$$\gamma = \alpha + j\beta \qquad (5)$$

where the real part α is the line *attenuation constant* and the imaginary part β is the *propagation constant*, which is also related to the phase velocity v, radial frequency ω and wavelength λ through:

$$\beta = \frac{2\pi}{\lambda} = \frac{\omega}{v} \qquad (6)$$

The second parameter is the *characteristic impedance*

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \qquad (7)$$

Using (4) and (7) and solving the differential equations (2) and (3), the line impedance for a cable at distance d from the end is:

$$Z_d = \frac{V(d)}{I(d)} = Z_0 \frac{1 + \Gamma_d}{1 - \Gamma_d} \qquad (8)$$

Where Γ_d is the *Generalized Reflection Coefficient*

$$\Gamma_d = \Gamma_L e^{-2\gamma d} \qquad (9)$$

and Γ_L is the *Load Reflection Coefficient*

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} \qquad (10)$$

In (10) Z_L is the impedance of the load connected at the cable end.

From eqs. (8), (9) and (10), it is easy to see that when the load matches the characteristic impedance, $\Gamma_L = \Gamma_d = 0$ and then $Z_d = Z_0 = Z_L$ for any length and frequency. In all the other cases, the line impedance is a complex variable governed by eq. (8), which has the shape of the curves in Figure 1 (amplitude and phase as a function of frequency).

Existing methods based on transmission line theory try to localize local cable failures (no global degradation assessment is possible) by a measure of V (equation (2)) as a function of time and evaluating the time delay from the incident wave to the reflected wave. Line attenuation and environment noise in real

5   environments limit its sensitivity preventing the possibility to detect degradations at an early stage, especially for cables longer than few kilometers. In addition, no global cable condition assessment is possible, which is important for cable residual life estimation in harsh environment applications (for example nuclear and aerospace applications).

10

SUMMARY OF THE INVENTION

The object of the invention is to solve or at least alleviate the problems indicated above.

15   In a first aspect the invention provides a method of monitoring a condition of an electrical cable, the method comprising providing a reference signal CH0, and a signal CH1, said signal CH1 being the reference signal CH0 after amplitude and phase modulation by a cable impedance Z_{DUT} of the electrical cable; calculating the cable impedance Z_{DUT} as a function of the applied signal frequency based on

20   the reference signal CH0 and the signal CH1; and analyzing said cable impedance providing an assessment of the cable condition.

In an embodiment the reference signal CH0 may be a white noise signal having a frequency bandwidth from w_1 to w_2, or a frequency sweep from a frequency w_1 to a

25   frequency w_2, w_1 and w_2 depending on the cable length. The method may further comprise calculating an amplitude and phase of the cable impedance Z_{DUT} as a function of frequency, by calculating the averaged windowed transfer function from the reference signal CH0 to the signal CH1 by using

30

$$Z_{DUT} = Z_1 \left(\frac{V_0}{V_1} - 1 \right)$$

where Z_1 is an internal impedance of a digitizer channel for signal CH1, and V_0 and V_1 are the voltage phasors measured at a digitizer channel for reference signal CH0 and a digitizer channel 1 for signal CH1, respectively. In an even further embodiment, the method may comprise evaluating at least one resonance frequency pattern of the cable impedance Z_{DUT}, wherein said at least one reson-ance frequency pattern provides information concerning cable degradation.

Said at least one resonance frequency pattern may be a Fourier transform of the impedance phase and amplitude, the method further comprising identifying a fundamental frequency f' in the Fourier transform due to a wave reflection at a distance d, wherein said distance d is a cable termination, identifying a further frequency component f'' in the Fourier transform due to a wave reflection at a location x, wherein said wave reflection at location x is due to a discontinuity in electrical parameters of said cable, and calculating said location x by:

$$\frac{f'}{f''} = \frac{d}{x}$$

d being the length of said cable.

Said at least one resonance frequency pattern may be a Fourier transform of the impedance phase and amplitude, the method may in an alternative embodiment comprise identifying a fundamental frequency f' in the Fourier transform due to a wave reflection at a distance d, wherein said distance d is a cable termination, identifying a further frequency component f'' in the Fourier transform due to a wave reflection at a location x, wherein said wave reflection at location x is due to a discontinuity in electrical parameters of said cable, and calculating said location x by:

$$x = \frac{v_r v_0 f''}{2}$$

wherein v_r is the relative phase velocity of an electrical signal in the cable, and v_0 the speed of light in vacuum.

In an even further embodiment of the invention said at least one resonance
5   frequency pattern is a Fourier transform of the impedance phase and amplitude, the method further comprising identifying two consecutive resonance frequency values f_k and f_{k+1} respectively, of the cable impedance Z_{DUT}; calculating a first value of a relative phase velocity v_r of the cable by applying $v_r = 2L(f_{k+1} - f_k)\Big/v_0$, where L is the length of the cable and v_0 is the light speed in vacuum; calculating a
10   fundamental frequency f' of said cable using said first relative phase velocity v_r

and applying $f' = \dfrac{2L}{v_r v_0}$, where L is the length of the cable and v_0 is the light speed

in vacuum; calculating a second value f'' of said fundamental frequency f' by finding a maximum peak value in the Fourier transform in the domain of t' in a selectable interval around f'; and calculating a final relative phase velocity v^{final}_r

15   by applying $v^{final}_r = \dfrac{2L}{v_0 f''}$, where L is the length of the cable, v_0 is the light speed in

vacuum, wherein said relative phase velocity provides information about global degradation of said cable.

In an even further embodiment providing information about global degradation of
20   the cable, the method comprises calculating a cable impedance phase shift, wherein said reference signal CH0 is a multi-tone sine wave at a resonance frequency, and calculating a phase difference between CH0 and CH1 in time domain.

In a second aspect the invention provides a system of condition monitoring of an
25   electrical cable, the system comprising a generating means providing a reference signal CH0; an acquisition means acquiring said reference signal CH0 and a signal CH1, said signal CH1 being the reference signal CH0 after amplitude and phase modulation by a cable impedance Z_{DUT} of the electrical cable; and an analyzing means calculating the complex cable impedance Z_{DUT} as a function of
30   the applied signal frequency based on the reference signal CH0 and the signal

CH1, and analyzing said cable impedance providing an assessment of cable condition and/or cable failure.

Said generating means may be operative to provide a reference signal CH0

5   selected from a group consisting of a white noise signal having a frequency band-width from 0 to a selectable frequency w_2, a sweep signal having a frequency bandwidth from w_1 to w_2 (both selectable), and a multi-tone sine wave at selected resonance frequencies.

10   The acquisition means may be a digital storage oscilloscope.

The system may further comprise a simulator operative to provide the analyzing means with said reference signal CH0 and said signal CH1 based on cable para-meters, load parameters and transmission line equations. A modulator may also

15   be arranged between said generating means and said acquisition means, said modulator being connected to the electrical cable, and being operative to output the reference signal CH0 and said cable impedance phase and amplitude modu-lated signal CH1.

20   In the claims the term monitor is to be widely interpreted and includes e.g. global/local condition monitoring, real-time diagnosis, and fault detection.

LIRA (Line Resonance Analysis System) improves the detection sensitivity and accuracy by analyzing the cable input impedance (equation (8) and Figure 1). In

25   essence, the following steps are provided:

   • Local degradation detection and localization:
      a. Noiseless estimation of the line input impedance as a function of frequency (bandwidth 0-X MHz, where X depends on the cable length).

30   b. Use of a hardware module called "Modulator" for the estimation of the line input impedance.

      c. Spectrum analysis of the line input impedance to detect and localize degradation spots (see detailed explanation).

- Global degradation assessment:

  a. Same as point a above

  b. Same as point b above

  c. Spectrum analysis of the line input impedance to estimate the right value of the phase velocity (equation (1)). The phase velocity is used as a condition indicator of the cable global state.

These steps are explained in detail later in this document.

LIRA (Line Resonance Analysis System) according to the invention is able to monitor the global, progressive degradation of the cable insulation due to harsh environment conditions (e.g. high temperature, humidity, radiation) and detect local degradation of the insulation material due to mechanical effects or local abnormal environment conditions. In this case, LIRA can estimate the location of the challenged part with an estimation error within 0.5% of the cable length.

The LIRA system may be used for detecting and monitoring insulation degradation and line breakage in all kinds of electrical cables (power and signal cables); i.e. cables in power generation, distribution and transmission, cables in process industries, cables in aerospace industry, on cable in onshore, offshore and subsea installations, and identify the position of the damage/breakage. The monitoring and detection may be performed from a remote location in real time.

The invention is defined in the appended claims.

BRIEF DESCRIPTION OF DRAWINGS

Embodiments of the invention will now be described with reference to the following drawings, where:

Figure 1 shows a graphical representation of a complex line impedance amplitude and phase as a function of frequency according to equation (8);

Figure 2 shows hardware and software modules of a system according to an embodiment of the invention;

Figure 3 shows a functional design of a modulator according to an embodiment of the present invention;

Figure 4 shows a functional diagram of a spot detection algorithm according to an embodiment of the invention;

Figure 5 is a power spectrum of a phase impedance in a domain of t', where the x-axis has been scaled to distance from cable start (d=300m), according to an

5   embodiment of the present invention;

Figure 6 is a power spectrum of phase impedance in the domain of t', where the frequency component at x=200 is visible, due to a capacity change of 20pF in a 30cm cable segment, according to an embodiment of the present invention; and

Figure 7 illustrates a real-time monitoring of impedance phase shift in an analyzing

10   means according to an embodiment of the invention.

DETAILED DESCRIPTION

Figure 2 shows an embodiment of the system with hardware and software modules. These modules will be described below.

15

- The **Arbitrary Wave Generator**. It is driven by the LIRA Generator software to supply the system with a reference signal CH0. The reference signal can be:
  - A white noise signal.
20   - A sweep signal, from 0 Hz to the selected bandwidth. Same effect as of a white noise signal.
      - A multi-tone sine wave. This is used for real-time monitoring of impedance phase shifts.

25   - The **Modulator**. A functional diagram of the modulator is shown in Figure 4. The output of this module is the reference signal (CH0), distorted by the generator internal impedance Rg, and a phase and amplitude modulated signal (CH1), which is modulated by the frequency dependent impedance Z_{DUT} of the cable provided to the modulator through a cable connection.

30

The modulator functional diagram is shown in Figure 4, where DUT is the connection to the cable under test. The impedance at DUT is calculated as:

$$Z_{DUT} = Z_1 \left(\frac{V_0}{V_1} - 1 \right)$$ (11)

where Z_1 is the digitizer channel 1 (CH1) internal impedance (50 ohm) and V_0 and V_1 are the voltage phasors measured at digitizer channel 0 (CH0) and channel 1 (CH1).

From equation (11) it follows that there is no influence on Z_{DUT} from Rb, Rg and any parasitic impedance on the left of CH0. Z_1 has some known capacitance (15pF) that the system can easily take into consideration.

Equation (11) shows that the cable input impedance is a simple function of the reciprocal of the transfer function between V_0 and V_1, both acquired by the digital storage oscilloscope. LIRA performs a windowed transfer function with an average technique to remove noise and applies eq. (11) to estimate the line impedance in the applicable bandwidth.

- The 2-channel **Digital Storage Oscilloscope**. It is used to acquire CH0 and CH1. This is a commercial hardware unit.

- The **LIRA simulator**. This module can be operated stand alone, or it can be connected to the LIRA Analyzer. In the last case the LIRA simulator works in frequency domain applying the transmission line equations (Eqs. 1 to 10) and then performing an inverse Fourier transformation to provide the analyzer with the 2 time domain signal channels (CH0, CH1), as they came directly from the Modulator connected to the tested cable. In addition to that, it employs a stochastic model to evaluate the uncertainties in the cable electrical parameters due to manufacturing tolerances and environment changes. Cable parameters and load parameters for the actual cable connection are input to the LIRA simulator.

The stochastic model evaluates and applies statistical variations (using a normal distribution with user selected standard deviation) in the electrical parameters (L, C and R) along the cable, due to manufacturing tolerances and environment noise.

- The **LIRA Analyzer**. It can be operated in real or simulation mode. In the first case it takes the input from the 2-channel Digital Storage Oscilloscope, in the second case the input comes from the LIRA simulator module. The LIRA Analyzer is the core of the wire monitoring system. The LIRA Analyzer works both in frequency and time domain, performing the following tasks:
  - Estimate and display the frequency spectrum of the line input impedance.
  - Calculate the resonance frequencies. Resonance frequencies are calculated from the impedance spectrum and correspond to frequency values where the phase is zero.
  - Estimate the cable characteristic impedance Z_{DUT}. It is also calculated from the impedance spectrum. The characteristic impedance is the value of the impedance amplitude at any local maximum (or minimum) of the impedance phase.
  - Estimate the cable length, if not known.
  - Detect local degradation areas and localize it.
  - Detect load changes.
  - Measure and display the amplitude ratio and the phase shift between the 2 acquired channels (CH0 and CH1). This is done when the reference signal is a multi-tone sine wave and LIRA evaluates in time domain the phase shift between the two channels. The phase shift is initially zero, at resonance conditions, and any deviation from that can be correlated to a change in the average cable electrical parameters.

Diagnosis and localisation of local degradation

LIRA implements 2 algorithms for the detection of local insulation defects, referred as the PRN (Pseudo Random Noise) method and the SWEEP method. The PRN method is the preferred one for cable lengths below 200 m, while the SWEEP method is used for longer cables. Both methods follow the scheme in Figure 4 and they differ only in the shape of the generated reference signal CH0. These

methods will therefore be explained in the following with reference to the PRN method, but the explanation will be equally applicable for the SWEEP method.

In the PRN method, the line impedance is calculated as the averaged windowed transfer function from the reference signal CH0 to the impedance modulated signal CH1, which result in the calculation of the amplitude and phase of the line impedance Z_{DUT} as a function of frequency (See Eq. (11)). Once the line impedance is calculated, the cable state is analyzed by the examination of the frequency content of the amplitude and phase components of the complex impedance. This will be explained in the following.

Eq. (8) is the mathematical expression of the function in Figure 1. Actually the line impedance Z_d (for a cable at distance d from the end of the cable), is a complex parameter and Figure 1 shows both the amplitude and phase of it. The pseudo-periodic shape of the phase is due to the periodicity of Γ_d, Eq. (9), that can be rewritten as:

$$\Gamma_d = \Gamma_L e^{-2\alpha d} e^{-2j\beta d} \qquad (12)$$

where the amplitude is decreasing with d (the cable length) because of the attenuation α (the phase is periodic if $\alpha = 0$). The period of Γd (and then of the line impedance phase) is $1/2\beta$, considering d as the independent variable, or $1/2d$, considering β the independent variable (as in Figure 1).

Using the expression for the propagation constant β from Eq. (6), Eq. (12) can be rewritten as:

$$\Gamma_d = \Gamma_L e^{-2\alpha d} e^{\frac{-2j\omega d}{v}} \qquad (13)$$

$$\Gamma_d = \Gamma_L e^{-2\alpha d} e^{\frac{-4j\pi fd}{v}} \qquad (14)$$

30

where f is the frequency of the applied signal and v is the phase velocity of the electrical signal in the cable.

Assuming f as the independent variable and writing the following translations:

$$f \rightarrow t' \qquad (15)$$

$$\frac{4\pi d}{v_r v_0} \rightarrow \omega' \qquad (16)$$

where $v_r = v/v_0$, v_r being the relative phase velocity of the electrical signal in the cable, and v_0 the speed of light in vacuum.

$$\Gamma_L e^{-2\alpha d} = A \qquad (17)$$

Eq. (14) becomes:

$$\Gamma_d = A e^{-j\omega' t'} \qquad (18)$$

Equation (18) is the mathematical expression of a pseudo-periodic function of radial frequency ω' and amplitude A. In the lossless case ($\alpha = 0$) A=1, in real life lossy cables α is an increasing function of signal frequency, so that amplitude A is a decreasing function of t', resulting in the damped oscillation of Figure 1. The frequency of this function (in the domain of t') is:

$$f' = \frac{\omega'}{2\pi} = \frac{2d}{v_r v_0} \qquad (19)$$

where f' is the fundamental frequency of the phase function in the domain of t' due to the wave reflection at distance d (the cable termination). Note that the expression of f' has the dimension of time and it is the time elapsed for a wave to reach the termination at the distance d and be reflected back. The Fourier transform

(power spectrum) of the impedance phase, in the domain of t', looks e.g. like Figure 5, where the x-axis has been scaled to d at the fundamental frequency given in Eq. (19). In Figure 5, the x-axis has been scaled to distance from cable start (d=300m).

When at a distance x the wave finds a discontinuity in the electrical parameters of the cable (for example a small change in the insulation dielectric), another reflection would be visible from distance x, which would add a new frequency component in the power spectrum of the impedance phase, where the frequency (from Eq. (19)) would be:

$$f'' = \frac{2x}{v_r v_0} \qquad (20)$$

And so:

$$\frac{f'}{f''} = \frac{d}{x} \qquad (21)$$

If the cable length is known, the knowledge of f' and f'' from the power spectrum of the impedance phase (in the domain of t') is sufficient for the calculation of the x location:

$$x = d\frac{f''}{f'} \qquad (22)$$

If d is not known, the knowledge of the relative phase velocity v_r (from the cable datasheet or by measuring it on a cable sample of the same type) can be used to calculate the x location based on Eq. (19):

$$x = \frac{v_r v_0 f''}{2} \qquad (23)$$

The final result is then a spike at any position where a change (even a very small change) of electrical parameters (mainly a dielectric value change) produces a reflected wave of the applied reference signal. This reflection appears as a frequency component in the phase/amplitude spectrum of the line impedance. The

5   frequency of the reflected wave is a linear function of the distance from the cable end to the deviation. Figure 6 shows a Fourier transform (power spectrum) of phase impedance in the domain of t', where a reflection due to a change of electrical parameters of the cable at location x=200m from cable start is visible as a frequency component at x=200. This spike is in the case of Figure 6, due to a

10   capacity change of 20pF in a 30cm segment of the cable under test.

When condition monitoring a cable, a number of discontinuities (n) in the electrical parameters of the cable may be present. Each of these discontinuities will appear in the power spectrum as distinct frequency components spikes f^n, and their posi-

15   tions x_n identified as explained above.

In order to have good sensitivity and digital resolution, it is important to operate with the highest possible bandwidth, which is however limited by the cable attenuation. Successful tests have been performed with 30m cables (100 MHz band-

20   width) up to 120 Km cables (20 KHz bandwidth) at the time of writing. Long cables require narrow bandwidths to overcome the increasing cable attenuation, which is a function of frequency.

Global degradation monitoring

25   LIRA makes use of 2 different methods for monitoring global changes in the cable condition:

   1. The *Relative Phase Velocity* estimation and monitoring.
   2. The line impedance phase shift from any resonance condition.

30   As for the local degradation and diagnosis, the first method for global degradation is also based on applying a reference signal CH0 having a frequency bandwidth from w_1 to w_2, which is then phase and amplitude modulated by the cable impedance Z_{DUT} of the cable under test, providing the signal CH1. The second method

is based on applying a multi-tone sine wave as a reference signal CH0. The analysis of the resulting signals CH0 and CH1 is explained in detail for the two methods below.

5   Method 1:

The *Relative Phase Velocity* is calculated by LIRA through a 2 step process:

1. A first approximate value is estimated using 2 consecutive resonance frequency values in the line impedance, applying the following equations: At any resonance, the cable length L is exactly equal to half wavelength or

10   any multiple of that (this is true when the cable is open ended, but different load reactances can be easily accounted for), or, using Eq. (1):

$$L = \frac{v_r v_0}{2 f_k} k \qquad (24)$$

15   where L is the cable length, v_0 is the light speed in vacuum, v_r is the relative phase velocity and f_k is the kth resonance peak frequency.

Applying Eq. (24) to two consecutive resonance peaks, we get:

$$v_r = \frac{2L(f_{k+1} - f_k)}{v_0} \qquad (25)$$

20

Eq. (25) is used by LIRA to evaluate a first value of v_r, after the estimation of the cable input impedance and the calculation of the resonance frequencies. Note that any load reactance shift would be eliminated by the difference term in the equation. The reason why this value is approximate is that

25   v_r is a slow function of f, but it has been assumed constant in Eq. (25).

2. The value of v_r found in step 1 is used to calculate the approximate value of the fundamental frequency f' (domain of t', see description above and Figure 5), as:

30   $$f' = \frac{2L}{v_r v_0} \qquad (26)$$

LIRA searches the maximum peak f" in the Fourier transform (power spectrum) in the domain of t', in a user selectable interval around f'. When an accurate value of f' (called f") is found from the spectrum, Eq. (19) is solved for v_r as:

$$v^{final}_r = \frac{2L}{v_0 f''} \qquad (27)$$

which is the final and accurate value of the phase velocity. The phase velocity decreases with the degradation of the cable insulation.

Method 2:

The line impedance has zero phase at any resonance condition. Using as reference signal a sine wave at a resonance frequency, the 2 output signals CH0 and CH1 are in phase. The phase difference between CH0 and CH1 (even in the order of 1 deg), calculated in time domain, is used to monitor any small change in the global electrical condition of the cable, because changes in the electrical parameters affect the cable resonance frequencies. Rather than monitoring directly frequency changes, LIRA monitors the impedance phase, because it can be estimated in a more reliable and accurate way. This method is suitable for unattended, real-time monitoring of cable global conditions.

Figure 7 shows an example of impedance phase shift monitoring using the LIRA (Line Resonance Analysis) system. The LIRA system shows in the graph in the middle left of Figure 7 the phase shift between a reference signal CH0 and the resulting signal CH1 modulated by the cable impedance as a function of time. The phase shift provides information concerning the insulation degradation.

The reasons why a resonance frequency is used for this purpose are:

- The phase derivative is the highest at resonance, achieving the maximum sensitivity to cable degradation.

- The phase changes linearly around a resonance condition. This makes easier to correlate a phase shift to the insulation degradation.

Having described preferred embodiments of the invention it will be apparent to those skilled in the art that other embodiments incorporating the concepts may be used. These and other examples of the invention illustrated above are intended by way of example only and the actual scope of the invention is to be determined from the following claims.

CLAIMS

1.   Method of monitoring a condition of an electrical cable, comprising:

- providing a reference signal CH0 and a signal CH1, said signal CH1 being the
reference signal CH0 after amplitude and phase modulation by a cable impedance
Z_{DUT} of the electrical cable;

- calculating the cable impedance Z_{DUT} as a function of the applied signal
frequency based on the reference signal CH0 and the signal CH1; and

- analyzing said cable impedance providing an assessment of the cable condition.

2.   Method according to claim 1, wherein the reference signal CH0 having a
frequency bandwidth from w_1 to w_2, and wherein said reference signal is white
noise or a frequency sweep from w_1 to w_2, w_1 and w_2 depending on the cable
length.

3.   Method according to claim 1, further comprising calculating an amplitude
and phase of the cable impedance Z_{DUT} as a function of frequency, by calculating
the averaged windowed transfer function from the reference signal CH0 to the
signal CH1 by using

$$Z_{DUT} = Z_1 \left(\frac{V_0}{V_1} - 1 \right)$$

where Z_1 is an internal impedance of a digitizer channel for signal CH1, and V_0
and V_1 are the voltage phasors measured at a digitizer channel for reference
signal CH0 and a digitizer channel 1 for signal CH1, respectively.

4.   Method according to claim 1, further comprising:

- evaluating at least one resonance frequency pattern of the cable impedance
Z_{DUT}, wherein said at least one resonance frequency pattern provides information
concerning cable degradation.

5.   Method according to claim 4, wherein said at least one resonance
frequency pattern is a Fourier transform of the impedance phase and amplitude,
the method further comprising:

- identifying a fundamental frequency f' in the Fourier transform due to a wave

5   reflection at a distance d, wherein said distance d is a cable termination,

- identifying a further frequency component f'' in the Fourier transform due to a
wave reflection at a location x, wherein said wave reflection at location x is due to
a discontinuity in electrical parameters of said cable, and calculating said location
x by:

10

$$\frac{f'}{f''} = \frac{d}{x}$$

d being the length of said cable.

15   6.   Method according to claim 4, wherein said at least one resonance
frequency pattern is a Fourier transform of the impedance phase and amplitude,
the method further comprising:

- identifying a fundamental frequency f' in the Fourier transform due to a wave
reflection at a distance d, wherein said distance d is a cable termination,

20   - identifying a further frequency component f'' in the Fourier transform due to a
wave reflection at a location x, wherein said wave reflection at location x is due to
a discontinuity in electrical parameters of said cable, and calculating said location
x by:

25

$$x = \frac{v_r v_0 f''}{2}$$

wherein v_r is the relative phase velocity of an electrical signal in the cable, and v_0
the speed of light in vacuum.

7.   Method according to claim 4, wherein said at least one resonance frequency pattern is a Fourier transform of the impedance phase and amplitude, the method further comprising:

- identifying two consecutive resonance frequency values f_k and f_{k+1} respectively, of the cable impedance Z_{DUT};

- calculating a first value of a relative phase velocity v_r of the cable by applying

$v_r = 2L(f_{k+1} - f_k)\bigg/v_0$, where L is the length of the cable and v_0 is the light speed in vacuum;

- calculating a fundamental frequency f' of said cable using said first relative phase velocity v_r and applying $f' = \dfrac{2L}{v_r v_0}$, where L is the length of the cable and v_0 is the light speed in vacuum;

- calculating a second value f'' of said fundamental frequency f' by finding a maximum peak value in the Fourier transform in the domain of t' in a selectable interval around f'; and

- calculating a final relative phase velocity v^{final}_r by applying

$$v^{final}_r = \frac{2L}{v_0 f''}$$

where L is the length of the cable, v_0 is the light speed in vacuum, wherein said relative phase velocity provides information about global degradation of said cable.

8.   Method according to claim 4, comprising calculating a cable impedance phase shift, wherein said reference signal CH0 is a multi-tone sine wave at a resonance frequency, and calculating a phase difference between CH0 and CH1 in time domain.

9.   System of condition monitoring of an electrical cable, comprising:
- a generating means providing a reference signal CH0;

- an acquisition means acquiring said reference signal CH0 and a signal CH1, said signal CH1 being the reference signal CH0 after amplitude and phase modulation by a cable impedance Z_{DUT} of the electrical cable; and

- an analyzing means calculating the complex cable impedance Z_{DUT} as a function
5   of the applied signal frequency based on the reference signal CH0 and the signal CH1, and analyzing said cable impedance providing an assessment of cable condition and/or cable failure.

10.   System according to claim 9, wherein said generating means is operative to
10   provide a reference signal CH0 selected from a group consisting of a white noise signal having a frequency bandwidth from 0 to a selected frequency w_2, a sweep signal from a selected frequency w_1 to a selected frequency w_2, and a multi-tone sine wave at selected frequencies.

15   11.   System according to claim 9, wherein the acquisition means is a digital storage oscilloscope.

12.   System according to claim 9, said system further comprising a simulator operative to provide the analyzing means with said reference signal CH0 and said
20   signal CH1 based on cable parameters, load parameters and transmission line equations.

13.   System according to claim 9, further comprising a modulator arranged between said generating means and said acquisition means, said modulator being
25   connected to the electrical cable, and being operative to output the reference signal CH0 and said cable impedance phase and amplitude modulated signal CH1.
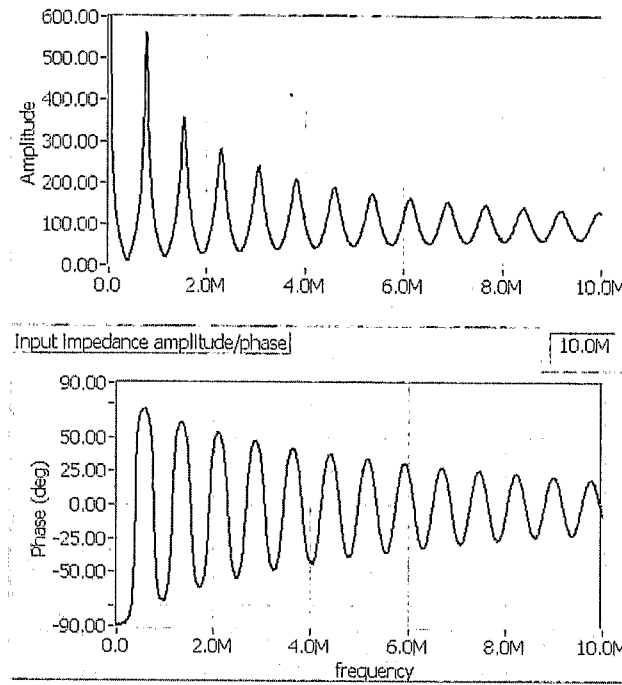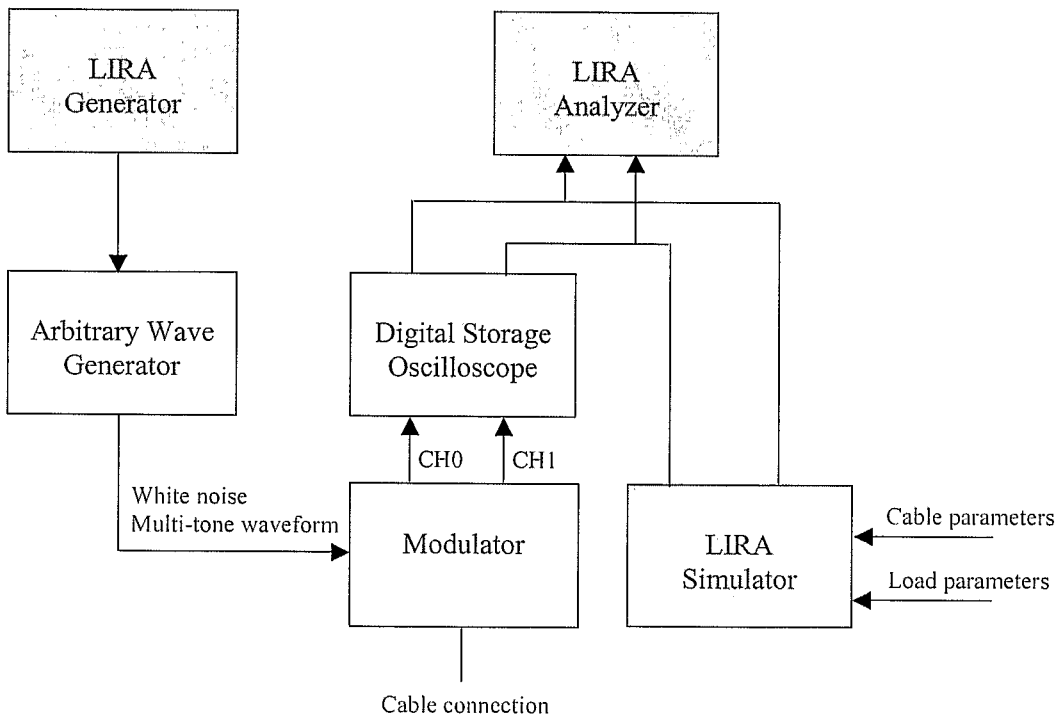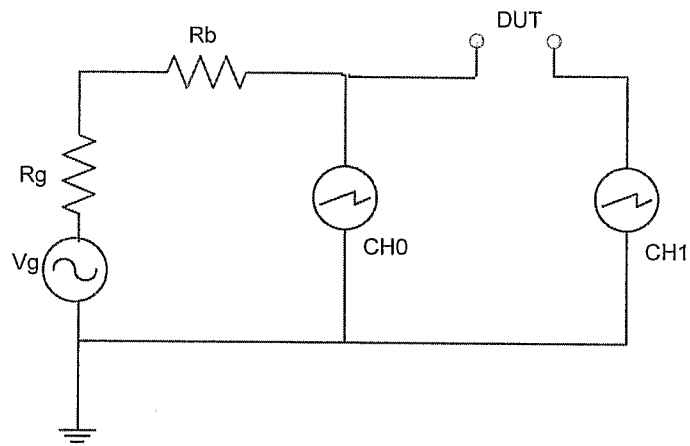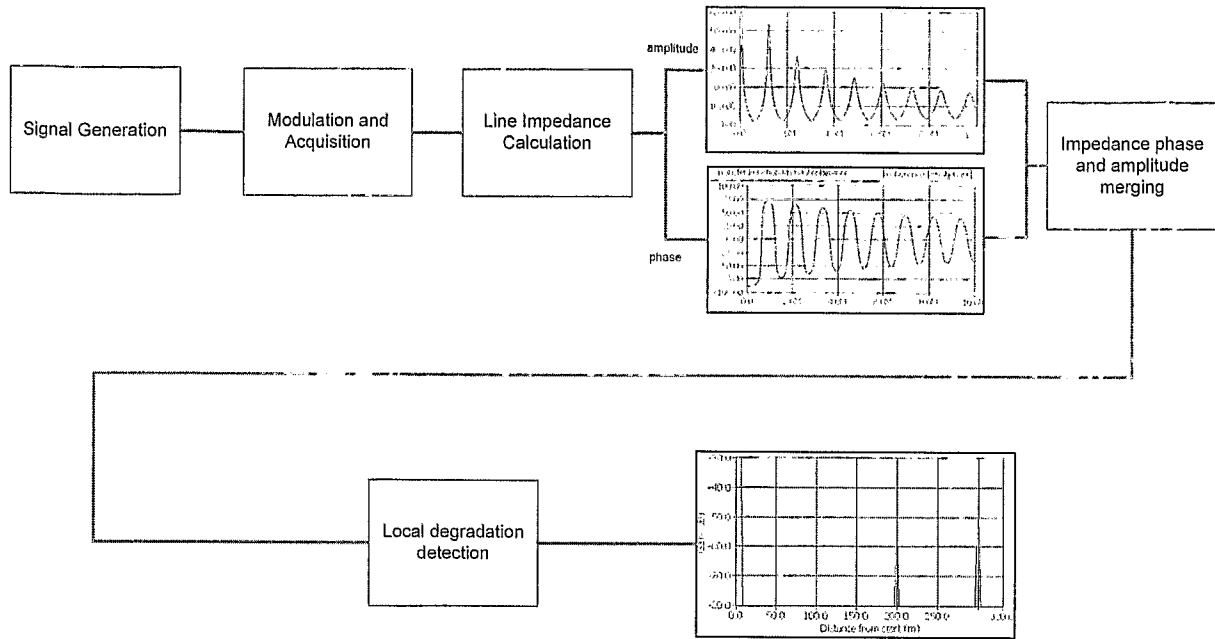
Figure 1

Figure 2

Figure 3

Figure 4
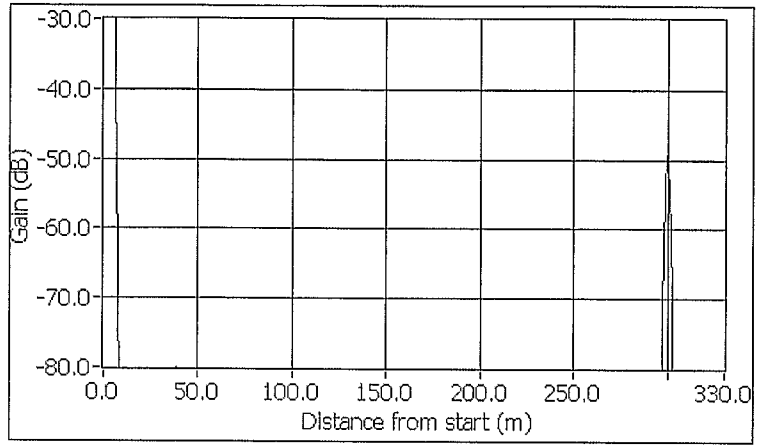
Figure 5
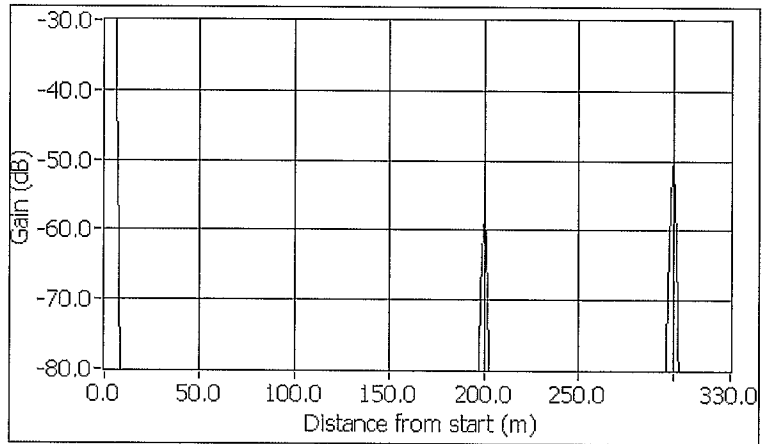
Figure 6
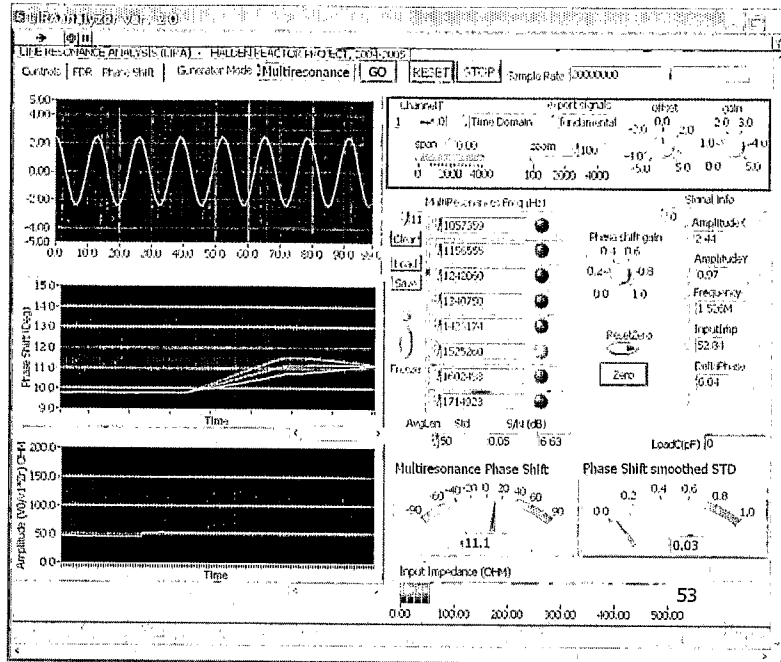
Figure 7

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

IPC: see extra sheet

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)

IPC: G01R

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-INTERNAL, WPI DATA, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4307267 A (JOHN T. PEOPLES), 22 December 1981 (22.12.1981), column 1, line 67 - column 2, line 12; column 3, line 1 - line 15	1-13
X	US 4630228 A (ZOLTAN TARCZY-HORNOCH ET AL), 16 December 1986 (16.12.1986), column 2, line 38 - line 68, figure 1	1,2,9,10
X	US 20040039976 A1 (JACOB GUNTER ET AL), 26 February 2004 (26.02.2004), claim 1, [0006],[0017],[0027],[0061],[0062]	1,2,9,10

| X | Further documents are listed in the continuation of Box C. | X | See patent family annex. |

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Date of the actual completion of the international search	Date of mailing of the international search report
31 January 2007	0 2 -02- 2007

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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 20050057259 A1 (RODNEY M. HORNSBY ET AL), 17 March 2005 (17.03.2005), figure 1, [0025]	1,9

Form PCT/ISA/210 (continuation of second sheet) (April 2005)

International patent classification (IPC)

G01R 31/08 (2006.01)
G01R 27/06 (2006.01)

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US	4307267	A	22/12/1981	NONE		
US	4630228	A	16/12/1986	NONE		
US	20040039976	A1	26/02/2004	US	7069163 B	27/06/2006
US	20050057259	A1	17/03/2005	US	7005995 B	28/02/2006