The Journal of CPRI,
Vol. 12, No. 4, December 2016 pp. 665-670

Non Intrusive Monitoring of Electrical Cables in Ship Power Systems

Shashidhar Kasthala* and Rajitha Saka**

The integrity of power cables is vital for the reliability and safety of an electrical system. The change in operating conditions of the electrical cable often leads to unanticipated faults or premature ageing and any such defects has to be monitored so that corrective measures can be taken within the time. This paper discusses about a non-intrusive power line quality monitoring technique that can be used on ships to detect the faults based on the Power Line Communication (PLC) technology. The relationship between the channel frequency response and the power line quality features are studied and any changes in the positions and values of peaks or valleys and distance between peaks or valleys are monitored.

Keywords : Attenuation, channel frequency response conductivity, multipath signal propagation, power line channel.

1.0 INTRODUCTION

Degradation of electrical cable system (especially for control and instrumentation) is a serious concern worldwide because of its huge impact in several fields like power generation, transportation and defence [1]. Typically the lifetime of a power cable is considered as 40 years but alteration in the network configuration i.e., change in type of load or variation in the number of branches may lead to unanticipated or premature breakdowns. Particularly, in a power distribution network like ship where the continuity of power supply and reliability of electrical machines is of utmost priority, cable faults are unacceptable. It is nevertheless to mention that, the length of cables on board ship is in few kilometers and is continuously exposed to vibration, heat, salinity and other hazardous conditions.

Due to this, the cables used for power distribution, control and instrumentation onboard ship often experience issues like cracks, ricks and nags, as shown in Figure 1, which impair the insulation performance of the cable. Hence it is important to develop an efficient cable monitoring technique to increase the reliability and maintain the safety of the ship and at the same time reduce the operational costs.

FIG. 1. CABLE FAULTS OBSERVED ONBOARD SHIPS DUE TO INSULATION FAILURE AND CORRSION [2]

Various test methods have been developed for cable monitoring such as insulation resistance, dielectric strength, dielectric loss, line resonance

*Indian Naval Academy, Ezhimala, Kerala, shashi_kb4u@rediffmail.com
**GNIT Campus, Hyderabad, rajithasaka@gmail.com

analysis, tanδ, partial discharge method etc [3]-[4]. Though these methods are sensitive to small changes in electric cable parameters, they are not very cost effective and the devices or sensors are to be placed in an intrusive manner.

The power line communication is a technology which uses the existing electrical network for data transmission. Because of the worldwide penetration of electrical network, it can play a vital role in telecommunication, automation services and network monitoring. Though the power line channel is a hostile medium for data transmission due to impairments such has noise, multipath, high attenuation etc. it can be overcome by network conditioning or using a better modulation technique [5].

Any change in the cable characteristics will result in the variation of data transmitted over the power line which can be expressed in terms of attenuation. This concept of continuous data transfer can be used as a methodology to monitor the physical conditions of the cable. The cable parameters such as conductivity, relative dielectric constant and relative magnetic permeability which have an impact on power line quality are affected by thermal and mechanical stress. These variations cannot be easily measured or monitored but are reflected in channel frequency response expressed in terms of attenuation. The difference in the position of peaks or valleys and distance between peaks and/or valleys can be used to estimate the impact of the physical conditions of the cable [6].

Based on the above concept, a non-intrusive cable monitoring system is developed in this paper using a two –port network analysis by dividing the electrical network into multiple cascaded networks. The two port network is based on this top-down approach which is developed from the extensive measurements on the electrical network. This approach is considered to be more accurate the bottom-top approach. The obtained information can be transmitted to the control center for analysis through power line by employing any of the modulation techniques like orthogonal frequency division multiplexing, spread spectrum modulation, multi-carrier-code division multiple access.

In the subsequent sections of this paper a relationship between the power line quality characteristics and the key channel characteristics is obtained. Using computer simulations the channel frequency response in terms of attenuation is estimated for a cable at varied conditions of conductivity, permeability and permittivity.

2.0 POWER LINE CHANNEL

2.1 Cable Parameters

Figure 1 shows a typical cross-sectional view of a widely used power cable. The cable configuration considered here is a three core cable (line, neutral and earth) all of equal radii r. Each conductor is wrapped in an insulating material with a homogeneous dielectric of relative dielectric constant ε_r and the distance between the centers of conductors is D.

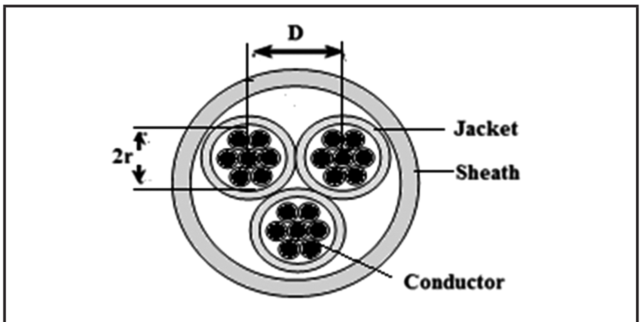

FIG. 2. THREE CORE POWER LINE CABLE

The cable considered here is a two-conductor uniform transmission line. The transmission parameters of a cable can be accurately defined by its primary electrical parameters per unit length viz. series resistance R, series inductance L, shunt conductance G, and shunt capacitance C as shown in Figure 2.

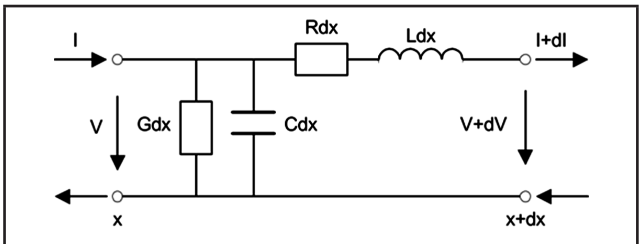

FIG. 3. DISTRIBUTED PARAMETER OF A CABLE

The four primary parameters of a power line i.e. resistance (R), inductance (L), capacitance (C) and conductance (G) are obtained from the transmission line theory [7].

The resistance is given by in Ω/m as

$$R = \frac{1}{\pi r \delta \sigma}\left[\frac{\frac{D}{2r}}{\sqrt{\left(\frac{D}{2r}\right)^2 - 1}}\right] \quad ...(1)$$

The skin depth (δ) of the cable is given as

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \quad ...(2)$$

The inductance of a cable in H/m is given as

$$L = \frac{\mu_r \mu_o}{\pi}\cosh^{-1}\left(\frac{D}{2r}\right) + \frac{R}{2\pi f} \quad ...(3)$$

The Capacitance in F/m is given as

$$C = \frac{\pi \varepsilon_o \varepsilon_r}{\ln\left[\left(\frac{D}{2r}\right) + \sqrt{\left(\frac{D}{2r}\right)^2 - 1}\right]} \quad ...(4)$$

The conductance of a cable in S/m is given as

$$G = 2\pi f c \tan\delta \quad ...(5)$$

The parameter values of these cables [8] are listed in Table I.

TABLE 1

CABLE PARAMETERS

Parameters	NYM 3x1.5mm^2
Resistance R (mm)	1.22
Distance between conductor (mm)	4.04
Conductivity of conductor σ_c (S/m)	5.8x10^7
Relative dielectric strength ε_r	-0.88logf +9.50 (1.6≤f<5MHz)
	-3.3x10^{-9}f+3.61 (5≤f<30MHz)
Relative magnetic permeability μ	1
Dissipation factor tanδ	-5.7x10^{-10}f +0.085 (1.6≤f<30MHz)

Where r is conductor radius, σ_c is the conductivity of the conductor, tanδ is the dissipation factor and μ_r is the relative magnetic permeability.

From the obtained parameters using (1) to (5), the two intrinsic parameters, i.e. characteristic impedance Z and propagation constant γ are obtained as:

$$Z_0 = \sqrt{\frac{(R + jwl)}{(G + Jwc)}} \quad ...(6)$$

$$\gamma = \sqrt{(R + j\omega C)(G + j\omega C)} \quad ...(7)$$

Where ω is the angular frequency of the signal.

2.2 Power line channel modelling

The transmission line model of a ship power system is as shown in Figure 3 with various types of loads connected to it.

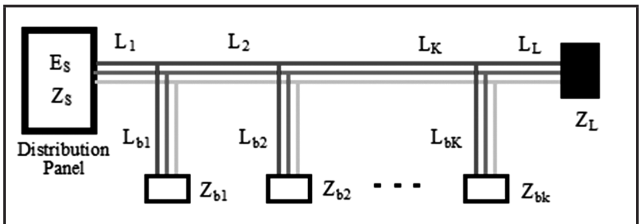

FIG. 4. TRANSMISSION LINE MODEL

The E_s is the source voltage and Z_s in the internal impedance of the source. The l_l is the length of the wire from source to first branch, l_k (k = 2,…n) is the length of the wire between the taps, l_{bk} (k = 1,2,…n) is the length of the branches and l_l is the length between the last branch to the load. The Z_{bk} (k=1,2,..n) is the load impedance of each branch, Z_{ok} is the characteristic impedance of each branch obtained by using (5) and Z_{bk} is the terminal impedance of each branch. The γ_{bk} is the propagation constant of each branch obtained from the (6).

$$Z_{bk} = Z_{ok}\frac{Z_{bk} + Z_{ok}\tanh(\gamma_{bk} l_{bk})}{Z_{ok} + Z_{bk}\tanh(\gamma_{bk} l_{bk})} \quad ...(8)$$

Using the chain matrix theory, the indoor electrical network is divided into various parts. For a n branch electrical network, the first and last matrix deals with the source and the load elements respectively. The second matrix deals from the right of the source to the left of the branch (including the branch) and third matrix deals from the right of first branch to the left of second branch (including the branch) and so on till the last branch. The matrices are as shown in (8) to (11).

$$T_1 = \begin{bmatrix} 1 & Z_S \\ 0 & 1 \end{bmatrix} \quad ...(9)$$

$$T_2 = \begin{bmatrix} \cosh(\gamma_1 l_1) + \frac{Z_{01}}{Z_{ib1}} & Z_{01}\sinh(\gamma_1 l_1) \\ \frac{1}{Z_{01}\sinh(\gamma_1 l_1)} + \frac{\cosh(\gamma_1 l_1)}{Z_{ib1}} & \cosh(\gamma_1 l_1) \end{bmatrix} (10)$$

$$T_{N+1} = \begin{bmatrix} \cosh(\gamma_N l_N) + \frac{Z_{oN}}{Z_{ibN}} & Z_{0N}\sinh(\gamma_N l_N) \\ \frac{1}{Z_{0N}\sinh(\gamma_N l_N)} + \frac{\cosh(\gamma_N l_N)}{Z_{ibN}} & \cosh(\gamma_N l_N) \end{bmatrix} (11)$$

$$T_{N+2} = \begin{bmatrix} \cosh(\gamma_L l_L + \frac{Z_{oL}}{Z_L} & Z_{0L}\sinh(\gamma_L l_L) \\ \frac{1}{Z_L\sinh(\gamma_L l_L)} + \frac{\cosh(\gamma_L l_L)}{Z_L} & \cosh(\gamma_L l_L) \end{bmatrix} (12)$$

Once the individual matrices are achieved, the chain matrix T of the whole circuit can be represented as.

$$T = \prod_{i=1}^{3} T_i = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \quad ...(13)$$

The transfer function for the electrical network can thus be obtained using the relationship between the chain matrix and transmission line theory [6].

$$H(f) = \frac{Z_L}{T_{11}Z_L + T_{12} + T_{12}Z_S Z_L + T_{22}Z_S} \quad ...(14)$$

2.3 Power line monitoring

The power line quality problem such has cable ageing or improper maintenance will change the fundamental parameters of the power line directly. The conductivity of a conductor will decrease due to thermal ageing, improper handling of cable or ageing of the insulator will result in decrease of dielectric constant, and exposure to electromagnetic interference will result in decrease of relative magnetic permeability.

Changes in some of the key channel characteristics, including the positions and values of the peaks and valleys of the CFR and the distances between the peaks or valleys in the amplitude response, can be found to detect the changes of one or more fundamental parameters of the power line so as to monitor and evaluate its quality.

3.0 SIMULATION RESULTS

In this paper, a sample distribution network representing the ship is as shown in Figure 4 is considered. The network is a 3 branch cable with a cross-section of 3x2.5 sq.mm across the network. The source impedance considered for the network is 50Ω and the load impedances are 61 Ω, 75 Ω and 45 respectively. The line is terminated with 50 Ω. Generally the cabling in ship is carried oit with PVC, PE, EPR, XLPE Insulated and RFOU mud resistant cables for different voltages. The cable cosnidered in this paper is XLPE insulated.

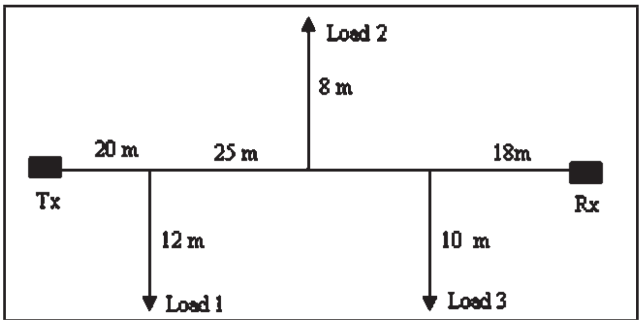

FIG. 5. ELECTRICAL NETWORK CONSIDERED

The properties of the cable onboard ship are [11].

TABLE 2

Parameters	Values
Radius of the cable (mm)	1.22
Distance between conductor (mm)	4.04
Conductivity of conductor σ_c (S/m)	$5.8\text{x}10^7$
Relative dielectric strength ε_r	-0.88logf +9.50 (1.6≤f<5MHz)
	$-3.3\text{x}10^{-9}$f+3.61 (5≤f<30MHz)
Relative magnetic permeability µ	1
Dissipation factor tanδ	$-5.7\text{x}10^{-10}$f +0.085 (1.6≤f<30MHz)

The simulation is carried out for the PLC channel as listed in Table II. The channel frequency responses is analyzed before and after the changing the fundamental parameters in the broadband range of 1 to 30 MHz.

Due to severe raise in temperature or any thermal attack on the conductor, the conductivity of the conductor decreases, the resistance R increases and then series attenuation increases leading to lower CFR amplitudes. This is shown in amplitude response by decrease in the value of the peaks as shown in Figure 5.

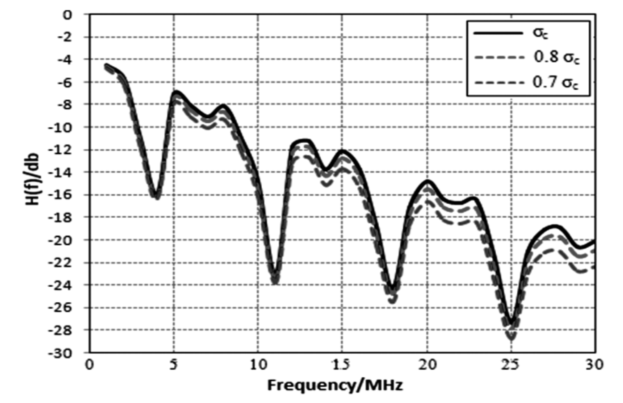

FIG. 6. RESPONSES UNDER DIFFERENT CONDUCTIVITIES

Due to the ageing of insulator material, or improper maintenance, the dielectric constant decreases, the capacitance C and conductance G decreases and then the parallel attenuation drops leading to higher CFR amplitudes and larger distances between the valleys. This is shown inamplitude response by increase in the value of the peaks and increase in the distance between the peaks as shown in Figure 6.

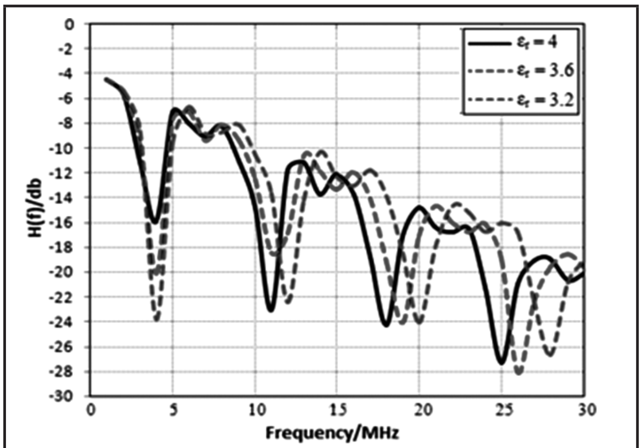

FIG. 7. RESPONSES UNDER DIFFERENT DIELECTRIC CONSTANTS

Due to severe exposure to electromagnetic interference or magnetic ageing in the cable, the magnetic permeability decreases, resistance R and inductance L decreases, leading to lower CFR and larger distance between valleys. This is shown in amplitude response by decrease in the value of the peaks and increase in the distance between the peaks as shown in Figure 7.

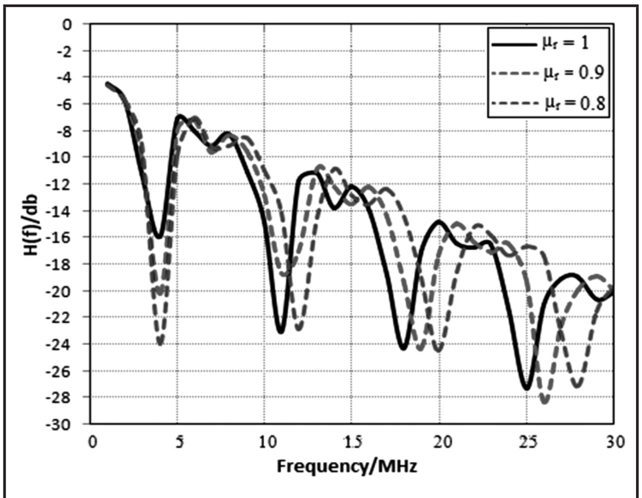

FIG. 8. RESPONSES UNDER DIFFERENT PERMITTIVITIES

4.0 CONCLUSION

After the Power cable is monitored and evaluated between the Tx and Tx as shown in Figure 4, the data in form of bits is transmitted to the nearby control centers such as Node C or Node D through power line communication. If any fault or ageing related issues is diagnosed then message can be sent to carry out the maintenance operations.

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