AN EFFICIENT METHOD FOR STUDYING AND ANALYSING THE PROPAGATION BEHAVIOUR OF OVERHEAD TRANSMISSION LINES

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Abstract

The paper describes a method, based on the solution of travelling-wave phenomena in polyphase systems by the use of matrix methods, of deriving the basic matrices of the conductor system taking into account the effect of conductor geometry, conductor internal impedance and the earth-return path. It is then shown how they may be expressed in symmetrical-component form where conductor asymmetry is neglected. The manipulation of these matrices to obtain the modal parameters of the line is also described. The methods of studying the effectiveness of the carrier channel on a power line under various power frequency load conditions are presented as well.

Keywords: Admittance matrix, conductor geometry, impedance matrix, load cycle, modal analysis, power line carrier.

1. Introduction

Since the advent of electrical power distribution networks, the need for intelligence transfer over power lines has become desirable. It is economically advantageous to use the lines themselves to enhance supervisory and control operations, provide fast information dispatch and to carry out discriminative protection of substation equipment by sending trip signals when faults occur. These important tasks can be achieved by using the Power Line Carrier (PLC). It is a term used to describe the significant use of carrier current communication when utilising the high voltage transmission line. This, therefore, allows for the provision of efficient and reliable communications both within and between power stations.

Recently, the modal analysis and methods of studying the effects of various cycles on transmission lines were applied to a model of the 330 kV single circuit (SC) NEPA transmission lines (Adegboye, 2002) for the purpose of determining the data transmission potentials of such lines. The work was previously carried out on the triangular configuration of the SC 132 kV transmission lines (Adegboye *et al.*, 2002). It was established that the 330 kV SC lines exhibits better data transmission capabilities.

In the USA, Ainsworth (1982) described the use of the three-phase PLC used for load control and tariff switching in the electricity supply network. In other recent researches, Adam Evans (1998) examined plans to use the national grid to transmit data. In this line, the Internet news reported that Nortel (Northern Telecommunications) and Norweb of UK signed an agreement to exploit the potential of the national electricity grid for transmitting data.

Gabel (1983) suggested the use of the German's electricity supply mains as carriers of signals in the region of 90 to 131 kHz suitably modulated for speech transmission and remote control of household electrical equipment. The use of power distribution lines as communications medium has proven to be a reliable, cost effective alternative to dedicated lines (Godfrey, 1983).

Goschler (1983) described a practical application of data networks utilising power lines during and after the erection of a 420 kV grid following the identification of the need for investments in data networks (Halme, 1983) due to the advanced automation applied in the transmission and distribution of electric power.

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In the USA, three-phase PLC employ in part power distribution lines as a communication medium and a telephone carrier system with a view of enhancing load management. The principle is extended to load control and tariff switching (Kendall, 1983) in the electricity supply network.

In London, the privatisation of electricity, gas and water led to the development of communication systems to provide automatic meter reading (AMR), price tariffs and load management. During these processes, Newbury (1996) discovered that the poor signal conditions over the low voltage mains network due to signal attenuation, leading to low Signal to Noise Ratios (SNR) and consequent reduced propagation conditions require specific transmission and reception conditions over the power line. Effective communication is achieved even when the effects of the loads on the line due to the switching on and off of electrical appliances were considered.

The present paper discusses the method for obtaining the electrical characteristics of overhead transmission lines. The power frequency parameters are based on symmetrical components while those at high frequencies are solved in terms of travelling-wave modes (Wedepohl, 1963). The effects of load current on the various transmission line characteristics were also considered.

2. Analysis Method and Studies

The NEPA transmission lines are composed of bundled conductors and therefore the multiconductor transmission line theory, which applies to both power and communication lines, is used as the analysis method. The method assumes the natural mode of propagation of voltage and current associated with the carrier signals transmitted on the line. The fundamental step is to determine the basic series impedance matrix, **Z** per unit length and the shunt admittance matrix, **Y** per unit length, each of which is derived from the physical and electrical characteristics of the lines, their geometric arrangement, height above the ground level and the earth resistivity.

2.1 Admittance matrix

Y is a function only of the physical geometry of conductors relative to the earth plane because the conductor and earth surfaces may each be regarded as equipotential surfaces. Further, since the air path conductance is negligible, **Y** is purely imaginary, that is, as a complex matrix, it has no real part. The physical location of the conductors is defined with respect to a co-ordinate system with the earth plane as the horizontal reference axis and the axis of the tower symmetry as vertical reference. This system is shown in Fig.1. From the co-ordinates of the conductors and the conductor radii, the charge coefficient matrix are calculated with i, j^{th} element as (Wedepohl, 1963):

$$\mathbf{B} = \log_e(D_{ij}/d_{ij}) \qquad (1)$$

where, d_{ij} is the distance between the i^{th} conductor and the j^{th} conductor for $i \neq j$ and is the radius of the i^{th} conductor for i=j; D_{ij} is the distance between the j^{th} conductor and the image of the i^{th} conductor. The order of **B** is 3p+q where, p is the number of circuits and q, the number of earth wires. **B** is inverted and the last q rows and columns are removed to form B_A^{-1}.

$$\mathbf{Y} = j2\pi\omega\varepsilon\, B_A^{-1} \qquad (2)$$

2.2 Impedance matrix

Determination of **Z** considers three effects: physical geometry reactance, X_g; Carson earth-return, $Z_e(=R_e+jX_e)$ and conductor, $Z_c(=R_c+jX_c)$. X_g is calculated directly from (Wedepohl, 1963):

$$X_g = \omega\mu\mathbf{B}/2\pi \qquad (3)$$

To calculate R_e and X_e, Carson's infinite series (Carson, 1926) is used. This is possible by obtaining the real and imaginary correction component matrices $\mathbf{P}_e$ and $\mathbf{Q}_e$, respectively which are expressed in terms of the parameters r whose elements are determined by:

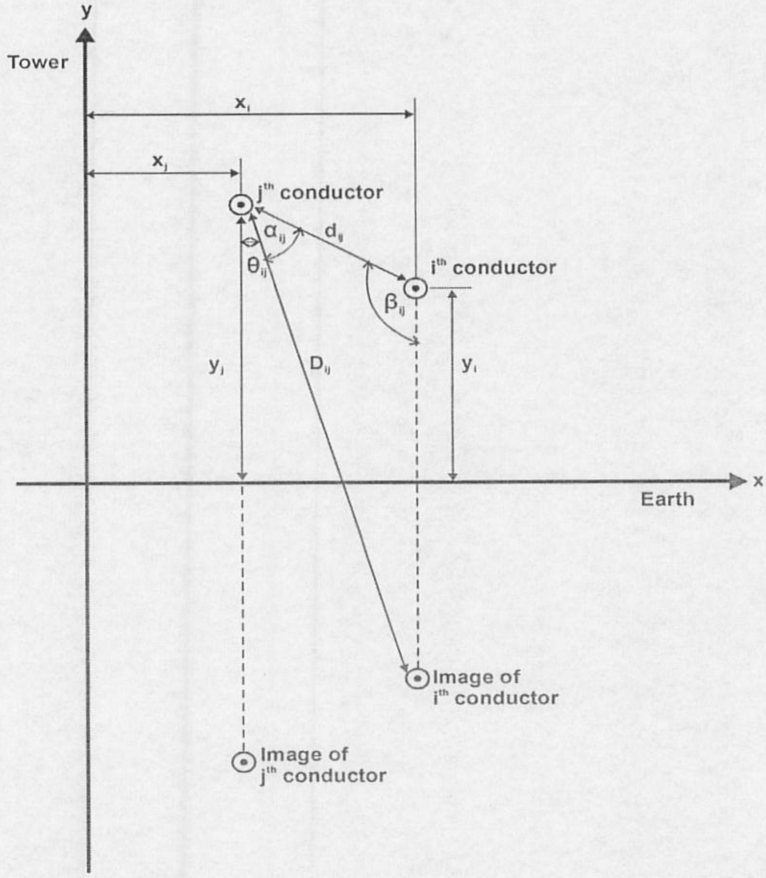

Fig. 1: Schematic of conductors

$$r_{ij} = \sqrt{(\omega\mu/\rho)}.D_{ij} \quad (4)$$

where, ρ is the resistivity of the earth. The elements of $\mathbf{P}_e$ and $\mathbf{Q}_e$ are determined for $r_{ij} \le 5$ as:

$$P_{eij} = \tfrac{\pi}{8}(1 - S_4) + \tfrac{1}{2}\log\left(\frac{2}{\gamma r_{ij}}\right) S_2 + \tfrac{1}{2}\theta_{ij} S_2^{'} - \frac{\sigma_1}{\sqrt{2}} + \frac{\sigma_2}{2} + \frac{\sigma_3}{3} \quad (5)$$

$$Q_{eij} = \tfrac{1}{4} + \tfrac{1}{2}\log\left(\frac{2}{\gamma r_{ij}}\right)(1 - S_4) - \tfrac{1}{2}\theta_{ij} S_4^{'} + \frac{\sigma_1}{\sqrt{2}} - \frac{\pi S_2}{8} + \frac{\sigma_3}{\sqrt{2}} - \frac{\sigma_4}{2} \quad (6)$$

Otherwise (for $r_{ij} > 5$),

$$P_{eij} = \frac{\cos\theta_{ij}}{\sqrt{2} r_{ij}} - \frac{\cos 2\theta_{ij}}{r_{ij}^{2}} + \frac{\cos 3\theta_{ij}}{\sqrt{2} r_{ij}^{3}} + \frac{3\cos 5\theta_{ij}}{\sqrt{2} r_{ij}^{5}} \quad (7)$$

$$Q_{eij} = \frac{\cos\theta_{ij}}{\sqrt{2} r_{ij}} - \frac{\cos 3\theta_{ij}}{\sqrt{2} r_{ij}^{2}} + \frac{3\cos 5\theta_{ij}}{\sqrt{2} r_{ij}^{5}} \quad (8)$$

where, $\varepsilon = 1.7811$ is the Euler's constant;

$$S_2 = \sum_{0}^{\infty} a_n \cos(4n + 2)\theta_{ij}$$

$$S_2' = \sum_{0}^{\infty} a_n \sin(4n+2)\theta_{ij}$$

$$S_4 = \sum_{0}^{\infty} c_n \cos(4n+4)\theta_{ij};$$

$$S_4' = \sum_{0}^{\infty} c_n \sin(4n+4)\theta_{ij}$$

$$\sigma_1 = \sum_{0}^{\infty} e_n \cos(4n+1)\theta_{ij}$$

$$\sigma_2 = \sum_{0}^{\infty} g_n (S_2)_n$$

$$\sigma_3 = \sum_{0}^{\infty} f_n \cos(4n+3)\theta_{ij}$$

$$\sigma_4 = \sum_{0}^{\infty} h_n (S_4)_n$$

and

$$a_n = \frac{-a_{n-1}}{2n(2n+1)^2(2n+3)}\left(\frac{r_{ij}}{2}\right)^4; \quad a_0 = \frac{r_{ij}^{\ 2}}{8}$$

$$c_n = \frac{-e_{n-1}}{(2n+1)(2n+2)^2(2n+3)}\left(\frac{r_{ij}}{2}\right)^4; \quad c_0 = \frac{r_{ij}^{\ 4}}{192}$$

$$e_n = \frac{-e_{n-1}}{(4n-1)(4n+3)^2(4n+5)} r_{ij}^{\ 4}; \quad e_0 = \frac{r_{ij}}{3}$$

$$f_n = \frac{-f_{n-1}}{(4n+1)(4n+3)^2(4n+5)} r_{ij}^{\ 4}; \quad f_0 = \frac{r_{ij}^{\ 3}}{45}$$

$$g_n = g_{n-1} + \frac{1}{4n} + \frac{1}{2n+1} + \frac{1}{2n+2} - \frac{1}{4n+4}; \quad g_0 = \tfrac{5}{4}$$

$$h_n = h_{n-1} + \frac{1}{4n+2} + \frac{1}{2n+2} + \frac{1}{2n+3} - \frac{1}{4n+6}; \quad h_0 = \tfrac{5}{3}$$

Note that the angle θ_{ij} is as shown in Fig. 1.

The elements of resistance and reactance matrices, therefore, will be respectively given as

$R_{eij} = 2P_{eij}$ É¼/2À (9)

$X_{eij} = 2Q_{eij}$ É¼/2À (10)

The internal impedance, $Z_c(=R_c+jX_c)$, is obtained from (Butterworth, 1954) as:

$$R_c = X_c = \frac{kpm}{\sqrt{2}r(n+2)\pi} \qquad (11)$$

where, k = 2.25 is the conductor stranding factor; ρ', the conductor resistivity; r, the radius of outer strand; n, the number of strands in the outer layer and

$$m = \sqrt{\frac{j\omega\mu}{\rho}}.$$

Now form matrix, $\mathbf{Z}' = \mathbf{R}_c + \mathbf{R}_e + j(\mathbf{X}_c + \mathbf{X}_e + \mathbf{X}_g)$; invert $\mathbf{Z}'$ and discard the last q rows and columns to get matrix, $\mathbf{Z}_A^{-1}$.
The impedance matrix, $\mathbf{Z} = [\mathbf{Z}_A^{-1}]^{-1}$.

2.3 Power frequency parameters
The elements of the basic matrices provide the series resistances, series reactance and the shunt susceptance parameters as follows (Galloway *et al.*, 1964):

$$Z_1 = \tfrac{1}{3}(Z_{11} + Z_{22} + Z_{33} - Z_{12} - Z_{13} - Z_{23}) \qquad (12)$$
$$Z_0 = \tfrac{1}{3}(Z_{11} + Z_{22} + Z_{33} + 2Z_{12} + 2Z_{13} + 2Z_{23}) \qquad (13)$$
$$Z_{00} = \tfrac{1}{3}(Z_{14} + Z_{15} + Z_{16} + Z_{24} + Z_{25} + Z_{26} + Z_{34} + Z_{35} + Z_{36}) \qquad (14)$$
$$Z_{pp} = \tfrac{1}{3}(Z_0 - Z_1) \qquad (15)$$
$$Z_p = Z_1 + Z_{pp} \qquad (16)$$
$$Z_{cc} = \tfrac{1}{3}Z_{00} \qquad (17)$$

where, $\mathbf{Z}_1$ is the positive sequence impedance, $\mathbf{Z}_0$, the zero sequence impedance, $\mathbf{Z}_{00}$, the zero-sequence mutual impedance, $\mathbf{Z}_p$, the earth-loop impedance, $\mathbf{Z}_{pp}$, the interphase mutual impedance and $\mathbf{Z}_{cc}$ is the intercircuit mutual impedance.
To calculate the shunt susceptance parameters, let $\mathbf{A} = \mathbf{Y}^{-1}$ where $\mathbf{A} = [a_{ij}]$ and $\mathbf{Y}$ is as given in equation (2). Therefore,

$$C_1 = \frac{3}{\omega(a_{11} + a_{22} + a_{33} - a_{12} - a_{13} - a_{23})} \qquad (18)$$

$$C_0 = \frac{3}{a_{11} + a_{22} + a_{33} + 2a_{12} + 2a_{13} + 2a_{23}} \qquad (19)$$

$$C_{00} = \frac{3}{a_{14} + a_{15} + a_{16} + a_{24} + a_{25} + a_{26} + a_{34} + a_{35} + a_{36}} \qquad (20)$$

$$C_{pp} = \frac{3}{\frac{1}{C_0} - \frac{1}{C_1}} \qquad (21)$$

$$C_p = \frac{1}{\frac{1}{C_1} + \frac{1}{C_{pp}}} \qquad (22)$$

$$C_{cc} = 3C_{00} \qquad (23)$$

where, $\mathbf{C}_1$ is the positive sequence capacitance, $\mathbf{C}_0$, the zero sequence capacitance, $\mathbf{C}_{00}$, the zero-sequence mutual capacitance, $\mathbf{C}_p$, the earth-loop capacitance, $\mathbf{C}_{pp}$, the interphase mutual capacitance and $\mathbf{C}_{cc}$ is the intercircuit mutual capacitance.

2.4 Modal parameters

Here, the solutions are obtained using the travelling-wave modes (Wedepohl, 1963). The procedure is as follows:

- Form a matrix, $\mathbf{P} = \mathbf{ZY}$ (Note: **P** is a complex matrix);
- Obtain the eigenvalues, λ_i of **P** and the corresponding eigenvector matrices, **Q**
- Mode distribution of current, $\mathbf{S}=[\mathbf{Q}']^{-1}$ where, $\mathbf{Q}'$ is the transpose of **Q**
- Propagation constant of mode i, $\gamma_i = \lambda_i^{1/2}$ $(=\alpha_i+\beta_i)$ where, α_i and β_i represent the attenuation and phase of mode i, respectively and the propagation velocity is $\mu_i = \omega/\beta_i$ where, ω is the angular frequency.
- Characteristic impedance matrix, $\mathbf{Z}_0 = \mathbf{Q}\gamma^{-1}\mathbf{Q}^{-1}\mathbf{Z}$ and
- Characteristic admittance matrix, $\mathbf{Y}_0 = \mathbf{YQ}\gamma^{-1}\mathbf{Q}^{-1}$.

It is noteworthy that different frequency values are used in carrying out this analysis, especially when considering the high frequency parameters.

2.5 Load cycle

As the load increases, the conductor temperature rises and hence, its resistivity increases. The temperature increase results in an increase in line length but at the same time, the reduced tension in the conductor tends to decrease the line length. The overall effect of temperature, however, is an increase in line length, which eventually causes an increase in sag.

Calculation of Temperature

The mean temperature rise of a conductor is a function of the load current. Other parameters affecting it are the ambient temperature and wind velocity, intensity of solar radiation, conditions of conductor surface and the conductor resistance. This temperature rise is given by Day *et al.* (1971):

$$t = \frac{I^2 r_0(1+\alpha_0 t_a) + \alpha_s s d}{13.8\times 10^{-4}(V_w d)^{0.448} + 4\pi E' \sigma d (t_a + 273)^3 - I^2 r_0 \alpha_0} \; {}^{o}C \qquad (24)$$

where, I is the load current, t_a, the ambient temperature, α_0, the resistance temperature coefficient of conductor at 0 °C, r_0, the conductor resistance per metre at 0 °C, α_s, the solar absorption factor, s, the solar radiation intensity, d, the conductor diameter, V_w, the wind velocity, E', the thermal emissivity of the conductor surface and σ is the Stefan's constant.

Calculation of Tension

To ensure that the maximum safe tension does not exceed the prescribed limit under severe loading conditions and wind pressure, it is necessary to determine the tension to which a conductor must be strung. This new tension, T_2, is obtained from (Cotton and Barber, 1970 and Gupta, 1997):

$$T_2^3 + T_2^2\left[aE\left(\phi_0 t + \frac{W_1^2 l_s^2}{6T_1^2}\right) - T_1\right] - \frac{W_2^2 l_s^2 aE}{6} = 0 \qquad (25)$$

where, W_2 is the weight per unit length of conductor taking wind pressure into consideration, E, the Young's modulus of the conductor material, l_s, the half span length, W_1, the weight of the conductor per unit length,

W_w, the force due to horizontal wind pressure on the projected area of the conductor and ϕ_0 is the thermal coefficient of linear expansion.

Calculation of Sag

The sag, D_s, corresponding to the tension, T_2, at a load current, I is given by:

$$D_s = \frac{W_2 l_s^2}{2T_2} \qquad (26)$$

Effective Height and Length

A higher load current results in a decrease of tension, an increase in sag and consequently, a decrease in the effective height of the conductor which is taken as the height of conductor at the tower and less two-thirds of the sag measured at the middle of the span, viz:

$$h_{eff} = (h - \tfrac{2}{3} D_s) \qquad (27)$$

The effective length of the conductor between adjacent towers corresponding to the load current I and tension, T_2, is given by Cotton and Barber (1970):

$$l_{eff} = 2\left(l_s + \frac{W_2^2 l_s^3}{6T_2^2} \right) \qquad (28)$$

Hence the total length of the conductor between two ends of the transmission line with N_s number of spans is:

$$l = l_{eff} N_s \qquad (29)$$

3. Twin-bundled Conductors

The sub conductors constituting the bundle are subjected to mutual forces caused by electrostatic and electromagnetic fields. When these two forces balance each other, the sub conductors remain in their primary positions. However, the sub conductors experience a shift from their primary positions and form a catenary with an increase in load current. The maximum shift of the conductor from its primary position at the middle of a span length, l_s, is given by Jasicki (1974):

$$\delta = \frac{\left\{ 8.7 \left[\dfrac{V}{\ln \dfrac{D}{\sqrt{ds}}} \right]^2 - I^2 \right\} l_s^2}{s f_p a (15.85 \times 10^8)} \qquad (30)$$

where, V is the rated line voltage in kV ; D, the average spacing between phases, f_p, the mechanical stress of conductor, *a*, the conductor total cross-sectional area and l_s is the distance between two adjacent spacers. Finally, the average spacing between the sub conductors of a phase is given by:

$$S_{av} = S - \tfrac{2}{3}\delta \qquad (31)$$

The spacing between the sub conductors varies with the load current and this, in turn, affects mainly the resistive part of the **Z** matrix. This part depends only on the loading condition and is independent of the spacing between the sub conductors.

4. Conclusions

The paper has described an efficient method for solving the wave equation for multiconductor transmission lines. Although this method is rigorous, it has been proved to be very accurate (Galloway *et al*, 1964 and Indulkar *et al*., 1983). The methods of studying the effects of various cycles on the lines have also been presented. Both methods have been applied to recent works (Adegboye, 2002 and Adegboye *et al*., 2002) and encouraging results were obtained. In addition, the bundled conductor lines have been included because they possess wide band capability for power line carrier. A power line as a communication channel is characterized with low signal-to-noise ratio (SNR), which is time and weather dependent. A power line is a noise source in itself. Major source of noise presents the corona noise. The noise level caused by the corona strongly varies in the power frequency period and is dominant at rainy weather.

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