Parameter Estimation of Transmission Lines using Fault Records and Modal Analysis

E. C. M. Costa, J. T. R. Pineda, S. Kurokawa

***Abstract*—A parameter identification procedure for transmission lines is proposed based on the line representation by lumped parameters and modal analysis from synchronized measurements of fault records at both line terminals. This method represents a simplification of other complex identification methods directly in the phase and frequency domains. The evaluation of the proposed method is carried out as a function of the line length since the line representation by a single π circuit is not adequate for long transmission lines. A proposal to overcome this problem is discussed for further researches by mean of a new line sensor based on telecom technology GSM, which could be installed at intermediary line sections. Thus, considering that the currents and voltages along the line could be identified, the transmission line can be modeled by a cascade of π circuits, representing more accurately the distributed nature of the line parameters.**

***Keywords*: transmission lines; longitudinal impedance; transversal admittance; parameter estimation; modal analysis.**

I. Introduction

THIS research proposes an alternative procedure for identification of electrical parameters of power transmission lines based on measurement data. There are a few methods available in the technical literature, however, most of them are restrict to specific operational situations (faults, unbalanced operation, type of measurement, etc) or have a complex application for practical cases [1]-[4].

Another method to obtain the longitudinal and transversal parameters of transmission lines is based on the classical calculation using the Carson trigonometric functions (earth-return impedance) and Bessel functions (skin effect). Nevertheless, the calculation of the earth-return impedance is carried out considering an ideal soil (i.e. constant soil conductivity) and the skin effect is approached considering only the geometrical and physical characteristics of the cables [5]. The conventional formulation for electrical parameter calculation presents several approximation which leads to some inaccuracies. This way, the parameter estimation based on measurement data shows to be an attractive solution.

As previous mentioned, there are a few methods based on measurements obtained from *Phase Measurement Units* – PMUs and fault records obtained from digital relays [1, 4]. From these measurements, several parameters of transmission lines (R, L, G and C) could be obtained depending of the quality of the measurement data and also the line modeling. Initially, a measurement unit (a PMU or fault relays) has recorded *n* samples of current and voltage at the sending and receiving ends of a transmission line. A line representation should be modeled to represent the transmission system which the current and voltage samples are included to estimate the electrical parameters of the line. However, the line modeling is not a trivial task, the mutual parameters of the line should be properly modeled to represent the electromagnetic coupling among the phases, which is not a trivial task taking into account the approach by the classical electromagnetic field theory. The proposed method for identification of transmission line parameters is based on a three-phase line decoupling using modal analysis, i.e., each phase of a given transmission line are modeled as a single-phase transmission line without the explicit modeling of the mutual parameters [6]. By using an appropriated modal transformation matrix, a transmission line can be decoupled into three independent propagation modes and represented as being three single-phase lines. After identification of the longitudinal and transversal parameters in the modal domain, the same parameters can be converted to the phase domain with minor estimation errors. The well-established method of the least squares is applied to solve the system of *n* equations (number of samples) obtained from the first-order differential equations resulted of the line representation by π circuits.

The proposed method is firstly applied for a conventional 440-kV transmission line and the synchronized measurements are obtained based on simulations of single-phase faults recorded by fault relays. As a complementary and interesting content, the paper promotes a discussion on a new method to measure currents and voltages at any point of transmission lines based on telecom technology GSM [7]. A new sensor has been recently developed for measurement of detailed current and voltage profiles in transmission lines and represents a significant contribution to extend the proposed identification method for very-long transmission lines with more than 1.500 km length.

This research was supported by *Fundação de Amparo à Pesquisa do Estado de São Paulo – FAPESP* (Proc. 13/00974-5).

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Paper submitted to the International Conference on Power Systems Transients (IPST2015) in Cavtat, Croatia June 15-18, 2015

II. Transmission line parameters

The propagation characteristics of transmission lines are defined by the electrical parameters of the impedance and the admittance matrices, [Z] and [Y], respectively. They are expressed in (1) and (2).

$$[\mathrm{Z}] = \begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1n} \\ Z_{21} & Z_{22} & \cdots & Z_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{n1} & Z_{n2} & \cdots & Z_{nn} \end{bmatrix} \quad (1)$$

$$[\mathrm{Y}] = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Y_{n1} & Y_{n2} & \cdots & Y_{nn} \end{bmatrix} \quad (2)$$

Matrices [Z] and [Y] are square matrices with dimension similar to the number of phases *n*. Terms in the main diagonal are self parameters whereas remaining terms are mutual parameters between phases. The self and mutual impedances in [Z] are composed of a frequency-dependent resistance and a frequency-dependent inductance, generically described as [5]:

$$Z = R(\omega) + j\omega L(\omega) \quad (3)$$

The self impedance has a frequency-dependent resistance $R(\omega)$, where ω is the angular speed as a function of the frequency. The self resistance is composed of three partial resistances: skin-effect resistance, earth-return resistance and external resistance.

The resistance due to the skin effect is observed only in the self resistances and is more accentuated at low frequencies. The earth-return resistance is related to the current return through the soil and soil conductivity. The soil effect on the line electrical parameters is usually calculated using the approach by the Carson trigonometric series and considering constant soil conductivity. This last statement is an improper approach since the soil conductivity is highly variable with soil geological formation and environment conditions. The skin-effect resistance is predominant on the earth-return impedance only at low frequencies. Differently of the resistances resulted from the skin and soil effects, the external resistance is constant with the frequency variation and is calculated based on the geometrical and structural characteristics of the line. The same description is applied for the self inductance, except for the inductance resulted of the skin effect, which is usually neglected if compared to the earth-return inductance and the external inductance.

The mutual impedance has the same structure described in eq. (3). Impedance is calculated taken into account the current return through the soil, composed of a frequency-dependent resistance and a frequency-dependent inductance, analogously to the self impedance. The external mutual impedance is characterized only by a constant inductance, calculated based on the geometrical characteristics of the line. Thus, the external mutual impedance is solely composed of an inductive reactance [5].

Based on (1) and (3), the resistance and inductance matrices can be expressed as:

$$[\mathrm{R}] = \begin{bmatrix} R_{11} & R_{12} & \cdots & R_{1n} \\ R_{21} & R_{22} & \cdots & R_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ R_{n1} & R_{n2} & \cdots & R_{nn} \end{bmatrix} \quad (4)$$

$$[\mathrm{L}] = \begin{bmatrix} L_{11} & L_{12} & \cdots & L_{1n} \\ L_{21} & L_{22} & \cdots & L_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ L_{n1} & L_{n2} & \cdots & L_{nn} \end{bmatrix} \quad (5)$$

Therefore, the matrix formulation obtained from (1) and (3)-(5) is expresses as follows:

$$\begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1n} \\ Z_{21} & Z_{22} & \cdots & Z_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{n1} & Z_{n2} & \cdots & Z_{nn} \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} & \cdots & R_{1n} \\ R_{21} & R_{22} & \cdots & R_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ R_{n1} & R_{n2} & \cdots & R_{nn} \end{bmatrix} + j\omega \begin{bmatrix} L_{11} & L_{12} & \cdots & L_{1n} \\ L_{21} & L_{22} & \cdots & L_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ L_{n1} & L_{n2} & \cdots & L_{nn} \end{bmatrix} \quad (6)$$

Differently of the impedance matrix, each element of the admittance matrix [Y] is composed of a constant conductance *G* and capacitance *C*, as described in (7).

$$Y = G + j\omega C \quad (7)$$

Conventionally, in transmission line modeling - TLM, the transversal conductance is not considered in the admittance calculation. Thus, the real part of the complex admittance is neglected, which means that Y is an imaginary value representing a capacitive reactance [5].

The self and mutual parameters of the matrix [Y] are calculated from the self and mutual capacitances. Differently of the longitudinal parameters, self and mutual capacitances are not variable with the frequency and are calculated as a function of the line geometrical characteristics using the method of the images. This procedure also represents an improper approach, since the shunt capacitance and capacitance between phases are intrinsic associated with the environmental conditions, such as: air humidity, dielectric constant (air, forest, moisture, etc) and weather [5].

Therefore, from the same development in (6), the matrix formulation of the admittance is expressed in (8).

$$\begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ Y_{n1} & Y_{n2} & \cdots & Y_{nn} \end{bmatrix} = j\omega \begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1n} \\ C_{21} & C_{22} & \cdots & C_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ C_{n1} & C_{n2} & \cdots & C_{nn} \end{bmatrix} \quad (8)$$

Where the capacitance matrix is expressed as:

$$[\mathrm{C}] = \begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1n} \\ C_{21} & C_{22} & \cdots & C_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ C_{n1} & C_{n2} & \cdots & C_{nn} \end{bmatrix} \quad (9)$$

III. MODAL-DOMAIN ESTIMATION PROCEDURE

The proposed estimation method is carried out considering the previous knowledge of p samples of voltage and current during a single-phase fault. These values can be obtained based on fault records from the relays at the line terminals. Thus, the voltages and currents through a fault are known and expressed in vector form:

$$[v_A]_m = [v_{A1} \quad v_{A2} \quad v_{A3}]^T \quad (10)$$

$$[v_B]_m = [v_{B1} \quad v_{B2} \quad v_{B3}]^T \quad (11)$$

$$[i_A]_m = [i_{A1} \quad i_{A2} \quad i_{A3}]^T \tag{12}$$

$$[i_B]_m = [i_{B1} \quad i_{B2} \quad i_{B3}]^T \tag{13}$$

The p samples are indicated as $m = 1, 2, ..., p$. The index T represents the transposed form of the vectors (10)-(13).

From (10)-(13), the phase values can be decoupled into the modal domain by using a modal transformation matrix [T]:

$$[v_{AM}]_m = [\mathrm{T}]^T [v_A]_m \tag{14}$$

$$[v_{BM}]_m = [\mathrm{T}]^T [v_B]_m \tag{15}$$

$$[i_{AM}]_m = [\mathrm{T}]^{-1} [i_A]_m \tag{16}$$

$$[i_{BM}]_m = [\mathrm{T}]^{-1} [i_B]_m \tag{17}$$

Matrix [T] is obtained from the product [Z][Y] or [Y][Z], where the line and columns of [T] are function of the eigenvalues and eigenvectors of the referred matrix product. However, a real and constant transformation matrix is possible for transmission lines with vertical symmetric plane or with low asymmetry of the elements into the matrices [Z] and [Y]. Considering a low variation of terms out of the main diagonal of [Z] and [Y], a transformation matrix is characterized by elements with constant real values and negligible imaginary values [8]. This means that matrix [T] can be represented by a constant and real matrix in the time domain, since the p samples are given in the time domain as well; this modal propriety represents a fundamental characteristic for the development of the proposed estimation method.

The voltage and current matrices in (14)-(17) are diagonal whose the main diagonals are composed by the voltage and current values of three independent propagation modes: α, β and 0. Thus, a three-phase line is decoupled into three independent single-phase lines which can be modeled by a single two-port circuit as follows:

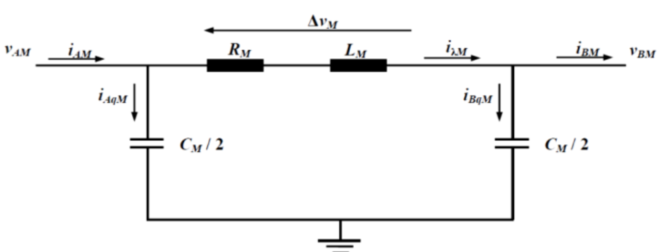

Fig. 1. Modal-domain representation through a single π circuit.

In fig. 1, terms R_M, L_M, and C_M are the resistance, inductance and capacitance in the modal domain, where the index M represents the modes α, β and 0.

The differential equation of the propagation modes α, β and 0 can be expressed in the matrix form as follows:

$$[\Delta v_{\mathrm{M}}]_m = [\mathrm{R_M}][i_{\lambda\mathrm{M}}]_m + [\mathrm{L_M}]\frac{d}{dt}[i_{\lambda\mathrm{M}}]_m \tag{18}$$

Where $[\Delta v_{\mathrm{M}}]_m$ and $[i_{\lambda\mathrm{M}}]_m$ are diagonal matrices with the voltage drops on the modal longitudinal parameters and currents through the modal resistances at the time sample m, respectively. Matrices $[\Delta v_{\mathrm{M}}]_m$ and $[i_{\lambda\mathrm{M}}]_m$ are expressed as:

$$[\Delta v_{\mathrm{M}}]_m = \begin{bmatrix} \Delta v_\alpha & 0 & 0 \\ 0 & \Delta v_\beta & 0 \\ 0 & 0 & \Delta v_0 \end{bmatrix} \tag{19}$$

$$[i_{\lambda\mathrm{M}}]_m = \begin{bmatrix} i_{\lambda\alpha} & 0 & 0 \\ 0 & i_{\lambda\beta} & 0 \\ 0 & 0 & i_{\lambda 0} \end{bmatrix} \tag{20}$$

In (19) and (20), matrices $[\Delta v_{\mathrm{M}}]_m$ and $[i_{\lambda\mathrm{M}}]_m$ have no mutual terms out of the main diagonal which means that the propagation modes α, β and 0 are completely decoupled each others, as previously described.

The modal capacitance can be calculated following the differential equations of the shunt currents at the terminals A and B, respectively.

$$[i_{Aq\mathrm{M}}]_m = \frac{[\mathrm{C_M}]}{2}\frac{d}{dt}[v_{A\mathrm{M}}]_m \tag{21}$$

$$[i_{Bq\mathrm{M}}]_m = \frac{[\mathrm{C_M}]}{2}\frac{d}{dt}[v_{B\mathrm{M}}]_m \tag{22}$$

As previously described, the G parameters are usually neglected in TLM [8]. This way, the shunt currents can be calculated just as a function of the modal capacitance C_M.

The matrices with modal shunt currents $[i_{Aq\mathrm{M}}]$ and $[i_{Bq\mathrm{M}}]$ are expressed for the generic sample m as follows:

$$[i_{Aq\mathrm{M}}]_m = \begin{bmatrix} i_{Aq\alpha} & 0 & 0 \\ 0 & i_{Aq\beta} & 0 \\ 0 & 0 & i_{Aq0} \end{bmatrix} \tag{23}$$

$$[i_{Bq\mathrm{M}}]_m = \begin{bmatrix} i_{Bq\alpha} & 0 & 0 \\ 0 & i_{Bq\beta} & 0 \\ 0 & 0 & i_{Bq0} \end{bmatrix} \tag{24}$$

Based on (21) and (22), the shunt modal currents in $[i_{Aq\mathrm{M}}]$ and $[i_{Bq\mathrm{M}}]$ are reformulated as a function of the modal voltages at terminals A and B:

$$[i_{Aq\mathrm{M}}]_m = [i_{Bq\mathrm{M}}]_m [\dot{v}_{B\mathrm{M}}]_m^T \left([\dot{v}_{B\mathrm{M}}]_m [\dot{v}_{B\mathrm{M}}]_m^T\right)^{-1} [\dot{v}_{A\mathrm{M}}]_m$$

$$[i_{Aq\mathrm{M}}]_m = [i_{Bq\mathrm{M}}]_m [Q]_m \tag{25}$$

The matrix $[Q]_m$ is described as follows:

$$[Q]_m = [\dot{v}_{B\mathrm{M}}]_m^T ([\dot{v}_{B\mathrm{M}}]_m [\dot{v}_{B\mathrm{M}}]_m^T)^{-1} [\dot{v}_{A\mathrm{M}}]_m \tag{26}$$

The matrices with the derivatives of the modal voltages at terminals A and B are expressed as:

$$[\dot{v}_{A\mathrm{M}}]_m = \begin{bmatrix} \frac{dv_{A\alpha}}{dt} & 0 & 0 \\ 0 & \frac{dv_{A\beta}}{dt} & 0 \\ 0 & 0 & \frac{dv_{A0}}{dt} \end{bmatrix} \tag{27}$$

$$[\dot{v_{BM}}]_m = \begin{bmatrix} \frac{dv_{B\alpha}}{dt} & 0 & 0 \\ 0 & \frac{dv_{B\beta}}{dt} & 0 \\ 0 & 0 & \frac{dv_{B0}}{dt} \end{bmatrix} \quad (28)$$

The unknown matrix $[i_{\lambda M}]_m$, whose the main diagonal is composed of the current i_λ for each propagation mode, is expressed according with the π circuit in fig. 1:

$$[i_{\lambda M}]_m = [i_{AM}]_m - [i_{AqM}]_m = [i_{BM}]_m + [i_{BqM}]_m \quad (29)$$

Substituting $[i_{BqM}]_m$ in (29), the current matrix $[i_{AqM}]_m$ can be reformulated as a function of the known modal voltages and modal currents at the terminals A and B in the fig. 1:

$$[i_{AqM}]_m = ([i_{AM}]_m - [i_{BM}]_m)[Q]_m([I] + [Q]_m)^{-1} \quad (30)$$

The relationship of (29) and (30) results in the following expression for $[i_{\lambda M}]_m$:

$$[i_{\lambda M}]_m = [i_{BM}]_m + ([i_{AM}]_m - [i_{BM}]_m)([I] + [Q]_m)^{-1} \quad (31)$$

Since the modal currents in $[i_{AqM}]$, $[i_{BqM}]$ and $[i_{\lambda M}]_m$ can be calculated from the p (m = 1, 2, ..., p) voltage and current measurements at both line terminals, the system of differential equations based on (18), (21) and (22) can be solved using the least-square method. Thus, the modal-domain R, L and C parameters are also obtained.

In a further step, the phase-domain matrices [R], [L] and [C] are obtained from the modal-domain matrices $[R_M]$, $[L_M]$ and $[C_M]$, respectively. The modal matrices are converted to the phase domain using the same transformation matrices in (14)-(17):

$$[R] = [T]^T[R_M][T]^{-1} \quad (32)$$

$$[L] = [T]^T[L_M][T]^{-1} \quad (33)$$

$$[C] = [T]^{-1}[C_M][T] \quad (34)$$

This way, [R], [L] and [C]; in (4), (5) and (9); are obtained for a three-phase transmission line (for n = 3).

IV. Performance of the Estimation Method as a Function of the Line Length

The estimation method from the line modeling in the modal domain is applied to identify the electrical parameters of an asymmetrical transmission line based on single-phase faults. The reference R, L and C parameters are given:

$$[R] = \begin{bmatrix} 58.221 & 47.104 & 47.063 \\ 47.104 & 58.224 & 47.104 \\ 47.063 & 47.104 & 58.221 \end{bmatrix} \quad \text{m}\Omega/\text{km} \quad (35)$$

$$[L] = \begin{bmatrix} 1.6876 & 0.8652 & 0.7267 \\ 0.8652 & 1.6876 & 0.8652 \\ 0.7267 & 0.8652 & 1.6876 \end{bmatrix} \quad \text{mH/km} \quad (36)$$

$$[C] = \begin{bmatrix} 11.305 & -2.446 & -0.820 \\ -2.446 & 11.775 & -2.446 \\ -0.820 & -2.446 & 11.305 \end{bmatrix} \quad \eta\text{F/km} \quad (37)$$

The electrical parameters shown in (35)-(37) are calculated based on a conventional 440-kV transmission line. A variable line length is considered in order to evaluate the proposed estimation method for several line lengths. The sending end of the line is connected to a three-phase voltage source at 60 Hz. The receiving end is connected to a balanced three-phase load of 500 kVA and power factor of 0.97. A short-circuit is simulated at the load terminal for a single phase per time. The fault voltages and currents are synchronously obtained at both line ends.

The simulation is carried out for $0 < t < 0.3$ *s*. However, the time window is from 0.1 to 0.3 *s* in order to eliminate the transients after the short occurrence. Otherwise, if the high-frequency oscillations are taken into account in the transient state, digital signal processing techniques should be applied to model voltage and current signals, as in reference [4].

The performance of the estimation method is evaluated based on the relative error of the reference values given in (35)-(37) and the estimated values obtained using the voltage and current values simulated using the *Electromagnetic Transient Program* – EMTP. The relative error is presented as a function of the line length.

A. Longitudinal parameters

The longitudinal parameters are expressed by the self and mutual resistance and inductance of the line.

Figure 2 shows the percent relative error as a function of the line length for the self resistance in the phase 1; considering a single-phase fault at phases 1, 2 and 3 of the load terminal.

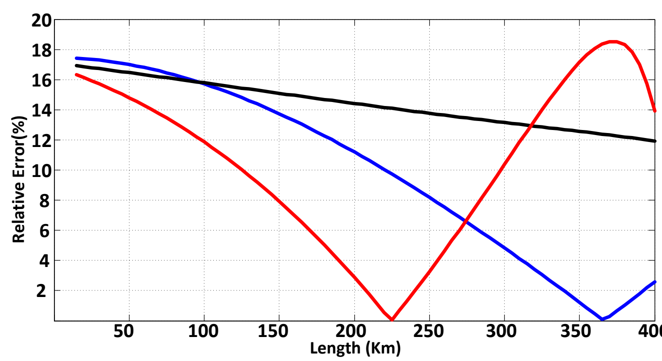

Fig. 2. Relative error of the self resistance of the phase 1 estimated from a single-phase fault at phases 1 (blue curve), 2 (black curve) and 3 (red curve).

The line length was varied from 10 up to 400 km. A minor relative error was observed for a restrict range of length between 150 up to 400 km, depending of the phase where the fault occurs. A similar behavior was prior observed in the parameter estimation method developed in reference [1], however, the evaluation was carried out based on a variable load profile in terms of apparent power and power factor.

The estimated mutual resistance between two consecutive phases (two nearest phases) is evaluated in fig. 3 considering the same single-phase fault at the load terminal at phases 1, 2 and 3.

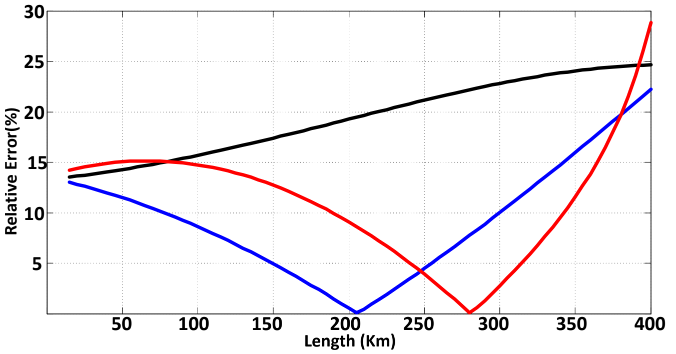

Fig. 3. Relative errors of the mutual resistance estimated from a single-phase fault at phases 1 (blue curve), 2 (black curve) and 3 (red curve).

The relative errors for the self inductance of the phase 1 are described in fig. 4.

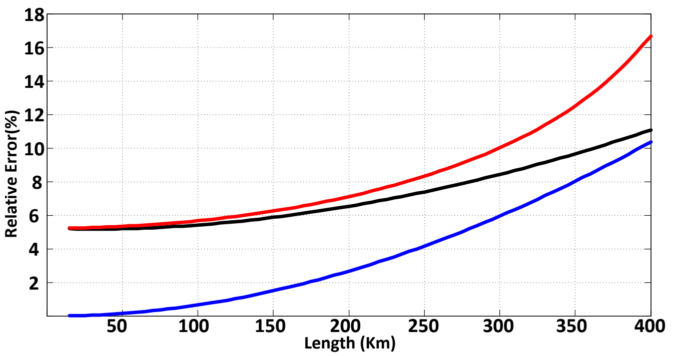

Fig. 4. Relative errors of the self inductance of the phase 1 estimated from a single-phase fault at phases 1 (blue curve), 2 (black curve) and 3 (red curve).

Figure 4 shows that from a general conclusion, the estimated self inductance presents a minor relative error for short transmission lines, up to 250 km. After a line length longer than 300 km the relative errors increase significantly.

Figure 5 describes the behavior of the mutual inductance estimated by the proposed estimation method, considering the same two consecutive phases as in fig. 3. From the same way, the relative errors are calculates considering three independent simulations: single-phase fault at the load terminal at phases 1, 2 and 3.

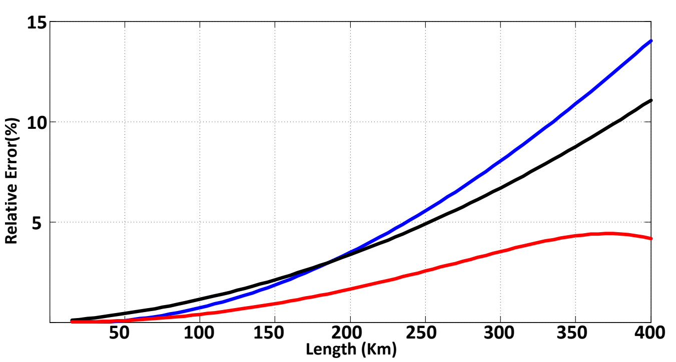

Fig. 5. Relative errors of the mutual inductance estimated from a single-phase fault at phases 1 (blue curve), 2 (black curve) and 3 (red curve).

The relative errors of the mutual inductance in fig. 5 are approximately minor than 10% up to 350 km.

B. Transversal parameters

The transversal parameters of the transmission lines are composed of self and mutual admittances which are represented only by the imaginary part related to the self and mutual capacitances of the multiphase system. Usually, in transmission line theory, the transversal conductance is neglected [5].

From the same procedure carried out for the longitudinal parameters, single-phase faults are simulated for each phase independently and voltage and current values are registered at the sending and the receiving ends of the line. Self and mutual capacitances are estimated from these values following the method described in the section III.

First, the estimation errors of the self capacitance of the phase 1 are analyzed in fig. 6.

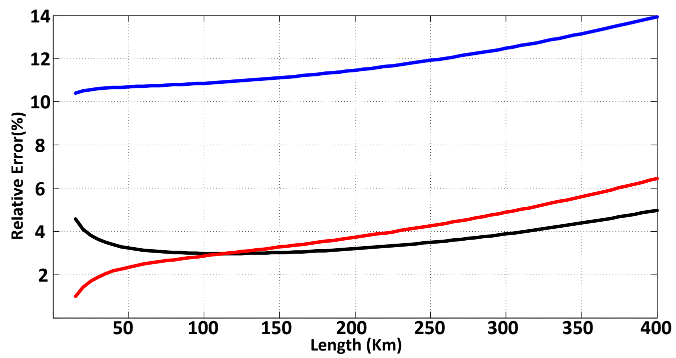

Fig. 6. Relative errors of the self capacitance of the phase 1 estimated from a single-phase fault at phases 1 (blue curve), 2 (black curve) and 3 (red curve).

In fig. 6, the relative errors are below 6% for faults occurred at the phases 2 and 3. On the other hand, the relative error concerning a fault at the phase 1 is over 10%. A hypothesis for this behavior is that the low capacitive current through the shunt capacitance could result possible inaccuracies in the estimation of the shunt capacitance for phase 1, since the major part of the total current is flowing through the short circuit at the load terminal.

The relative errors of the mutual capacitance of two consecutive phases are shown in fig. 7.

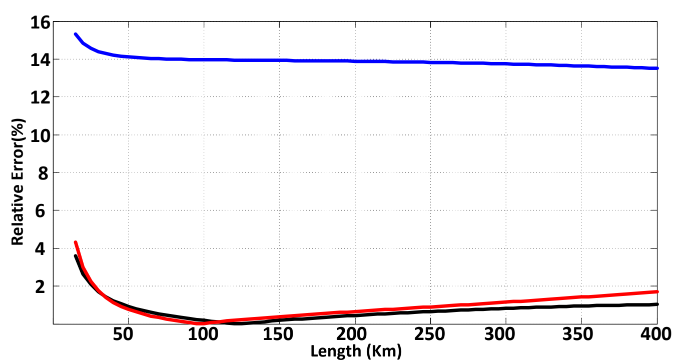

Fig. 7. Relative errors of the mutual capacitance estimated from a single-phase fault at phases 1 (blue curve), 2 (black curve) and 3 (red curve).

The estimated mutual capacitance shows errors up to 2% for line lengths from 30 up to 400 km, considering the single-phase fault occurrence at the phases 2 and 3.

V. Discussion and further developments

Results described in this paper show that the proposed identification method has a performance variable with the line length and phase where the single-phase fault occurs. Although low relative errors are observed for several fault characteristics and line lengths, further analyses should be carried out for long lines, with more than 500 km length. In these cases, the line modeling by a single π circuit could not properly represent the distributed nature of the longitudinal and transversal parameters of the line. Furthermore, only the voltage and current samples at the two line terminals could not be sufficient for a good estimation of the line parameters using the least-square method.

A relative new sensor has been used for monitoring several line data in real time, such as: voltage and current at any point along the line; line inclination; temperature of the wires. This monitoring device is the USi Power Donut™. It is connected directly at the phase conductors and the remote monitoring is carried out using telecom technology GSM and communication protocol TCP/IP (fig. 8) [7]. Thus, voltage and current measurements can be obtained at any time and on several intermediary sections of the line, enabling the line modeling by a cascade of π circuits (better representation of the distributed characteristic of the electrical parameters) and a major amount of voltage and current data (improving the solution using the least-square method).

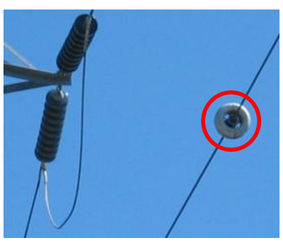

Fig. 8. Power Donut™ installed in a transmission line.

If the voltages and currents are known at *k* points along the line (including the sending and receiving ends), a cascade with *k*-1 equivalent circuits can be modeled to represent the distributed parameters of long transmission lines. This segmented representation results a large system of differential equations, as larger as the quantity of time samples and line sections, which can be solved using the same least-square method.

Figure 9 shows a transmission line segmented in *k*-1 sections. The measurements points along the line are indicated by 1, 2, …, *k*. Terms Z_1, Z_2 and Z_{k-1} are the total impedances of the line sections 1, 2, …, *k*-1, respectively; whereas Y_1, Y_2 and Y_{k-1} are the total admittances at each line section. The number of line segments is dependent of the number of measurement points along the line.

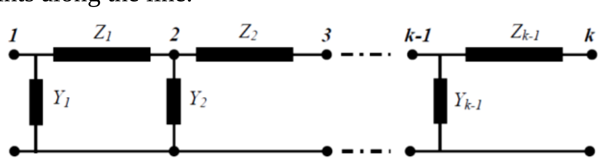

Fig. 9. Transmission line represented by *k*-1 sections and *k* measurement points.

The impedance and admittance parameters of each line section (1, 2, …, *k*-1) are dependent of the distance between consecutive measurement points. This means that the transmission line can be segmented into non-homogeneous sections.

VI. Conclusions

The proposed estimation method showed a performance variable with the line length and with the phase where the fault occurs. However, the use of modal analysis for line parameters estimation presented a good accuracy as a function of the line length. With a previous knowing of the estimation method performance as a function of the line length, most of the self and mutual parameters can be estimated with accuracy, especially for transposed transmission lines.

Further analyses concerning the quantity of time samples and other types of faults could be interesting for a better understanding and complementary knowledge on the proposed method.

The line length analyzed in this research was up to 400 km. As a next step, the proposed estimation procedure could be evaluated for lines up to 1.500 km. However, there is an important issue on the validity of the proposed method for long transmission lines, since the distributed characteristics of the electric parameters could not be properly represented considering only one single π circuit. From this analysis, a possible solution was proposed to extend the estimation method for longer transmission lines, taken into account more than two measure points along the line (voltage and current samples) and modeling by several equivalent line segments.

VII. References

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