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Modeling and Diagnosis of Joints in High Voltage Electrical Transmission Lines

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Abstract. In this paper a new method is developed and described, aimed at the modeling and diagnosis of the joints connecting the ends of two cables on a high voltage electricity pylon. Identifying the anomalous joint behaviour through the line frequency response analysis is the first objective of the work. For this reason, it is necessary to model the whole overhead line with a lumped circuit and studying the joint electrical parameter variation. The problem is approached in multiple steps: modelling, testability analysis of the model, optimal frequency selection, identification of the possible failures. Some simulated cases are included in order to show the potentialities of the method.

1. Introduction

The assessment of operating conditions of overhead transmission lines is an important aspect in the management of an electrical energy distribution system and can be performed in different ways. By using the state estimators based on the load flow analysis, it is possible to obtain the voltage profile at each node of the network [1-3]. The anomalous behaviour of the power line is detected by means of this method, but the exact location of the failure is not possible. Often, the anomalous behaviour of the power grid depends on the state of the joints, therefore it is very important to obtain information about their deterioration at an early stage. In many cases, time domain reflectometry techniques are used for remote detection of the joint impedance; these techniques are based on the study of the reflected signals from the conductor discontinuity regions [4-5]. The reflected signal analysis is influenced by measurement errors, environmental noise and other factors; several difficulties are due to line length and different environmental conditions along the line. As a result the remote estimation of joint conditions is not a simple task.

This paper presents the theoretical basis for developing a method of fault location of joints in high voltage electrical lines. It is a diagnostic method that allows to identify the cause of malfunction by analysing the electrical characteristics of the whole transmission line. In fact, the network model includes the electrical parameters of the most stressed parts conductors and joints[6-7]. In this paper, only the joint conditions are considered because many drawbacks – such as voltage drops, power losses and power quality decrease – may depend on the change of joint characteristic electrical parameters. Therefore, only these parameters are considered variable, while the electrical parameters of the conductors are fixed at the nominal value. The frequency response of the line equivalent circuit is used by the diagnostic system and a multifrequency approach is considered, as it is common in many diagnosis techniques (see, for example, the pioneering one in [8]).



The paper is organized as follows. In Section II the phase conductors are modelled as standard transmission lines constituted by two longitudinal parameters and two transversal parameters, defined per unit of length and dependent on the physical and geometrical characteristics of conductors. The equivalent circuits of the joints are also described on the base of their physical structure. In Section III, the whole procedure is outlined, describing the various steps. Section IV presents some specific application cases. In the last section, conclusions are reported.

2. Conductor and joint modelling

The first step of the modelling is to define the electrical parameters of the main components in the overhead power line. The transmission line can be considered as a succession of joints and stretches of conductor. Thus, the overall equivalent circuit of the line is formed by a cascade of equivalent circuits of conductors and joints. The junction region must guarantee electrical continuity between two conductor parts of the same phase. A standard circuit with four components can be used for the conductors, as shown in Fig. 1. A line series resistance ($R_l' \Delta \lambda_l$) and a line series inductance ($L_l' \Delta \lambda_l$) are used to account the voltage drop along a line stretch. A shunt conductance ($G_l' \Delta \lambda_l$) and a shunt capacitance ($C_l' \Delta \lambda_l$) take into account the current losses along the line [1, 9].

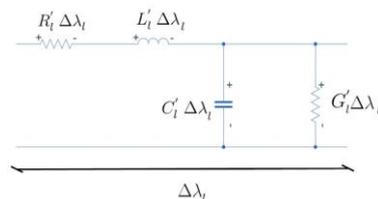


Figure 1. Equivalent circuit of the conductor.

In the overhead lines there are two different types of joints: compression joints and bolted joints [4]. In this work only bolted joints are considered: they have a physical structure different from that of the conductors and are positioned at the pylons [4]. An electrical model of the bolted joint can be determined by the physical structure of the solder joints [1, 9]. The solder joints are typical for signal applications, but they can be used for the present purpose without a significant loss of representability. In Fig. 2 (a) the solder joint simplified structure is shown, where:

$\Delta \lambda$ is the length of the junction region;

d is the width of the junction region;

H is the height of the junction region.

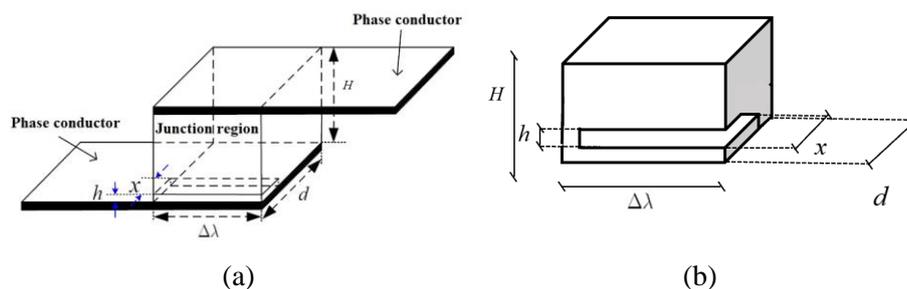


Figure 2. Solder joint: (a) Simplified structure (b) fracture dimensions.

The joint model is shown in Fig. 3, where three circuit parameters are considered: R_{sj} , L_{sj} and C_{sj} . The joint resistance is the parameter sensitive to the formation of oxide on the structure because this modifies its resistivity, while L_{sj} and C_{sj} take into account any break in the joint [10-11].

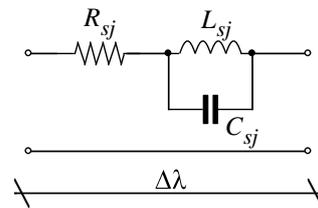


Figure 3. Equivalent circuit of the joint.

In the analytical formulation of R_{sj} , the skin effect is introduced, and this limits the surface available for conduction in alternating current. In conditions of perfect functioning the following relations are valid [10]:

$$R_{sj} = \frac{\rho H}{2\delta(\Delta\lambda + d - 2\delta)} \quad (1)$$

$$L_{sj} = \frac{\mu_0 \mu_r H}{2\pi} \left[\ln\left(\frac{2H}{\Delta\lambda + d}\right) + 0.5 \right] \quad (2)$$

$$\delta = \frac{1}{\sqrt{\pi f \mu_0 \mu_r \sigma}} \quad (3)$$

where δ is the depth of penetration of the current at the frequency f . The value of the capacitor C_{sj} is negligible in the absence of breakage, therefore it is fixed at 0.01 pF. This value maintains inductive the impedance given by the parallel connection with L_{sj} and can be considered inside the tolerance, where “tolerance” in this case means a vertical breaking value equal to 5% of the H value and x equal to 5% of the joint width. For this reason, 0.01 pF can be considered the nominal value of C_{sj} .

The dependence of the circuit parameters with respect to the dimensions of the damage can be derived by introducing a typical breaking mechanism of the solder joints [11]:

$$R_{sj} = \begin{cases} \rho \left[\frac{H-h}{2\delta(\Delta\lambda + d - 2\delta)} + \frac{h}{2\delta(\Delta\lambda + d - x - 2\delta)} \right] & (d-x) \geq 2\delta \\ \rho \left[\frac{H-h}{2\delta(\Delta\lambda + d - 2\delta)} + \frac{h}{\Delta\lambda(d-x)} \right] & (d-x) < 2\delta \end{cases} \quad (4)$$

$$L_{sj} = \frac{\mu_0 \mu_r (H-h)}{2\pi} \left[\ln\left(\frac{2(H-h)}{\Delta\lambda + d}\right) + 0.5 \right] + \frac{\mu_0 \mu_r h}{2\pi} \left[\ln\left(\frac{2h}{\Delta\lambda + d - x}\right) + 0.5 \right] \quad (5)$$

$$C_{sj} = \epsilon_o \epsilon_r \frac{x \Delta\lambda}{h} \quad (6)$$

where, relating to Fig. 2 (b):

x is the width of the crack;

h is the height of the crack.

By connecting in cascade the models of the conductor and of the joint, it is possible to model a very large electrical power grid by means of a small number of components. In the following section a procedure for identifying the joint parameters, based on the analysis of the frequency response of the equivalent circuit, is presented.

3. Procedure outlines

Once that the models of the line and joint have been established, the fault diagnosis phase can start. The frequency response of the line equivalent circuit and a multifrequency approach are used in the developed procedure, as is common in many diagnosis techniques. The steps of the procedure are:

- Circuit simulation;
- Testability analysis;
- Optimum frequency set selection;
- Parameter identification.

3.1 Circuit simulation

The developed procedure requires simulations at several frequencies. The number of simulations can be very high in some circumstances, and the simulator SapWin[®] (Symbolic Analysis Program for Windows) [12] is suited to this purpose. It is a simulation package developed by the authors, available at [13]. It provides in output the response of a circuit in symbolic format. This allows to perform the necessary simulations in a very short time. On the circuit constructed in SapWin[®] the test points are chosen and the program yields as output the network functions relevant to test points.

3.2 Testability analysis

For any diagnosis procedure the knowledge a priori of the solvability degree of the problem is of fundamental importance to avoid wasting time in the attempt to determine unidentifiable parameters. In fact the term solvability degree indicates how many and what parameters are identifiable starting from measurements carried out at a test point set chosen on the system under analysis. The testability analysis helps in this direction, as reported in recent papers [14-16], which also present some efficient approaches to testability analysis. It consists of testability evaluation and ambiguity group determination. For analog circuits, the definition given in the seminal paper [8] states that testability T equates the solvability degree of the fault diagnosis equations, that is the number of parameters identifiable by elaborating a given input/output set of measurements. The testability value T cannot be greater than the total number N of potentially variable components of the system. When it is less than N , it is useful to determine the “ambiguity groups” of the circuit. The ambiguity groups are sets of components each other indistinguishable. In summary, testability value establishes the maximum number of parameters identifiable at the same time, ambiguity groups give precise information on which parameters can be identified [16]. In the proposed fault procedure testability analysis is performed by the program LINFTA [16], exploiting SapWin[®] for the model construction.

3.3. Optimum frequency set selection

In order to diagnose the behavior of the joint, a collection of measures taken at different frequencies can be necessary. In fact, if the number of network functions relevant to the selected test points is less than the number of unknowns, additional equations are introduced by means of measurements at different frequencies. To minimize the error deriving from tolerances and noise, a suitable choice of frequencies has to be made. To this end the efficient approach in [17] has been followed. It determines the Jacobian matrix \mathbf{J}_M of the set of nonlinear equations associated with the measurements and with the network functions at several frequencies, and then it extracts the index:

$$T.I. = (k(\mathbf{J}_M)^{-1}) \cdot \|\mathbf{J}_M^{-1}\|_2 = \frac{\sigma_{MAX} - \sigma_{MIN}}{\sigma_{MIN}^2} \quad (7)$$

being k the condition number of the Jacobian:

$$k(\mathbf{J}_M) = \|\mathbf{J}_M\|_2 \cdot \|\mathbf{J}_M^{-1}\|_2 = \frac{\sigma_{MAX}}{\sigma_{MIN}} \quad (8)$$

and σ_{MAX} and σ_{MIN} the maximum and minimum singular values of the Jacobian matrix, respectively. The index is then minimized with respect to the frequencies range, in order to find the region where the error due to tolerances and measurement noise is minimum, as demonstrated in [17]. A program for the determination of the optimum frequency set, based on this approach, is associated with the

software package SapWin[®]. In this phase many repeated simulations (hundreds or thousands) at several frequencies are necessary. SapWin[®], thanks to its symbolic nature, performs the necessary simulations in a very short time.

3.4 Parameter identification

Once the testability analysis of the circuit has been carried out and the most appropriate frequencies have been determined, the fault diagnosis equations are solved to identify the electrical parameters of the joint and to assess its state of health. The identification of the parameters is executed with the Matlab[®] software by means of the Newton-Raphson method. The fault equation system, nonlinear with respect to unknown parameters, has the following form

$$\left\{ \begin{array}{l} \left| \frac{N(j\omega)}{D(j\omega)} \right|_{\omega=\omega_1} = M_1 \\ \vdots \\ \left| \frac{N(j\omega)}{D(j\omega)} \right|_{\omega=\omega_n} = M_n \end{array} \right. \quad (9)$$

In principle, this approach can be used to identify any situation of circuit parameters. If the parameters do not belong to any ambiguity groups, it is possible to find their values through the inversion of the fault equations.

Actually, not always the exact value of the parameters can be extracted, due to the poor sensitivity of the output with respect to the parameter values. However the exact identification is not always necessary. To this aim it can be useful mentioning the typical classification of faults:

- *Manufacturing tolerance*: a slight variation of parameters caused by manufacturing processes is supposed to have no effect on the system performance.
- *Soft faults*: in this case the system is still functioning, but some of its characteristic properties lie outside their allowed intervals. The component variation leads to the loss of functionality and can be caused, for example, by temporary inappropriate operation conditions or component ageing.
- *Hard faults*: the deviation of parameters is extremely significant, and the system is not functioning at all.
- *Fatal fault*: this is a boundary condition of hard faults. In this case, the fault is usually accompanied by the destruction of a component and, in the case of electrical systems, can be modelled using a short or open circuit.

The low sensitivity in the “Manufacturing tolerance” is not a problem, in fact the method has not to identify the nominal conditions but those of malfunctioning.

4. Case studies

In order to validate the developed procedure, some fault situations have been simulated. Then, for the determination of the fault diagnosis equations, a suitable number of simulated responses of the circuit have been created using the SapWin[®] software [12-13], able to quickly calculate the output of the circuit when the parameter values are randomly varied over a given range.

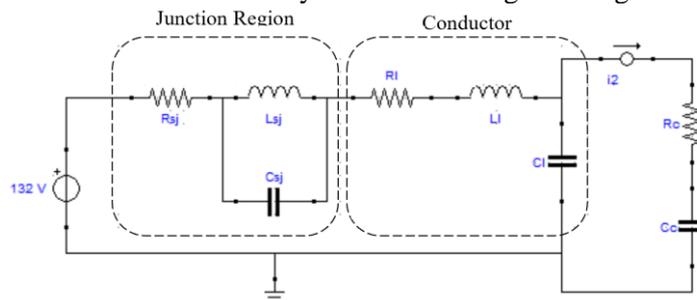


Figure 4. Circuital model for the first example.

Let us initially consider only one junction region and a 300 meters line stretch (Fig. 4). The chosen test point is the current, then the network function is an admittance function. The testability of the circuit is maximum ($T=6$). For this reason, there are not ambiguity groups and all components can be considered faulty at the same time. In the first examples of simulation, equivalent circuits are realized on SapWin[®] with only one symbolic parameter at a time, R_{sj} . This is due to the fact that the unknown parameter choice is based on the fault mechanism. In this case the oxidation mechanism is considered, which produces the resistivity variation, with the consequent increase of R_{sj} . To determine the variation magnitude, reference is made to the measurement results in [4], reported in table 1.

Acronym	Status	ACSR	R_{sjdc}
BJNew	New	22.8 mm	60 $\mu\Omega$
BJAged1	Aged	22.8 mm	5 m Ω
BJAged2	Aged	22.8 mm	2.5 m Ω
BJNewTape1	New+Tape1	22.8 mm	2 Ω
BJNewTape2	New+Tape2	22.8 mm	1.6 k Ω

Table 1 shows five different bolted joints considered in [4] to obtain the measurements of the junction region DC resistance R_{sjdc} . “BJNew” represents a joint in perfect condition that has not been used yet on the real network. “BJAged1” and “BJAged2” are two joints with different levels of oxidation, extracted from the same network during the maintenance period. “BJNewTape1” and “BJNewTape2” are artificial degraded joints, which represent the junction regions with a high oxidation level; these conditions are realized by inserting a low conductivity material between the opposing faces of the joint. All the joints used for these measurements are usually connected to the Aluminium Conductor Steel Reinforced (ACSR) with a 22.8 mm outer diameter.

The Newton Raphson algorithm is implemented in Matlab[®] to solve the fault equation. Three different resistance values are chosen for the simulation: the first one (60 $\mu\Omega$) represents the nominal value, the second one (100 m Ω) represents the “soft fault” condition, and the last one (2 Ω) represents the “hard fault” condition. The second value (100 m Ω) is chosen because it represents a limit condition between normal aging and artificial oxidation. As shown in Fig. 5, the sensitivity of R_{sj} is always very low. Without the oxidation mechanism, R_{sj} is close to the nominal value and the low sensitivity does not allow to identify its value. On the other hand, when the oxidation state of the joint begins to become relevant, the actual values move to a range where, even with low sensitivity, they become recognizable.

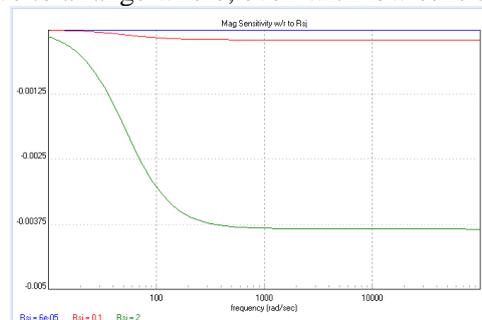


Figure 5. Sensitivity of the magnitude of the response with respect to the joint resistance

The same procedure can be followed to identify the variations of the other parameters. For L_{sj} and C_{sj} it is necessary to consider the joint breaking mechanism. The junction region inductance is particularly sensitive to the breaking height “h” and it is identifiable using the only unknown parameter L_{sj} on the

circuit of Fig. 4 and using a frequency of a few tens of MHz. In the case of the junction capacity C_{sj} , there are strong limits of sensitivity and this parameter is never identifiable. The results for the case of Fig. 4 are reported in Table 2.

Table 2. Results of junction parameter identification of the circuit in Fig.4

Range of values	Condition	R_{sj}		L_{sj}		C_{sj}	
		Testable	Identifiable	Testable	Identifiable	Testable	Identifiable
R_{sj} $60\mu\Omega \div 2.5m\Omega$	Manufacturing Tolerance	Yes	No (low sens.)	Yes	Yes	Yes	No (low sens.)
L_{sj} $(1.5642\div 1.4)\mu H$							
C_{sj} $0.01 pF$							
R_{sj} $(2.5\div 100) m\Omega$	Soft Fault	Yes	Yes	Yes	Yes	Yes	No
L_{sj} $(1.4\div 1.2)\mu H$							
C_{sj} $> 0.01 pF$							
R_{sj} $100 m\Omega \div 2 \Omega$	Hard Fault	Yes	Yes	Yes	Yes	Yes	No
L_{sj} $(1.2\div 1.057)\mu H$							
C_{sj} $> 0.01 pF$							
Fatal Fault		Short or Open circuit					

Table 2 reports, for each component, if it is testable, i.e. independently recognizable, and if it is actually identifiable, i.e. determinable from the measures of the admittance. As it can be seen (and said before), the components are always testable, but not always identifiable.

The next example is referred to the three-junction case shown in Fig. 6(a) and the oxidation mechanism is again considered. The first step is the equivalent circuit realization on SapWin®; in this case there are three unknown parameters, R_{sj1} , R_{sj2} and R_{sj3} . The circuit under test has maximum testability, so there are no ambiguity groups. The transfer function chosen is still the admittance function, then also in this case just one test point (the output current) is used. Since the unknown parameters are three and the network function is only one, it is necessary to consider three different frequencies in order to have three unknowns and three fault equations. The approach proposed in [17] and summarized in the paragraph 3.3 is followed for the choice of the test frequencies. Subsequently, using SapWin®'s multi-parametric simulation feature, the simulated frequency responses can be obtained. Finally, using the analytical form of the network functions at the three determined frequencies and the simulated measurements, it is possible to obtain the system of the fault equations. The iterative Newton Raphson algorithm is used to solve the system of non-linear equations. The solution of the system allows to identify all three oxidation conditions. The model and the results for this case are shown in fig. 6(b), showing that all fault cases are identified.

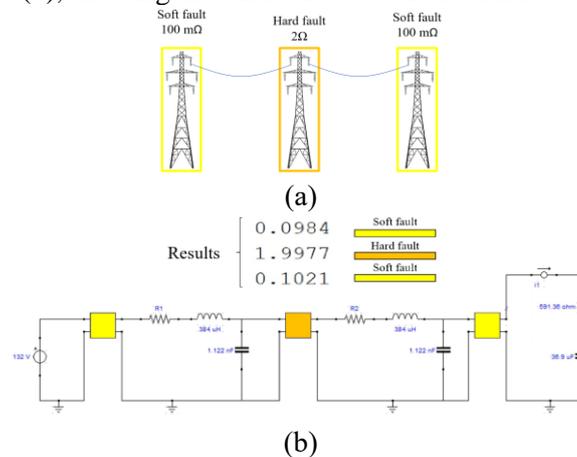


Figure 6. Three joint system.

5. Conclusions

An innovative method for diagnosing faults on joints of high voltage electric transmission lines has been presented. Starting from the simulation of the model of joints and stretches of conductor, the fault diagnosis equations, corresponding to a network function evaluated in a suitable set of frequencies, are solved with the Newton- Raphson method in order to identify the model electrical parameters. Each junction region in the network has a model with three electrical parameters: R_{sj} , C_{sj} and L_{sj} . The oxidation mechanism produces the resistance variation and this is the first effect that decreases the network functionality. When the value of R_{sj} exceeds the manufacturing tolerance limit, it is possible to identify its value. This means that it is possible to identify the first oxidation phase, which is very important because it allows to prevent high criticality failures. Furthermore the study of the junction resistance can be performed on circuits of any complexity and this allows to locate the joint in the worst conditions; in this way it is possible to reduce network recovery times and correctly organize maintenance operations. If the oxidation limit condition has been reached, it is possible to consider the partial breakage mechanism of the joint. In this condition all the electrical parameters of the joint are modified; the resistance variation cannot be used to quantify the joint break and the variation of the parameters L_{sj} and C_{sj} is taken into consideration. In the next future alternative techniques will be tried, in particular through the use of methods based on machine learning, both for identification and for the classification.

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