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A serial arc fault location algorithm based on impedance method for a domestic AC system

E. M. Calderon, P. Schweitzer, S. Weber

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Abstract— This article describes a fault location method developed within our laboratory. The method is based on the electric line physical parameters to estimate a serial arc fault distance in an experimental short transmission line. Using recorded data at two ends of the transmission line, the method estimates currents in many hypothetic fault points of the line, looking for a current difference minimization. The test bench used for our purpose is composed of a 49 m transmission line used in domestic networks (220V–50Hz) and a 47 ohms power resistor load. Across the line, an arc fault (carbonized path) can be inserted at many different points (40 points of insertion are available).

Keywords— Serial arc fault, transmission line, fault location.

I. INTRODUCTION

Serial arc faults frequently appear in low voltage distribution systems in unpredictable ways [1] when degraded aged wires are in contact each other. Many works have been developed to detect this type of faults. It includes commercial protection systems that are been successfully used in home electrical networks. However, a fault location methodology in low voltage systems was not properly developed. In this context, to know the distance at which a fault happened could avoid damages and also catastrophic incidents like fires [2]. In this work, we are focused on developing an algorithm able to estimate the fault distance in an experimental short transmission line.

For locating arc faults, many works have been developed algorithms using the impedance method [3, 4, 5, 6], traveling wave methods [7, 8, 9, 10] and intelligent methods [11, 12, 13]. However, these methods mainly locate parallel faults on high power distribution systems. Some works based on reflectometry methods (TDR, STDR) [14, 15, 16] developed algorithms to locate intermittent electric faults mainly in electrical aircraft systems.

Few works [1, 17] are dedicated to locating parallel faults in short transmission lines using the impedance method. The work developed by Yang Cao et al. [18] implemented an algorithm to locate a serial arc fault in an experimental DC electrical system constituted by physical modules that emulate a transmission line of 1200m. Using a similar approach, we developed an algorithm to estimate the location of a serial arc fault in a domestic AC experimental transmission line using the impedance method.

In part II, the paper presents the electrical line model under

normal and fault conditions operation. Then, a representation of the line based in quadripoles during a serial arc fault is developed

In part III, a fundamental fault distance equation is presented. Also, the algorithm for fault distance estimation is described.

In part IV, the test bench used for experimentation is described, also the R, L, C, G experimental parameters estimation and a frequency band selection was made. Then, in part V the results and performance evaluation of the algorithm implemented on MATLAB for many faults distances tested experimentally are displayed. Finally, the conclusion and future works are presented in VI.

II. ELECTRIC LINE MODELIZATION

A. Arc fault overview and classification

An electric arc fault is generated when a gaseous plasma cloud is present between solid conductors [19]. It can be represented by a variable random impedance across the time. It due to the evaporation process, the electrode material combustion and the magnetic field generated by the arc current itself [20]. The arc faults can be classified into two types: serial and parallel (see figures 1a and 1b).

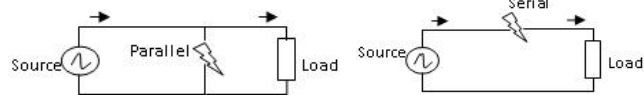


Figure 1a. Serial arc fault.

Figure 1b. Parallel arc fault.

B. Electric line modelization

A transmission line length “d” in the permanent sinusoidal regime under a normal operation is represented by a distributed parameter model [21] represented in figure 2.

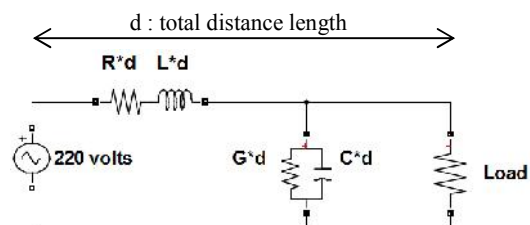


Figure 2. Transmission line model (normal operation).

The parameters R, L, C and G correspond to: the resistance, inductance, capacitance and conductance per meter. When a serial arc fault event happen to some distance “x” from the source. The arc fault represented by a random impedance, splits the transmission line into two parts. In this way, the line is modeled by using unknown impedance parameters (Z_s and

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Zp) that depend on the fault distance (see figure 3).

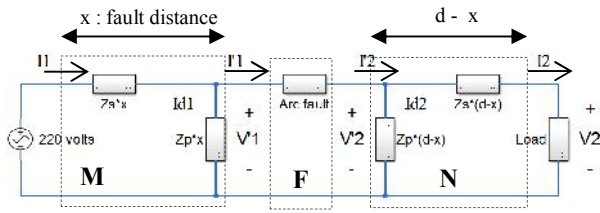


Figure 3. Transmission line model (fault operation).

Likewise, the circuitual model of the transmission line under a serial arc fault can be expressed by three quadripoles connected in cascade [22]. It allows describing the dynamic of the system in a simple way (figure 4).

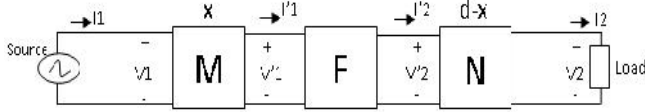


Figure 4. Quadripole representation of a line under a serial arc fault .

The matrix equations for each block are showed in matrix equations (1), (2), (3) and also (4):

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = M \begin{bmatrix} V_1' \\ I_1' \end{bmatrix} \quad (1) \quad \begin{bmatrix} V_1' \\ I_1' \end{bmatrix} = F \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} V_2 \\ I_2 \end{bmatrix} = N \begin{bmatrix} V_2' \\ I_2' \end{bmatrix} \quad (3) \quad \begin{bmatrix} V_1' \\ I_1' \end{bmatrix} = M^{-1} \begin{bmatrix} V_1 \\ I_1 \end{bmatrix} \quad (4)$$

where:

$$M = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} = \begin{bmatrix} \left(1 + \frac{Z_s}{Z_p}\right) & Z_s * x \\ \frac{1}{Z_p * x} & 1 \end{bmatrix}$$

$$F = \begin{bmatrix} 1 & Z_{arc} \\ 0 & 1 \end{bmatrix}$$

$$N = \begin{bmatrix} N_{11} & N_{12} \\ N_{21} & N_{22} \end{bmatrix} = \begin{bmatrix} 1 & Z_s * (d-x) \\ \frac{1}{Z_p * (d-x)} & \left(1 + \frac{Z_s}{Z_p}\right) \end{bmatrix}$$

F depends on unknown fault impedance Z_{arc} . Equation (3) allows us to estimate V_2' and I_2' values at any point of the line using recorded signals V_2 and I_2 . We can obtain a similar approximation for V_1' and I_1' by inverting matrix M presented in (1) to obtain (4).

III. FAULT LOCATION ALGORITHM

The input and output values of F are estimated by using equations (3) and (4). Then, we can establish the following rules: $I_1' - I_2' \approx 0$ and $V_1' - V_2' > 0$. For convenience, we choose the first rule, because currents must have very similar values at the fault point. The currents' difference can be expressed by the equation (5).

$$I_1' - I_2' = M_{21}^{-1} * V_1 + M_{22}^{-1} * I_1 - N_{21} * V_2 - N_{22} * I_2 \quad (5)$$

This equation is the fundamental pillar of our algorithm. Making a progressive variation of x (embedded in M and N), it is possible to find a minimum value ($I_1' - I_2' \approx 0$) which corresponds the fault distance estimation. In this context, the fault location algorithm is described by the following steps:

1. Data register (V_1, V_2, I_1, I_2), when a serial arc fault is being generated,
2. Applying discrete fast Fourier transform (DFFT) (frequency domain transformation): $|DFFT[V_1]|$, $|DFFT[V_2]|$, $|DFFT[I_1]|$ and $|DFFT[I_2]|$,
3. Selection of "x" value and replacing values from step 2 into equation (5),
4. Signal graphic representation in power units (db) of: $S = 20 * \log\left(\left| \frac{I_1'}{I_2'} \right| - \left| \frac{I_2'}{I_1'} \right| \right)$
5. Repetition of steps 3 and 4 (number of repetition determined by the user),
6. A frequency band selection to visualize the minimum trend trace of S ,
7. Finding the minimum trend of S ,
8. Fault distance estimation is done using an "x" value that corresponds to a minimum S .

IV. EXPERIMENTAL TEST BENCH AND PARAMETERS SELECTION

The test bench (figure 5) is composed of two 49 m parallel cables, a 47ohm power load resistor and a power supply (220V-50Hz). There are 40 points distributed across the line used for arc faults insertion (carbonized path).

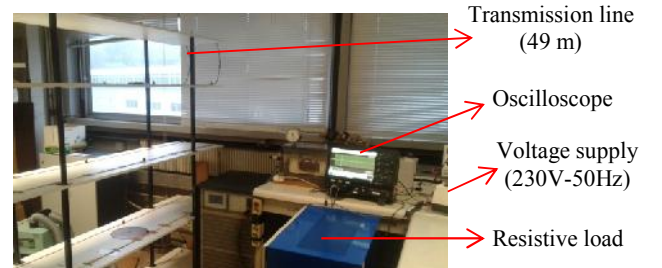


Figure 5. Experimental test bench.

Measurements are done using Lecroy AP015 current probes and TESTEC voltage probes at two points located at the beginning and at the end of the transmission line (figure 5). The signals values are recorded by the oscilloscope (Lecroy HDO 6104) at 1MHz sample rate. In each experimental test, the recorded data was for approximately 2 sec. Arc faults generation follows the UL 1999 and IEC 62606 standard. Each sample is prepared using a single cut in the insulating material of two chunks parallel joined cables (figures 7a and 7b). The carbonized path was obtained using a serial configuration: generator-sample-load.

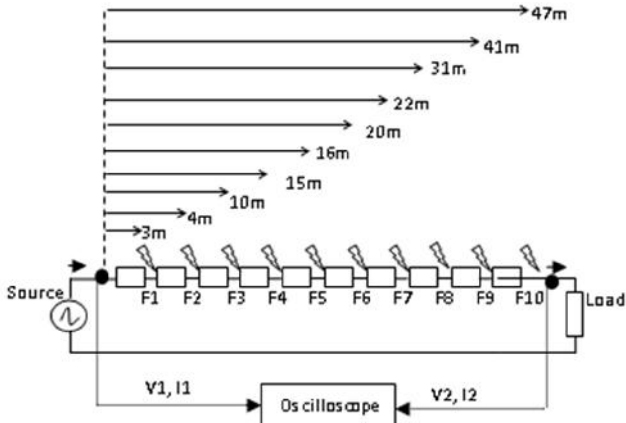


Figure 6. Test of 10 different arc fault position.

The RLCG parameters' estimation per unit meter during a normal operation of the transmission line was made using the LCR HP 4263A meter. In this way, the values are: $L = 0.00069592 \text{ mH/m}$, $R = 15.9643 \text{ m}\Omega / \text{m}$, $G = 0.0017 \mu\text{S/m}$

and $C = 0.0574 \text{ nF/m}$.

The complex behavior of the line under an arc fault event (figure 3), makes difficult the impedances' determination. Hypothetically due to a magnetic field generated by the arc, Z_p becomes a parallel inductance because of the mutual effect between the two lines. In this context, after some previous tests, the values: $Z_s = R + j\omega L$ and $Z_p = (j\omega)l7 * 10^{-10}$ were selected.

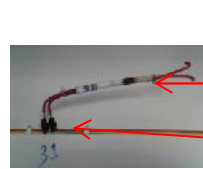


Figure 7a. Carbonized path.

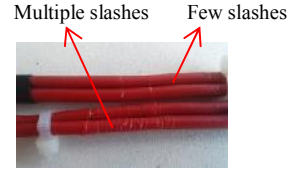


Figure 7b. Sample preparation.

V. EXPERIMENTAL TEST BENCH AND PARAMETERS SELECTION

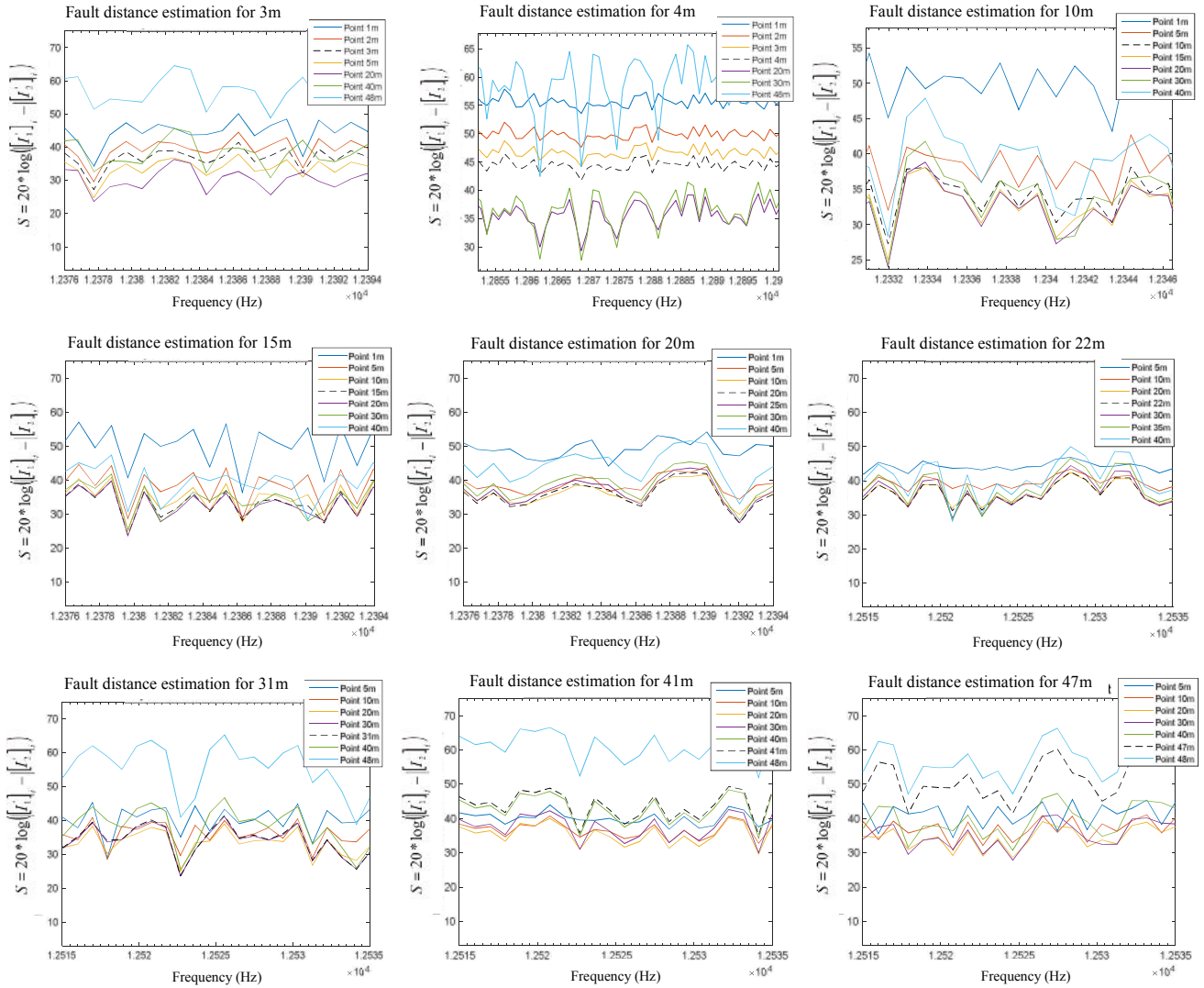


Figure 8. Graphics obtained from the frequency band (fault location algorithm test).

The fault location algorithm was validated by using recorded data from 10 different points following the order: F10, F1, F6, F5, F3, F7, F9, F4, F2, F8 (figure 6). Only one carbonized path was inserted across the line.

For DFDT decomposition a frequency range between 0 to 500kHz was selected. Also, this frequency range was used to obtain vectors Z_s and Z_p that are substituted in equation (5). Likewise, a frequency band (around 1.2kHz) was selected in order to identify visually fault distances (figure 8).

From figure 8, the faults distances estimated are pointed by intermittent black borders. The performance of the fault location algorithm developed in this work shows good estimations in points located between 15 m to 31 m. However, points located close to the source or load cannot be estimated in a good way. Figure 9, presents a trust zone in which it is possible to estimate a serial arc fault.

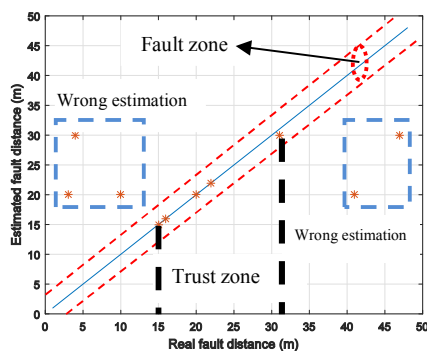


Figure 9. Graphic representation of the trust zone.

VI. CONCLUSION

This work uses an approach model to describe the dynamic of the experimental transmission line under a serial arc fault condition. The model generates a fundamental equation used in an algorithm for the fault distance estimation. The fault distance estimation is achieved making a good frequency band selection of S in order to see its minimum trend. It allows us to find the fault distance (“x” distance value used for minimum S). The results showed the performance of a fault location algorithm during experimental tests. In this context, we established a trust zone in which it is possible to estimate fault distances with a good performance. Future works will focus to improve the model of the line under a serial arc fault. It will allow expanding the trusted zone and consequently to improve the algorithm’s performance.

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