Electrical Power and Energy Systems 80 (2016) 347–355

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Arc fault location: A nonlinear time varying fault model and frequency domain parameter estimation approach

Renato G. Ferraz [a], Leonardo U. Iurinic [b], André D. Filomena [b,c], Daniel S. Gazzana [b], Arturo S. Bretas [d,*]

[a] Exact Sciences and Technology Center, University of Caxias do Sul, Av. Francisco Getúlio Vargas, 1130, 950170-560 Caxias do Sul, RS, Brazil
[b] Department of Electrical Engineering, Federal University of Rio Grande do Sul, Av. Osvaldo Aranha, 103, 90035-190 Porto Alegre, RS, Brazil
[c] Companhia Estadual de Energia Elétrica – CEEE-GT, Av. Ipiranga 8500, 91530-000 Porto Alegre, RS, Brazil
[d] Department of Electrical and Computer Engineering, University of Florida, 1064 Center Drive, 32611-6130 Gainesville, FL, USA

ARTICLE INFO

Article history:
Received 3 September 2015
Received in revised form 15 January 2016
Accepted 4 February 2016
Available online 17 February 2016

Keywords:
Fault location
Parameter estimation
Nonlinear arcing faults
Non-permanent faults
Frequency domain analysis
Synchronized measurements

ABSTRACT

In this paper a frequency domain formulation for nonlinear arcing fault location is presented. The proposed fault location formulation uses as input data first cycles after the fault inception voltages and currents. The formulation is based on circuit analysis and a parameter estimation method. To consider the main characteristics of nonlinear arcing faults, a time varying resistance embedded in a nonlinear model is proposed and used. The formulation is developed for the case of the most frequent single line-to-ground faults using phase components. The effects of fault inception angle, time-varying series resistance, source impedance, load flow, sampling frequency and others factors are investigated and analyzed. This new approach was successfully tested through computer simulation and real data obtained from a Southern Brazilian Energy Utility. The proposed method was developed as dedicated software and is currently used by CEEE-GT.

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Introduction

Transmission lines are used to transmit electric power over long distances and are naturally exposed to severe weather conditions, especially overhead lines. Such conditions are highly favorable to fault occurrence. Statistics show that between 70% and 90% of faults on overhead lines are nonpermanent (or transient), and present arcing. More than 90% of these faults are single line-to-ground [1,2]. Arcing is the main characteristic of these faults, and is the result of poor contact between an energized conductor and the ground or a grounded object [3].

In the last decades, great efforts have been made to improve the transmission system's reliability, security and power quality. For this purpose, protection schemes and fault detection/location techniques have been proposed and implemented. An accurate fault location algorithm improves the power system's reliability, security and power quality by reducing the interruption time caused by a fault [4]. In this aspect impedance-based fault location methods are widely used due to its simplicity and low implementation cost [5].

Several works have been presented and published based on the impedance-based fault location approach for power systems [6,7]. Nevertheless, impedance-based techniques for nonlinear arcing faults (NAF), as high impedance faults (HIF/NHIF), using a frequency domain approach are relatively underexplored [2,8–10]. In [2,8,9], arcing fault recognition and fault distance estimation are developed. From the estimated arc voltage amplitude a decision can be made as to whether the fault is permanent or transient. Nevertheless, several NAF characteristics, as the time-varying behavior, are not considered in these works. The technique presented in [10] uses the zero-sequence current (applied to ideally transposed lines) from both terminals and source impedance data for line-to-ground NHIF formulation. However, in the cases of non-transposed lines, the symmetrical component method is not suitable. Furthermore, the source impedances are dynamic and difficult to estimate in real time.

NAF present some uncommon fault characteristics [11] that are not considered by current state-of-the-art impedance based formulations hindering their performance. Such fault characteristics must be addressed and considered during problem formulation. In this sense, time-varying, nonsymmetrical and nonlinear characteristics must be considered in Impedance based formulations [12].

In this paper, an impedance-based fault location formulation developed in frequency domain and phase components that considers NAF characteristics is proposed. The proposed formulation

* Corresponding author. Tel.: +1 352 392 4949.
E-mail addresses: rgferraz@ucs.br (R.G. Ferraz), uiurinic@ece.ufrgs.br (L.U. Iurinic), andredf@ceee.com.br (A.D. Filomena), dgazzana@ece.ufrgs.br (D.S. Gazzana), arturo@ece.ufl.edu (A.S. Bretas).

http://dx.doi.org/10.1016/j.ijepes.2016.02.003
0142-0615/Published by Elsevier Ltd.

considers a parameter estimation approach, based on a least square method (LSM) and synchronized phasors measurements obtained at both line terminals. Still, the proposed approach uses as input data only the first cycles after the fault inception voltages and currents.

The proposed formulation contributes to the state-of-the-art impedance based fault location formulations explicitly by considering three main NAF characteristics: time-varying, nonsymmetrical and nonlinear characteristics. Still, the proposed approach can be used for fault location of permanent and nonpermanent faults. On the last, as currently used on CEEE-GT, the formulation enables preventive maintenance, as the great majority of nonpermanent faults develop into permanent faults.

The remainder of this paper is organized as follows. The modeling of NAF with a time-varying series resistance is presented in section ‘Modeling of NAF’. Section ‘Proposed NAF formulation’ presents the proposed fault location formulation. Section ‘Results and algorithm evaluation’ presents a case study with simulated and real life data. Conclusions are presented in section ‘Conclusion’.

Modeling of NAF

NAF, as HIF, is a special fault class type that appears, for example, when an energized conductor makes electrical contact with a highly resistive surface. The main characteristics of these faults are: fault current with a very erratic waveform, arcing [3], buildup, shoulder, nonlinearity, and asymmetry [11]. The NAF model used in this paper was based on the work of [12], where the arc was modeled using two DC sources, V_p and V_n, connected antiparallel by means of two diodes. The second and third harmonic currents are presented as function of $\Delta V = V_n - V_p$ and $\tan\theta = X_f/R$. In this work, it is proposed a slight modification of the model presented by [12]. This modification comprises the constant R value being replaced by a time-varying series resistance $R_f(t)$. This allows the correct representation of the buildup and shoulder characteristics. Fig. 1(a) depicts the NAF used and Fig. 1(b) shows the typical fault current with a time-varying series resistance embedded in the nonlinear model.

The parameters of the NAF model presented in Fig. 1(a), V_p, V_n, X_f and $R_f(t)$, depend on the characteristics of the contact surface of the faulted point, such as porosity, humidity, density and composition [13]. In this work the proposed formulation performance is accessed, between others, with simulated NAF having different contact surfaces, as: local soil, tree, sand, asphalt, and grass. As an example, illustrations of such fault current behavior for each of these cases are presented in Fig. 2.

The time-varying behavior of $R_f(t)$ can be approximated by a polynomial function:

$$R_f(t) = \begin{cases} a_n\, t^n + a_{n-1}\, t^{n-1} + \cdots + a_1\, t + a_0, & \text{for } t_{fi} \leqslant t \leqslant t_{ss} \\ a_0, & \text{for } t > t_{ss} \end{cases} \qquad (1)$$

where t_{fi} is the instant of the fault inception and t_{ss} is the instant at which $R_f(t)$ reaches a steady state.

This procedure was first presented in [13], where a HIF modeling process is obtained through field tests with several contact surfaces. The $R_f(t)$ value for NAF on local soil and a tree were estimated using synchronized measurements of a real fault case that occurred on a 230 kV transmission line in southern Brazil. The other values for $R_f(t)$ are modified versions from those presented in [13]. These modifications were made in order to obtain similar time duration for the build-up phenomenon, in comparison with the first two cases. V_p, V_n, X_f were adjusted in order to approximate the behavior of the local soil curve. All values used in simulations are presented in Table 1 of the Appendix.

Proposed NAF formulation

The main idea of the proposed approach is the obtaining of an overdetermined linear system. The equations are derived by circuit analysis considering several synchronized voltage and current phasors estimation at both ends of the transmission line during the fault period. The equations developed constitute an overdetermined linear system that is solved using the LSM in order to estimate the fault distance. In the following the proposed formulation is derived.

Faulted transmission line

The fault location problem in transmission lines can be described by the single-line diagram illustrated in Fig. 3 for a phase-to-ground NAF/NHIF.

In Fig. 1, the following notations are adopted:

- $\boldsymbol{V}_S$ vector of phase voltages at bus S (V);
- $\boldsymbol{V}_R$ vector of phase voltages at bus R (V);
- $\boldsymbol{V}_f$ vector of phase voltages at the fault point (V);
- $\boldsymbol{I}_S$ vector of line currents at bus S (A);
- $\boldsymbol{I}_R$ vector of line currents at bus R (A);
- $\boldsymbol{I}_f$ vector of fault currents at the fault point (A);
- $\boldsymbol{Z}_l$ series line impedance matrix (Ω/km);
- $\boldsymbol{Z}_S$ source impedance matrix at bus S (Ω);

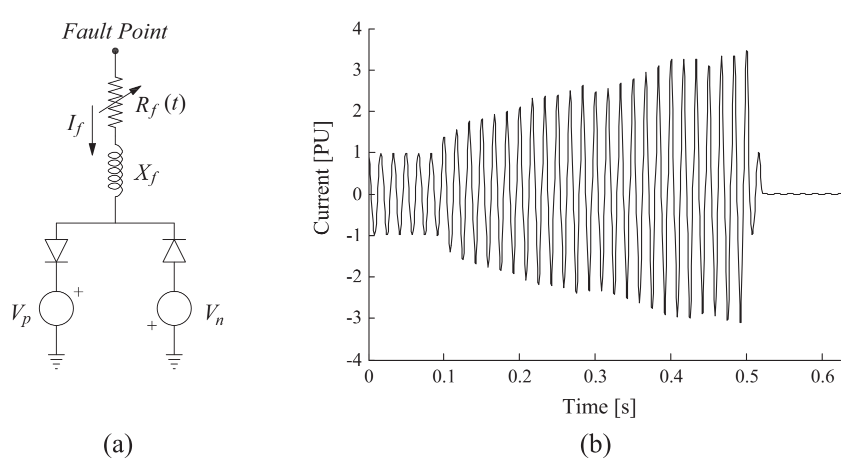

Fig. 1. (a) NAF model. (b) Typical current waveform at the relay bus for a single line-to-ground NAF.