Retardation in the Service of Real Time Fault Detection and the Difference Between Distributed and Lumped Fault Models

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Abstract

A new method for short circuit fault detection is proposed based on instantaneous voltage measurement and its derivatives. Faults are described in terms of lumped fault models and also by distributed models using the telegraph equations. Those equations are used to derive a transmission line transfer function and an exact analytical description of the short circuit signal propagating in the transmission line is obtained. The analytical solution was verified by numerical simulations.

1 Introduction

The primary focus of this article is to locate transmission line faults using voltage and current waveforms generated during the creation of the faults [1]. Power transmission lines have a broad range of faults. These fault classifications appear in various previous articles [1, 2, 3, 4, 5, 6, 7, 8]. There are several approaches to fault allocation algorithms, including various approaches regarding measurements and data processing and their proposed applications. A bridge circuit method [9] employs an adjustable impedance to calculate the location of the fault. M. N. Alam et al. [10] presents a method based on surface electromagnetic waves propagating along a transmission line. In M. Aldeen and F. Crusca's study [11], the faults are modelled as unknown inputs, decoupled from the state and output measurements through coordinate transformations, and then estimated via the use of the observer theory. The article by Qais Alsafasfeh et al. [12] presents a method that integrates the symmetrical components technique with principal component analysis (PCA) for fault classification and detection. In another research [13], Petri nets were used to obtain the modeling and location detection of faults in power systems. Another widely used method is that of wavelet transform analysis [14, 15, 16, 17].

Our method is based on the difference between the time it takes the signal generated by the fault to reach two sensors as depicted in figure 1. The

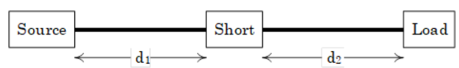

Figure 1: Transmission line with a short

total distance between the source and the load is: $d = d_1 + d_2$. Hence, the signal formed due to the short at t_0 reaches the sensors at the source and the load at t_1 and t_2, respectively. Such that: $v(t_1 - t_0) = d_1; \quad v(t_2 - t_0) = d_2$, v is the signal propagation velocity. Defining the time difference: $\Delta t \equiv t_2 - t_1$, the distance to and from the source to the short may be written as follows: $d_1 = \frac{1}{2}(d - v\Delta t)$. If the required distance measurement precision is of a 1 meter order, then the time measurement sampling resolution should be $\Delta t_{\min} = \frac{2}{v} \cong \frac{2}{3}10^{-8}$ sec $\cong 6$ $[ns]$. In this paper, we restrict the study to the case of a two-wire power line. In the proposed technique, instantaneous voltage or current measurement at detectors located along the line and its derivatives are used to determine fault detection and allocation. We discuss two types of fault models: lumped and distritbuted. While the first class of models is useful for understanding the general characteristics of faults such as short currents it is useless in describing fault propagation. For distritbuted models we use the telegraph equations to find the transmission line transfer characteristics. The analytical and numerical solutions show a high level of conformity with the experimental measurements and data processing conducted in the laboratory. The developed algorithm enables the establishment of the fault location with an accuracy of $\pm 0.005\%$. This accuracy is significantly better than various methods mentioned in the previous literature. The structure of this paper is as follows: first we discuss two types of lumped models in which in the first case we neglect line inductance leading to simple algebraic equation which are easily solved and in the second case we take into account inductance which leads to differential equations which we solve numerically. Then we introduce the lumped model and solve it using frequency domain methods. Finally we mention briefly the experimental results.

2 Lumped models of a Fault

Let us consider a simple circuit as described in figure 2. The short-circuit

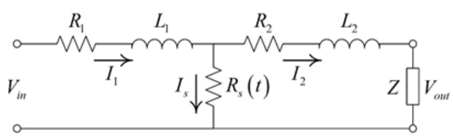

Figure 2: Short circuit example

resistance is assumed to behave exponentially:

$$R_S(t) = R_{S0} e^{-\frac{t}{\tau_S}} \tag{1}$$

In which R_{S0} is a very large number signifying the proper state of the system and τ_S specifies the time it takes the short to develop enabling current transfer between the lines that do not pass through the load. The equations connecting voltages and currents in the circuit are given below:

$$\begin{array}{c} V_{in}\left(t\right) = R_1 I_1\left(t\right) + L_1 \frac{dI_1(t)}{dt} + V_S\left(t\right) \\ V_S\left(t\right) = R_2 I_2\left(t\right) + L_2 \frac{dI_2(t)}{dt} + V_{out}\left(t\right) \end{array} \tag{2}$$

We assume a transmission line is a two-wire copper cable; each wire has a diameter d ,and the distance between them is D. The total cable length is l. Values used in our concrete example are concentrated in table 1. The

Table 1: Two-wire cable parameters

Parameter	Value	Unit
σ_c(Copper)	$5.96 \cdot 10^7$	S/m
d	0.06	m
D	2	m
l	1000	m

surface resistance in $[\Omega]$ may be written as follows:

$$R_{Surface} = \sqrt{\frac{\omega\mu_c}{2\sigma_c}} = \sqrt{\frac{\pi f \mu_c}{\sigma_c}} \tag{3}$$

Hence, the resistance per unit length $[\Omega/m]$can be written as:

$$R = 2\frac{R_{surface}}{2\pi\frac{d}{2}} = 2\frac{R_{surface}}{\pi d} \tag{4}$$

The values used for the cable description example appear in table 2. We

Table 2: Two-wire cable resistance

Parameter	Value	Unit
$\mu = \mu_c$	$4\pi \cdot 10^{-7}$	H/m
f	50	Hz
$R_{surface} = \sqrt{\frac{\pi f \mu_c}{\sigma_c}}$	$1.82 \cdot 10^{-6}$	Ω
$R = 2\frac{R_{surface}}{\pi d}$	$1.93 \cdot 10^{-5}$	$\frac{\Omega}{m}$

assume a short at a distance l_1 from the input. We further assume a characteristic time $\tau_S = 10 \div 100$ $[ns]$ which in reality depends on conditions and geometry of the short circuit region. The short circuit resistance at $t = 0$ represents the region's air resistance. The parameters related to the short are concentrated in table 3. The short resistance $R_S(t)$ is shown in figure 3.

Table 3: Short circuit parameters

Parameter	Value	Unit
l_1	300	m
$l_2 = l - l_1$	700	m
τ_S	100	Nano-Second
ρ_{S0} (Air)	$1.3 \cdot 10^{16}$	$\Omega\, m$
$\mathrm{l_S}$	0.1	m
A_S	0.0004	m^2
$R_{S0} = \frac{\rho_{S0} l_S}{A_S}$	$3.25 \cdot 10^{18}$	Ω

The transmission line resistances and the load impedance are described in table 4. The input voltage is assumed to be of the form $V_{in}(t) = A_0 \cos(\omega \cdot t)$, where $A_0 = 220$ $[V]$, $\omega = 2\pi f = 100\pi$ $[rad/s]$.

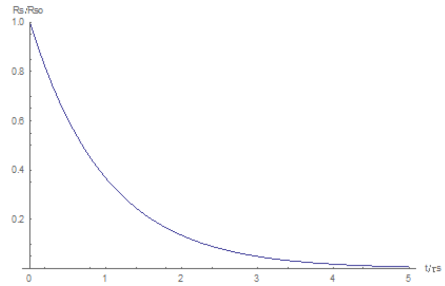

Figure 3: Short circuit resistance

Table 4: Transmission line resistance and the load impedance

Parameter	Value	Unit
$R_1 = R \cdot l_1$	0.00579	Ω
$R_2 = R \cdot l_2$	0.0135	Ω
$R_T = R_1 + R_2$	0.0193095	Ω
Z	15.625	Ω

2.1 The Case of Negligible Inductance

Let us ignore the inductance, this enables an algebraic calculation of the currents as follows:

$$\begin{aligned} I_1(t) &= \frac{Z+R_2+R_S(t)}{R_1\cdot[Z+R_2+R_S(t)]+R_S(t)\cdot(Z+R_2)} \cdot V_{in}(t) \\ I_2(t) &= \frac{R_S(t)}{R_1\cdot[Z+R_2+R_S(t)]+R_S(t)\cdot(Z+R_2)} \cdot V_{in}(t) \\ I_S(t) &= \frac{Z+R_2}{R_1\cdot[Z+R_2+R_S(t)]+R_S(t)\cdot(Z+R_2)} \cdot V_{in}(t) \end{aligned} \quad (5)$$

The calculation results are given in the following figures. The source current before (figure 4) and after (figure 5) the short formation time is described in figures 4 and 5. A pulse shape can easily be found using the source current derivative (figure 6). The figures demonstrated a dramatic change in the source current that are easily manifested in the current derivative.

2.2 The Effect of Inductance

In this model, the transmission line inductance is no longer neglected. Therefore equations 1 become coupled differential equations that can only be solved numerically. The two-wire cable induction can be calculated and is given in Table 5. The current before the formation of the short is given, as

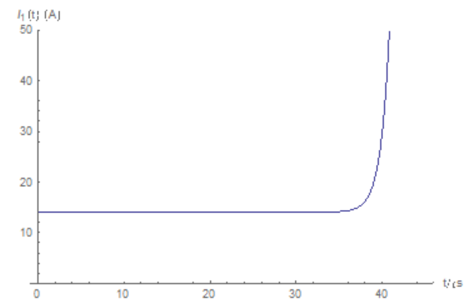

Figure 4: Source current before the short formation

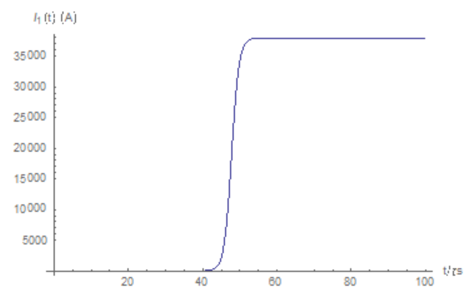

Figure 5: Source current after the short formation

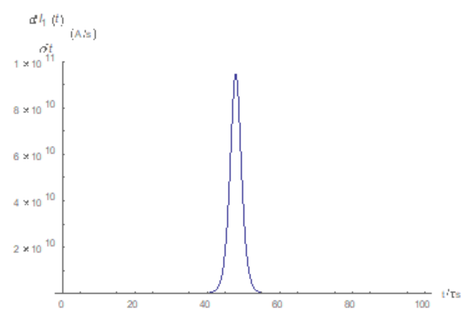

Figure 6: Source current derivative

follows:

$$I_{10}\left(t\right) = I_{20}\left(t\right) = \frac{\mathrm{A_0}\cdot\mathrm{A_t}}{\mathrm{Z}+\mathrm{R_T}}\cdot\cos[\omega\cdot\mathrm{t}+\varphi_\mathrm{t}] \tag{6}$$

where: $A_t \equiv \frac{1}{\sqrt{1+(\omega\cdot\tau_p)^2}}$ $\varphi_t \equiv -\arctan[\omega\cdot\tau_p]$,$\tau_p \equiv \frac{\mathrm{L_T}}{\mathrm{Z}}$. This current is depicted in figure 7. The model's numerical solution results for the source current are demonstrated in the figure 8 (right after the short formation). In

Table 5: Transmission line inductance

Parameter	Value	Unit
$L = \frac{\mu}{\pi} ar\cosh\left(\frac{D}{d}\right)$	$1.68 \cdot 10^{-6}$	$\frac{H}{m}$
$L_1 = L \cdot l_1$	0.000503938	H
$L_2 = L \cdot l_2$	0.00117585	H
$L_T = L_1 + L_2$	0.00167979	H

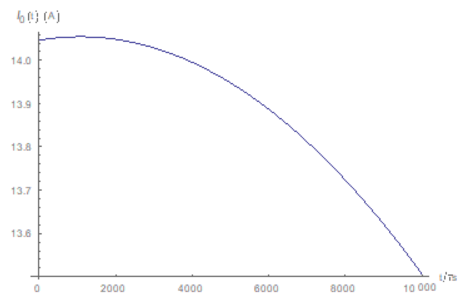

Figure 7: The initial current

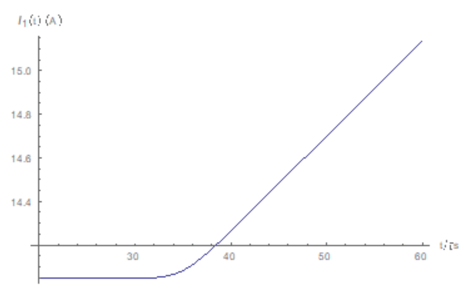

Figure 8: Source current right after the short formation

the previous model, the derivative had a pulse shape this is not the case in the current model (figure 9). However, the current second derivative (figure 10) has a pulse shape.

3 Distributed Model

Until now, we have ignored the signal propagation in the circuit and assumed that the changes in the voltage and the current occur immediately and simultaneously everywhere. This assumption is not compatible with the

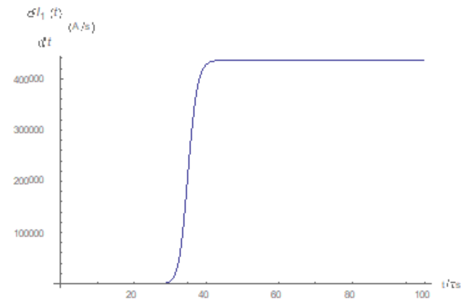

Figure 9: The source current derivative.

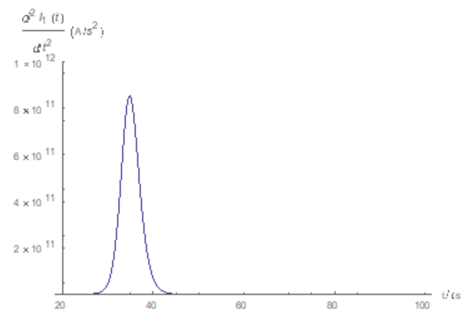

Figure 10: The source current second derivative

theory of special relativity, which says that any signal propagates with a finite velocity smaller than the speed of light in a vacuum. To describe this behavior, we use the TEM transmission line propagation model [22], based on figure 11. Here G is the conductance and C is the capacitance, per unit

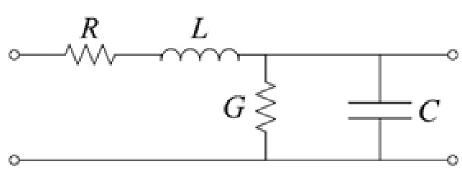

Figure 11: Transmission line structure

length. The equations that describe the voltage and the current dependence are as follows:

$$\begin{array}{l} \frac{\partial V(x,t)}{\partial x} = -RI - L\frac{\partial I(x,t)}{\partial t} \\ \frac{\partial I(x,t)}{\partial x} = -GV - C\frac{\partial V(x,t)}{\partial t} \end{array} \quad (7)$$

Which, in the frequency domain, take the form:

$$\begin{aligned}\frac{\partial V(x,\omega)}{\partial x} &= -\left(R+i\omega L\right) I\left(x,\omega\right)\\ \frac{\partial I(x,\omega)}{\partial x} &= -\left(GV+i\omega C\right) V\left(x,\omega\right)\end{aligned} \tag{8}$$

Combining these equations, one can write separate equations for the voltage and current:

$$\begin{aligned}\frac{\partial^2 V(x,\omega)}{\partial x^2} &= \gamma^2 V\left(x,\omega\right)\\ \frac{\partial^2 I(x,\omega)}{\partial x^2} &= \gamma^2 I\left(x,\omega\right)\end{aligned} \tag{9}$$

where we define: $\gamma \equiv \sqrt{\left(R+i\omega L\right)\left(G+i\omega C\right)}$. These equations have a solution of the form:

$$\begin{aligned}V\left(x,\omega\right) &= V^{(+)}\left(\omega\right)e^{-\gamma x} + V^{(-)}\left(\omega\right)e^{\gamma x}\\ I\left(x,\omega\right) &= \tfrac{1}{Z_0}\left(V^{(+)}\left(\omega\right)e^{-\gamma x} - V^{(-)}\left(\omega\right)e^{\gamma x}\right)\end{aligned} \tag{10}$$

The functions $V^{(\pm)}\left(\omega\right)$ are derived from the initial conditions. The impedance Z_0 is defined as follows: $Z_0 \equiv \sqrt{\frac{R+i\omega L}{G+i\omega C}}$. In the case where the resistivity and the leakage admittance are small enough: $R << \omega L, G << \omega C$, they can be neglected and the approximated impedance takes the form: $Z_0 \cong \sqrt{\frac{L}{C}}$. Hence: $\mathrm{Re}\left(\gamma\right) \approx \frac{\sqrt{LC}}{2}\left(\frac{R}{L}+\frac{G}{C}\right)$, $\mathrm{Im}\left(\gamma\right) \approx \omega\sqrt{LC}$. Using this approximation the voltage along the transmission line is as follows:

$$V\left(x,t\right) \approx V_{in}\left(t-\sqrt{LC}x\right)\exp\left(-\frac{\sqrt{LC}}{2}\left(\frac{R}{L}+\frac{G}{C}\right)x\right) \tag{11}$$

This describes a decaying signal propagating with a velocity $v = \frac{1}{\sqrt{LC}}$.

4 Conclusions and Summary

Signal propagation, due to a short circuit fault in a two-wire transmission line system, shows that the short can be detected either by current measurements. By measuring the current derivatives, the short can be detected either on the source or the load side. In order to achieve a high accuracy level in determining the location of the short, a sampling rate in the order of the GHz frequency range should be used. More Detailed theoretical results and comparison to experiment will be given in a comprehensive paper that will follow.

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