Estimation of the Zero-Sequence Impedance of Undergrounds Cables for Single-Phase Fault Location in Distribution Systems

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1. Introduction

This paper focus on the problem of locating single-phase faults in mixed distribution electric systems, with overhead lines and underground cables, using voltage and current measurements at the sending-end and sequence model networks. Since calculating series impedance for underground cables is not as simple as in the case of overhead lines, the paper proposes a methodology to obtain an estimation of zero-sequence impedance of underground cables starting from previous single-faults occurred in the system.

Keywords: Power quality, voltage sags, underground cable, fault location.

2. Introduction

Traditionally, fault location techniques have been developed for transmission electric lines due to the impact that faults would have on these kinds of lines. More recently, distribution lines have been taken more into account due to the improvement in the quality of power supply, derived from operating in a deregulated environment and the high competition between companies. Due to the growing interest in power quality, digital recorders that capture power quality phenomena have become an important tool, so measurements of voltage and current before and during the fault are easily available and suitable to be used to estimate where the origin of the fault is located.

In literature, different methods for estimating the location of distribution line faults are described. One of these methods uses the fundamental frequency voltages and currents measured at the origin terminal of the line. It is known as impedance-based method, since it consists of calculating line impedance as seen from the line origin terminal and associating that value directly to a distance to the fault. R. Das describes in [2] the implementation of a fault location methodology based on impedances. For locating single-phase faults, the zero-sequence network is employed and information about the zero-sequence impedance of the line is needed.

Calculating series sequence impedance for underground cables is not as simple as calculating the series impedance of overhead lines [3]. An usual value for zero-sequence impedance of overhead lines is three times the positive-sequence impedance [4] but the zero-sequence impedance of the cable is often difficult to be determined.

The paper proposes a methodology for estimating the zero-sequence of the cable starting from previous faults occurred in the distribution system. Fault voltage and current measurements at the sending-end of the line and analysis of the fault (causes and location are known in that previous cases) are used to obtain a value for the zero-sequence impedance of underground cables, assuming that this data is known for overhead lines. The estimated value is used in new single-phase faults to locate their origin. The methodology is tested with real distribution system and fault data and results are discussed.

3. Fault location algorithm

Impedance-based fault location methods use the line parameters and the measurements of voltages and currents to obtain an estimation of the location of the fault. This estimation can be calculated by comparing the apparent reactance computed by using the faulted phase voltages and currents at one terminal and the modified reactance of the line between this terminal and the location of the fault [2]. The modified reactance between two nodes M and R is computed as

$$X_{\mathrm{MR}}^{m} = X_{1\mathrm{MR}} + \frac{X_{0\mathrm{MR}} - X_{1\mathrm{MR}}}{3} \qquad (1)$$

where, X_{0mr} and X_{1mr} are the zero and positive sequence reactance between nodes M and R, respectively.

If the modified reactance is less than the apparent reactance then the fault is located beyond node R. For a phase-to-ground fault, the apparent reactance is calculated as follows,

$$X_{m1} = \text{Im}\left(\frac{\overline{V}}{\overline{I}}\right) \tag{2}$$

where $\overline{V}$ and $\overline{I}$ are the voltage and current of the faulted phase at the monitored terminal.

4. Estimation of zero-sequence of cables

Electrical parameters in underground cables are different from overhead lines. The shield of a cable use to be connected to ground in different points and the way the shields are connected and its connection resistance determines the path of zero-sequence impedance [5]. Therefore, zero-sequence impedance of cables is often difficult to be determined.

The methodology proposed in this paper is based on the assumption of knowing the location of previous faults occurred in the line. By analyzing those previous faults, for which the location of the fault is known, an estimation of a zero-sequence impedance for cables is calculated. This estimation would be used in case of new faults for calculating its location.

The methodology consist in the next steps:

1) Apparent impedance is calculated from voltage and current registered at the substation during a phase-to-ground fault. Being the location of the fault known, the apparent impedance should be equal to the modified reactance from the substation to the fault.
2) For overhead lines, zero-sequence impedance is considered to be equal to three times the positive-sequence impedance [4].
3) For cables, zero-sequence impedance is considered to be zero.
4) Modified impedance from the substation to the fault is calculated, Eq. (1).
5) The difference between apparent impedance and modified impedance is considered that is due to zero-sequence impedance of cable.
6) An estimation of zero-sequence impedance of cable, Ω/km, is obtained by dividing the previous difference between the length of cable from the substation to the fault.

Several hypothesis have been taking into account in this methodology: a) all the difference between apparent and modified impedance are due to cable; b) the cable has homogeneous characteristics.

5. Case study

The power distribution system used to test the methodology is an actual distribution system owned by the power supplier company ENDESA Distribución. The system has a radial topology and it has a high degree of heterogeneity as a result of the existence of different kind of conductors with different impedance, both overhead and cable lines and lines with different length. The power supplier company has provided complete information about the system and phase-to-ground faults occurred in it (voltage and current registers at the substation and its fault location). Figure 1 shows the registers of voltages and currents for a phase-to-ground faults.

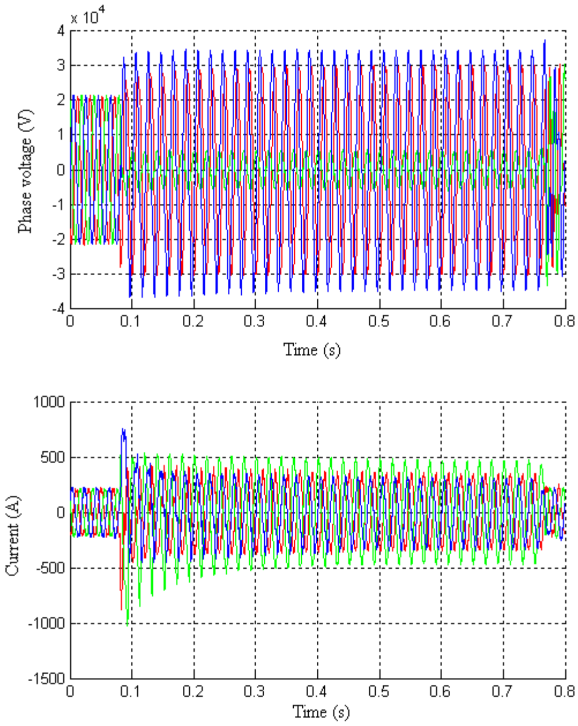

Fig. 1. Phase-to-ground fault registers: voltages and currents.

Table I shows the analysis for a phase-to-ground fault whose location is known. According to the actuation of protections and the operation to find the fault, several registers are obtained from the power quality monitor (registers #1 to #9). Column 'Exact X0' shows, for each register, the value of zero-sequence impedance that should have cable to locate the fault where it really has occurred. From the different values obtained, a mean value of X_0 has calculated. In this case, this mean is nearly to 5.8 (Ω/km). With this value, the error between real fault location and estimated fault location showed in Table I should be very small, as it can be noticed. Due to the radial nature of the line, the fault location algorithm can have more than one solution, since the method is based on the comparison of impedances.

The estimation of X_0 has been tested with other faults to check its accuracy. Table III shows results for several faults occurred in the same line as the previous case. For most of the cases, the error in location the fault were lower than 10 %. But there were cases, such as fault D, with high errors. From the analysis of the waveforms, it was noticed that in fault D voltage in the faulted phase had a waveform very different from the case that was used to do the estimation, Fig. 2. This fact may suggest to use the cycle with a lower distortion during the fault for calculate the voltage phasor (cycle with a waveform close to a sinusoidal wave), for example.

Table I. Analysis of a phase-to-ground fault to estimate X_0

REGISTER	REAL LOCATION (km)	EXACT X_0 (Ω/km)	ESTIMATED LOCATION (km)	ERROR (%)
#1	5.97	6.07	5.98	0.02 %
			5.91	-0.39 %
			5.91	-0.39 %
			5.21	-4.80 %
#2	5.97	5.89	5.98	0.02 %
			5.91	-0.39 %
			5.91	-0.39 %
			5.21	-4.80 %
#3	5.97	5.83	5.98	0.02 %
			5.91	-0.39 %
			5.91	-0.39 %
			5.21	-4.80 %
#4	5.97	5.98	5.98	0.02 %
			5.91	-0.39 %
			5.91	-0.39 %
			5.21	-4.80 %
#5	5.97	5.82	5.98	0.02 %
			5.91	-0.39 %
			5.91	-0.39 %
			5.21	-4.80 %
#6	5.97	5.69	4.98	-6.27 %
			5.21	-4.80 %
#7	5.97	5.59	4.98	-6.27 %
			5.21	-4.80 %
#8	5.97	5.54	4.98	-6.27 %
			4.88	-6.88 %
			5.08	-5.60 %
			5.05	-5.77 %

Table II. Location of phase-to-ground faults

REGISTER	REAL LOCATION (km)	EXACT X_0 (Ω/km)	ESTIMATED LOCATION (km)	ERROR (%)
A #1	12.13	5.02	10.16	-12.38 %
			11.65	-3.06 %
			11.75	-2.40 %
			6.06	-38.14 %
A #2	12.13	4.42	9.91	-13.93 %
			10.79	-8.46 %
			10.79	-8.46 %
			5.42	-42.16 %

Table II. Location of phase-to-ground faults (cont.)

REGISTER	REAL LOCATION (km)	EXACT X_0 (Ω/km)	ESTIMATED LOCATION (km)	ERROR (%)
B #1	13.30	2.9743	11.29	-12.60 %
			11.98	-8.27 %
			12.05	-7.86 %
			11.94	-8.50 %
			7.33	-37.45 %
			7.33	-37.45 %
B #2	13.30	4.7919	13.08	-1.37 %
			13.91	3.83 %
			9.25	-25.42 %
B #3	13.30	5.1294	12.54	-4.74 %
			11.62	-10.53 %
			8.70	-28.85 %
REGISTER	REAL LOCATION (km)	EXACT X_0 (Ω/km)	ESTIMATED LOCATION (km)	ERROR (%)
C #1	5.05	3.5051	0.00	-31.73 %
C #2	5.05	7.3036	6.97	12.03 %
			6.86	11.30 %
			8.17	19.55 %
			5.42	2.29 %
C #3	5.05	7.952	7.76	16.95 %
			8.80	23.50 %
			8.90	24.18 %
			8.17	19.55 %
			5.42	2.29 %
REGISTER	REAL LOCATION (km)	EXACT X_0 (Ω/km)	ESTIMATED LOCATION (km)	ERROR (%)
D #1	12.54	6.2252	13.93	8.67 %
			12.13	-2.57 %
			12.37	-1.06 %
			8.79	-23.59 %
			7.61	-30.96 %
			7.70	-30.43 %
			8.53	-25.19 %
D #2	12.54	4.4845	10.45	-13.15 %
			10.42	-13.30 %
			11.94	-3.76 %
			6.06	-40.71 %
D #3	12.54	4.3595	10.45	-13.15 %
			10.86	-10.59 %
			10.85	-10.61 %
			11.94	-3.76 %
			6.06	-40.71 %
D #4	12.54	4.0267	8.29	-26.67 %
			5.42	-44.73 %

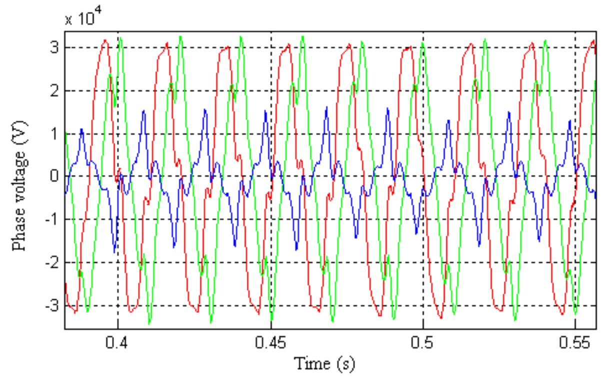

Fig. 2. Phase-to-ground fault registers: voltage waveforms.

6. Conclusion

A methodology for estimating the zero-sequence impedance of cables, in order to be used in fault location algorithms in distribution systems. The methodology is based on the analysis of previous faults, which are well studied and the fault location is known. Although the results are accurate and promising in the analysis of new faults, the error can be high in case of having faults with waveforms signals very different from the documented cases. The waveforms, and the analysis of the type of fault, may suggest new approaches for estimating the impedance.

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