Diagnostics of Low-Voltage Power Cables by Using Broadband Impedance Spectroscopy

Antti Pinomaa, Jero Ahola, Antti Kosonen, and Tero Ahonen
Lappeenranta University of Technology, LUT School of Energy Systems

FLEXe Future Energy System
EPE'2015 ECCE Europe
8-10 September 2015
17th European Conference on Power Electronics and Applications
CICG, Geneva International Conference Centre, Geneva, Switzerland

Abstract

The amount of underground low-voltage cabling will increase in future smart grids to guarantee safe and uninterrupted power distribution. The diagnosis of cable condition and prognosis of the remaining life time will be thus essential functions. In this paper, a broadband impedance-spectroscopy-based cable diagnosis method is researched, and evaluated with laboratory tests. The proposed method is applicable for fault detection and fault locating in low-voltage power cables.

Introduction

- Cables are prone to faults, such as
  - Moisture and water (speed up in aging)
  - Damages in installation
- Cable condition diagnostics essential
  - Faults can cause wide area blackouts
  - Fault locating difficult
- Broadband impedance spectroscopy (BIS)
  - Measurement of broadband impedance response
  - Benefits: cable faults and changes in insulation material can be seen
  - Scanning range adjustable by the selection of frequency band

Input-impedance model of a cable with phase-to-phase fault

- Parameter-adjustable model for possible cable fault types, fault location and severity
- Compare the measured impedance spectrum with the ones produced by the models

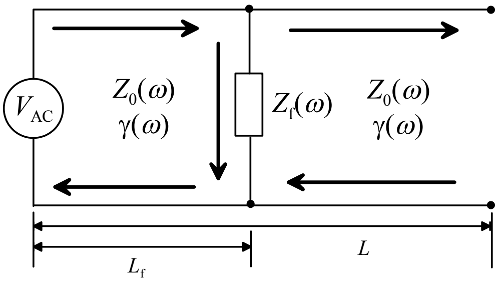

Fig. 1. Open-ended cable with a phase-to-phase fault between L1 and L2 conductors. Reflected and propagated currents are marked with arrows.

$$\boldsymbol{Z}_{\mathrm{cable,oc}}(\omega) = \boldsymbol{Z}_0(\omega)\coth[\boldsymbol{\gamma}(\omega)(L - L_{\mathrm{f}})]$$

- The total load impedance at the cable fault location can be presented with

$$\boldsymbol{Z}_{\mathrm{load}}(\omega) = \frac{\boldsymbol{Z}_{\mathrm{cable,oc}}(\omega)\boldsymbol{Z}_{\mathrm{f}}(\omega)}{\boldsymbol{Z}_{\mathrm{cable,oc}}(\omega) + \boldsymbol{Z}_{\mathrm{f}}(\omega)}$$

- $\boldsymbol{Z}_{\mathrm{in}}$ for the whole system at the signal source

$$\boldsymbol{Z}_{\mathrm{in}}(\omega) = \boldsymbol{Z}_0(\omega)\frac{\boldsymbol{Z}_{\mathrm{load}}(\omega) + \boldsymbol{Z}_0(\omega)\tanh[\boldsymbol{\gamma}(\omega)L_{\mathrm{f}}]}{\boldsymbol{Z}_0(\omega) + \boldsymbol{Z}_{\mathrm{load}}(\omega)\tanh[\boldsymbol{\gamma}(\omega)L_{\mathrm{f}}]}$$

Cable fault diagnosis algorithm

1. Set initial value for the fault impedance $\boldsymbol{Z}_{\mathrm{f}}(\omega)$
2. Divide cable into segments, filter $|\boldsymbol{Z}_{\mathrm{in,meas}}(\omega)|$
3. Adjust fault location $L_{\mathrm{f}} = 0 \ldots L$ in model, and take
4. Correlation between $|\boldsymbol{Z}_{\mathrm{in,meas}}(\omega)|$ & $|\boldsymbol{Z}_{\mathrm{in,model},L_{\mathrm{f}}}(\omega)|$
5. Take FFT from $|\boldsymbol{Z}_{\mathrm{in,meas}}(\omega)|$ healthy & faulty cases
6. High impedance at fault; spikes in FFT (index)
7. FFT for each $|\boldsymbol{Z}_{\mathrm{in,model},L_{\mathrm{f}}}(\omega)|$; L_{f} is the one that gives the highest value at the expected FFT index
8. Estimate fault impedance $\boldsymbol{Z}_{\mathrm{f}}(\omega)$ with

$$E = \frac{1}{N}\sum_{i=0}^{N-1}\left[|\boldsymbol{Z}_{\mathrm{in,model},L_{\mathrm{f}}}(\omega)| - |\boldsymbol{Z}_{\mathrm{in,meas},L_{\mathrm{f}}}(\omega)|\right]^2$$

Laboratory evaluation

- Fault algorithm tested with cables in laboratory setup
- AXMK 4x16 mm^2 and AMCMK 3x16+10 mm^2, both 50 meters long
- Cable sheath fault (phase to phase) at 17 m from other cable end (Case A)
- Faulty part kept under water in a container (for 30h)

Fig.2 Cable sheath removed from the AMCMK cable (left). Both cables installed at a container (right).

Table I: Parameters used for modeling of 50 m AMCMK low-voltage cable in (L1, L2) and (L1, PE) signal couplings, and of 50 m AXMK cable in (L1, L2) coupling.

Signal coupling	Z_0 (Ω)	v_{p}/c_0	l (nH/m)	c (pF/m)
AMCMK (L1, L2)	42	0.535	249	138
AMCMK (L1, PE)	30	0.535	178	191
AXMK (L1, L2)	95	0.740	384	44

$$\alpha(\omega)_{\mathrm{AMCMK}} = 0.5 \cdot 10^{-6} \cdot f^{0.6}$$

$$\alpha(\omega)_{\mathrm{AXMK}} = 0.75 \cdot 10^{-6} \cdot f^{0.5}$$

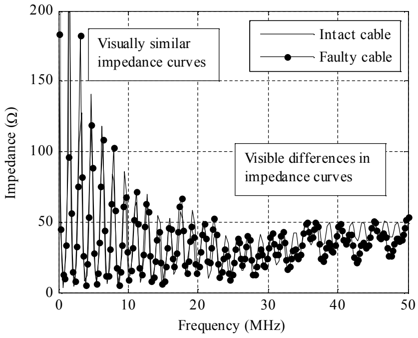

Fig. 3. Input-impedance spectra of healthy and faulty (sheath fault, faulty location of cable kept 30 hours in water) AMCMK 3x16+10 mm^2 cable in (L1, L2) coupling.

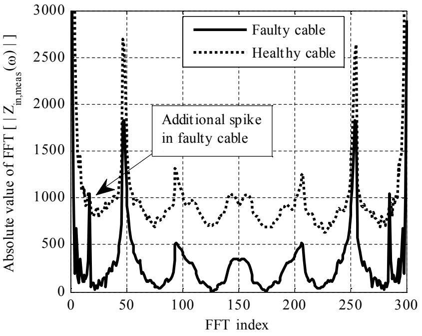

Fig. 4. Absolute value of FFT taken from $|\boldsymbol{Z}_{\mathrm{in,meas}}(\omega)|$ in faulty and healthy AMCMK 3x16+10 mm^2 cable in (L1, L2) coupling.

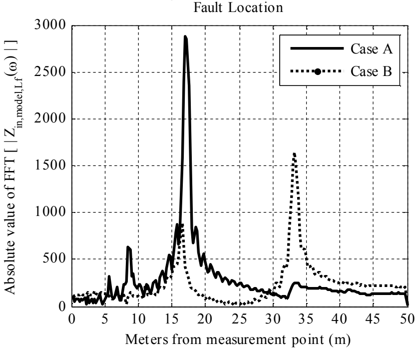

Fig. 5. Fault location estimated with the fault diagnosis algorithm for faulty AMCMK 3x16+10 mm^2 cable in (L1, L2) coupling. Case A and B.

Conclusion

BIS-based cable condition monitoring (off-line) method presented. The proposed fault diagnosis algorithm is able to detect and locate faulty location in range <1m (phase-to-phase fault). Model is parameter adjustable with frequency and range; $|\boldsymbol{Z}_{\mathrm{in,meas}}(\omega)|$ requires filtering. Further studies:

- Include frequency dependency of $\boldsymbol{Z}_{\mathrm{f}}(\omega)$ in modeling
- BIS-based modeling for cables that are terminated to end devices (on-line)
- Extend and test the algorithm for power grids diagnosis
- Implement the monitoring functionality to modern PLC modems (OFDM multicarrier-based technologies)

Open your mind. LUT.
Lappeenranta University of Technology