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State of the art analysis of online fault location on AC cables in underground transmission systems

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Abstract

In this article the state of the art research for online fault location on cross-bonded transmission level cables is presented. The article is focused on the difficulties in using the algorithms developed for OHL-systems and distribution cables directly on cross-bonded transmission cables. Impedance based methods, methods based on solving the line differential equations, methods based on traveling wave methods and methods based on artificial intelligence networks are presented and discussed.

1. Introduction

The transmission grid has up to present time been laid out as an almost purely overhead line (OHL) network except for crossing of water, in densely populated areas and crossing areas of natural beauty. The introduction of transmission voltage level XLPE cables and the increasing political interest in the environmental impact of OHL has resulted in an increasing interest concerning the use of underground cables for the transmission level.

In Denmark, as a leading country, the entire 150 kV and 132 kV transmission network shall be undergrounded during the next 20 years [1]. Higher transmission voltage levels, such as 400 kV transmission lines, will also be undergrounded gradually as more experience is gathered.

In a transmission system based on power cables, it is essential to be able to locate a fault quickly and within a very short and precise distance. An accurate fault location technique will prevent digging up long lengths of cable in order to look for the failure. This will reduce the overall repair time and therefore ensure better overall continuity and reliability of the transmission network.

Until now most research on transmission level fault location methods have been focused on overhead lines. Because of the very different electrical parameters and the use of cross-bonding, the task of locating a cable fault becomes more difficult compared to a fault on an OHL. The methods available for OHL-systems can in general be divided into four categories: impedance based methods, methods based on solving the line differential equations, traveling wave methods, and methods based on fuzzy logic and artificial intelligence. In this paper, the difficulties of using the different OHL-methods directly on cross-bonded cable systems are discussed in more details.

2. Impedance based fault location methods

Impedance based methods are widely adopted for fault location on OHL-systems. A short review of the basic principles is given here for comparison reasons.

The impedance methods are generally divided into one and two terminal methods. The simplest are the one terminal methods where current and voltage measured in the relay circuit are used to calculate the impedance seen from the relay point. In Figure 1 a single line single phase representation of an OHL is seen. In the representation the line shunt capacitance is neglected.

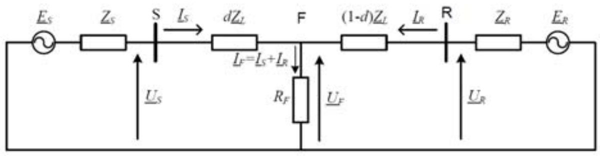

Figure 1 Fault location based on impedance measurement from one end on a single phase circuit.

The fault impedance seen from one end is used to determine the fault location. Because only one end measurements are used, the algorithm is derived using various assumptions depending on the method proposed [2][3]. This makes the algorithms sensitive to the reactance effect, none-transpositions of the line, strong and weak sources, load flow etc.

To overcome some of the difficulties existing for the algorithms where only data is available at one terminal, several authors have proposed the use of either synchronized or unsynchronized data from two terminals. Because two sources of data are available, the difficulties existing for the one terminal methods can be limited or completely disregarded.

3. Fault location algorithm for cross-bonded cables using the singularity of the sheath impedance matrix

One of the general problems using the one or two terminal impedance based method for cross-bonded cable systems is that the series impedance matrix changes at each minor section because of the shift of the cable screen between the tree cables (cross-bonding).

In [4] and [5] (same authors, same method) the authors present an impedance based fault location algorithm that includes the change in series impedance matrix caused by the cross-bonding of the cable screen. These are the only two publications up to date that include the complicated nature of the screen in an impedance based formulation.

The proposed method uses non-linear equations including the distance to fault. These equations describe the voltage drops from the core to the screen based on synchronized measurements of the three phase voltage and currents at both terminals. The equations are arranged about the screen currents which yields the screen impedance matrix. This matrix is singular independent of the fault location. Therefore it has either no or countless many solutions. The fault location algorithm finds the condition that for which a solution exits in order to find the fault location.

The algorithm is tested by means of simulations in ATP on a 4.49 km 154 kV cross-bonded cable with 5 major sections. Each minor section has a different length ranging from 270 m to 330 m. All cable parameters are calculated using the EMTP cable constant subroutine. The cables are laid in flat formation and the Discrete Fourier transform is used to extract the fundamental phasors of the voltage and current.

The authors of the article conclude that the algorithm performs well with a maximum estimation error of 0.2038 %. It is independent of fault resistance and fault inception angle. Based on the results, the authors state that the method is useful for locating fault on cross-bonded cable systems.

3.1 Method discussion

The impedance based methods suffers from several drawbacks both when used for OHL and cable systems [6][7][8][9]. The impedance based algorithms require the three phase voltage and currents measured at one end of the transmission line.

Because these algorithms are derived using several assumptions they are in general sensitive to:

- Line parameters
- Combined effect of fault resistance and load
- Zero-sequence mutual coupling
- Zero-sequence modeling errors
- System non-homogeneity
- Remote or third terminal infeed
- Tapped load with zero-sequence source
- Inaccurate relay and instrument transformers

Some of these issues are solved using two terminal data for the fault location. Still, the method is sensitive to line parameters, zero-sequence modeling errors, mutual coupling, and system non-homogeneity. Furthermore the majority of the algorithms are derived neglecting the shunt capacitance of the line. This is not a valid assumption for power cables of any kind.

For cross-bonded cables the measured fault impedance shows discontinuities at each cross-bonding link point. Figure 2 shows a PSCAD simulation of the magnitude of the fault impedance of a single phase/screen loop on a 150 kV 6 km cross-bonded cable. The cable is divided into 2 major sections with each minor section having a length of 1 km.

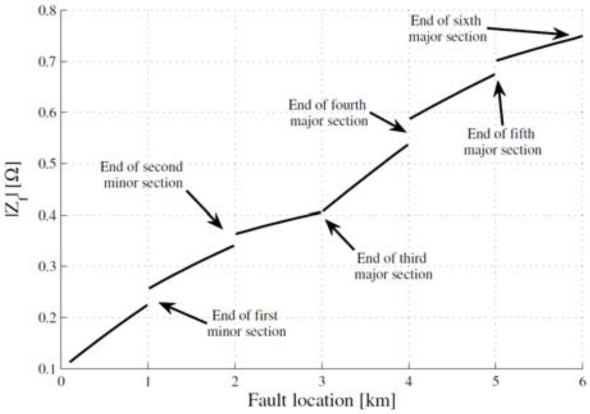

Figure 2 Magnitude of impedance for a single phase-screen fault loop on a 150 kV 6 km cross-bonded cable with 2 major sections and each minor section with an equal length of 1 km.

The discontinuity of the impedance seen from the relay point makes the assumed linear relationship between the fault distance and the impedance used in most algorithms invalid and therefore most of the methods will result in errors if used directly on cross-bonded cables.

Some impedance based methods have been proposed for distribution systems where the capacitive effect of the cables is taken into consideration using an iterative process [10][11][12]. For all methods proposed, the series impedance matrix of the cables is considered constant. These methods are therefore not directly usable for cross-bonded cable systems.

The general approach presented in [4] and [5], where the effect of the cross-bonding is included using the advanced equations describing the behavior of the cable seems the only way to obtain accurate results for impedance based fault location methods. However, for the presented work it is a problem that the grounding resistances between the three short circuited cable screens and ground at the end of each major section are neglected. This will have a strong influence on the zero-sequence impedance and therefore lower the accuracy.

4. Methods based on solving the transmission line differential equations

A large amount of work has been published where fault location is carried out using synchronized phasor measurements from both end of the transmission line - for instance [13][14][15]. The fault location is found by manipulating the differential equation describing the behavior of the voltage and current waves along the line.

A transmission line is divided into two homogenous parts by a fault occurring at an arbitrary location *d* on the line. This is illustrated in Figure 3.

Transmission line equations describing the voltage and current along the line are setup from both ends. The voltage in the fault location is eliminated by combining the two equations and the fault location is found. The method is very robust and independent of the fault resistance.

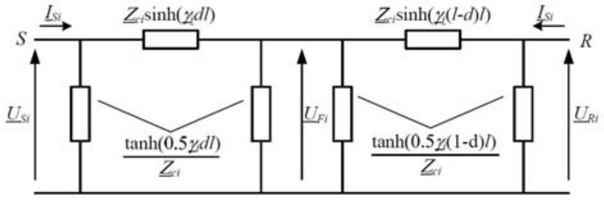

Figure 3 Transmission line divided into two homogenous sections by a fault.

4.1 Method discussion

The two terminal methods are not usable for cross-bonded cables. First of all, simple modal decomposition using Clark's constant transformation matrix will generally lead to inaccurate results when applied to a cable circuit. This is because the modal transformations matrices are strongly frequency dependent [16]. Secondly, the transmission lines are considered homogeneous meaning the series impedance and shunt admittance matrix do not change along the line. The is not the case for a three phase cross-bonded cable system where the series impedance matrix changes each time the screen from one cable is connected to another cables screen (at each minor section). As a third more general limitation, the equations are derived assuming a lossless transmission line. This will lead to errors both for OHL and cables.

5. Traveling wave methods

The idea to analyze traveling waves for fault location on transmission lines was first proposed in 1978 [17]. Different signal processing tools are being used to capture the arrival time of the fault generated traveling waves at the substation busses. One of the tools that has received most attention over the last ten years is the Wavelet Transform. The potential advantages of using this transform in fault location have been recognized by many authors. The work carried out involving fault location on the transmission level, is however mainly focused on overhead lines - for instance [18][19][20]. Actual experience with traveling wave fault location on a 400 kV and 132 kV OHL system is presented in [21]

High frequency methods are also widely adopted for fault location on distribution systems [22][23][24].

The algorithms are, as for the impedance based methods, divided into one and two terminal methods. For cross-bonded cables discontinuity points exists at every cross-bonding. This means that an incoming wave is divided into a forward and a backward traveling wave each time it encounters one of these points. This makes one-terminal algorithm very difficult to use as it needs the two first waves coming directly from the fault location. Another problem for the one terminal method is to distinct between fault that occurs in the first or second half of the cable. This is both the case for OHL and cable systems. The many reflections are not as important for two-terminal algorithms because only the arrival times of the first wave from the fault location at each bus are needed to calculate the fault location.

In 2005 and 2007 two articles were published dealing with the issue of how to discriminate the fault generated traveling waves from the noise in a one ended fault location scheme for cross bonded power cables [25][26]. The one ended scheme is, according to the authors, preferred because of the simple system structure and because the errors associated with the GPS-synchronization are avoided. However in Denmark this problem could be solved using one of the fiber optic cables that are laid along the power cables.

The stationary wavelet transform is used instead of the traditionally used Discrete Wavelet Transform. The stationary wavelet transform uses up-sampling at each level that causes redundancy. This is an advantage for de-noising the signals. The article presents the result of the stationary wavelet transform of the time signals for three different fault resistance values, inception angles and distances. The first level detail is used to locate the fault. The level one detail coefficients are seen in Figure 4 for a single phase to ground fault with an inception angle of 0^0 and fault resistance of 0 Ω.

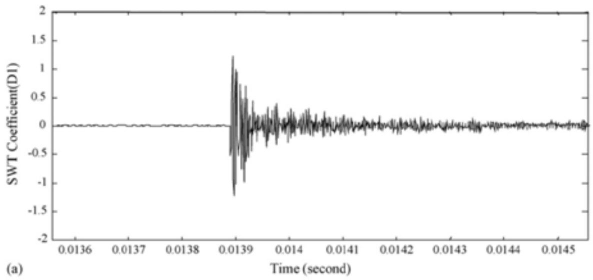

Figure 4 First level detail of the wavelet transformation at 1 km with fault inception angle 0^0 and fault resistance 0 Ω on a 6.3 km cable [26]

Figure 4 shows many spikes at the first detail level because of reflected waves from both the fault point, the other end of the cable and because of cross-bonding (Two spikes are needed for accurate fault location).

A method to remove the noises is presented in the article. The filtering technique was developed for image processing and is presented in [27]. Variation of the wavelet data at adjacent scales is used. In order to implement the filtering algorithm, direct multiplication of the data at adjacent scales is carried out.

In Figure 5 the absolute value of level one detail coefficients are seen after the filtering process proposed. The figure shows that only two spikes are left after the noise is removed. This is the first and the second wave from the fault for a fault located in the first half of the cable. The arrival time of these two waves are directly used to calculate the fault location.

The proposed method is tested by performing simulations on a cross-bonded three phase single core 154 kV cable system with a total length of 6.3 km and varying fault- inception angle and resistance. With the wave velocity known and having the knowledge of in which half part of the cable the fault occurs, the algorithm is tested by several different simulations. The results show that the method works well for fault location estimation on the studied system.

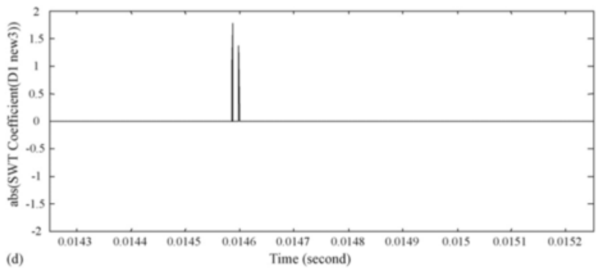

Figure 5 First level detail after filtering process.

The authors conclude that fault location on cross bonded cables is very difficult but possible for one terminal methods if the developed method is used. The method requires that it is known in which half part of the cable the fault occurs and the propagation velocity of the traveling waves. In [28] the work of [26] is continued. GPS-synchronized data from both terminals is used to determine in which half of the cable the fault occurs. This eliminates one problem, but the unknown propagation velocity is still an issue.

5.1. Article discussion

The main problem with the work presented in the article is the use of only simulation data for validation purposes. For a real life system additional noise will be present due to the influence of the measuring equipment [29]. The higher attenuating of the high frequency components in real life systems could also be an issue as the presented method is only validated on a short cable (6.284 km). Also reflections from other parts of the system can be a problem. This is not discussed in the article.

6. Application of artificial intelligence for fault location

Most of the theories developed for power system protection and fault location are based on deterministic evaluation schemes [30]. Generally artificial neural networks (ANN) are used for pattern recognition. Instead of implementing a model of the system the ANN is trained through a number of training cases to recognize a certain behavior. The capability of the ANN of non-linear mapping, parallel processing and learning makes it useful for fault location if the ANN is given the right input and trained in a proper manner [31]. The ANN type of algorithm is especially useful if no explicit solution can be put up for the system (multiended transmission and distribution systems with laterals).

Different ANN's must be used for different types of faults because of the different fault behavior. This means that each ANN must be trained according to the correct type of fault. The typical inputs for an impedance based fault location algorithm using artificial networks are the pre and post voltage and currents at either one or two ends. No work regarding fault location on pure cross-bonded cable systems using artificial intelligence have been published. Only fault location schemes for hybrid systems (combined OHL and cable systems) have been found.

In [32] the article author proposes a fault location scheme for a hybrid line. The scheme is based on Adaptive Network Based Fuzzy Inference system (ANFIS). The proposed algorithm consists of 10 ANFISs; 1 for fault calcification, 1 for selection between faulted section (OHL or cable) and 8 for the accentual fault location (two for each fault type). The article presented an interesting approach for fault location on hybrid systems. Assuming the data used to train the network is accurate, the method can be practically applicable. The algorithm is verified on a single infeed system and could also be implemented in a two terminal system. It could be chosen to give more input parameters to the algorithm and thereby possible increase the accuracy.

In reference [33] the article authors propose a fault location algorithm for single line to ground fault using the Wavelet transform and a neuro-fuzzy based system. Level one detail coefficients are used to detect the fault. Then a neuro-fuzzy system uses these coefficients to identify the faulted sections (OHL or cable). The fault location is calculated using A_3 coefficients as they contain the power frequency components. These coefficients are feed to one of two neuro-fuzzy systems depending on whether the fault occurs in the OHL or the cable section.

6.1. Method discussion

The application of artificial networks for fault location on OHL has been discussed by many authors. Some work is also published on hybrid systems. No authors have, however, dealt with the fault location problem on pure cross-bonded cable systems. Because the artificial network learns by example (supervised learning) it should however not be a problem to develop such a method. The problem is the extensive amount of training data needed and to ensure that the models used to create the training data are accurate enough. None of the implemented methods are tested in real life. If the models used to train the artificial networks are wrong or oversimplified good results can still be obtained when verifying the algorithm against the same model but the results will not be useable in practice.

7. Conclusion

The work presented in this paper shows that there is no obvious choice for type of online fault location algorithm (impedance, high frequency etc.) for cross-bonded cable systems. The research already carried out is limited to a few publications per method. None of the methods are implemented in practice and their accuracy in real life is therefore unknown. This is both because the influence of the measuring equipment and the accuracy of the simulation data used to verify the methods are unknown. These issues show that more research in the field is necessary. The research must both include the theoretical and practical parts as none of them are well established. Also, the influence of the measuring equipment must be investigated. In general all algorithms are developed and verified disregarding this effect.

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