Chapter 2
Fault in Transmission Cables and Current Fault Location Methods

The problem formulation of this thesis will depend on already existing fault location methods for crossbonded cables. Therefore, a literature study is conducted and the most important references are presented in the following chapter. Firstly, however, the mechanisms leading to faults in high voltage cables are briefly covered in order to examine which fault location methods are applicable.

2.1 Faults in Transmission Cables

Solid dielectrics, typically cross-linked polyethylene (XLPE) is often used as the main insulation material in high voltage AC-cables today [1]. Internal failures in these cables result from gradual deterioration of the insulation materials between core and sheath [2]. Voids and impurities in the insulation material or between boundaries of different material can initiate a process called treeing leading to insulation breakdown [3].

Electrical trees are formed by locally increased electrical stress and propagate relatively fast in the insulation material until it breaks down. Water trees are another cause of insulation breakdown. They are formed by a local defect and in the presence of moisture, water trees can propagate in the dry insulation under low electrical stress. Water trees have propagated very slowly over the years and are hard to detect as no partial discharges will appear.

When the insulation breaks down, an electric arc forms a low impedance path between the cable’s core and sheath. The arc typically burns until the protection system disconnects the cable after the fault is initiated.

At the moment of fault, all internal faults on shielded cables are shunt faults [4]. A low impedance path exists between core and sheath and large fault current flows. When the protection system disconnects the cable, the fault can develop into a series fault or stay as a shunt fault [4]. A combination of both is possible as well. A shunt exists if mechanical forces have ensured a connection between core and sheath, if a
carbon-metal bridge exists or if evaporated insulation permits a low resistance path. A series fault is defined as a fault where the conductor is disconnected at one location [4]. This can occur if a part of the conductor or a joint is blown apart at the instance of fault. In case of a shunt fault, two things can happen. The fault can either stay bolted with a solid connection between core and sheath or, as in most case, turn into a fault with a voltage dependent fault resistance [4]. At a low voltage less than 500 V the cable seems non-faulted when measurements are performed from the cable ends. If a voltage larger than 500 V, is applied, flash over at the fault location re-initiates the fault and a fault current can flow.

Internal faults on cables are typically single core to sheath faults. The ground can be included as return path directly from the fault location if the other jacket is damaged by the fault. Two or three phase faults are most often caused by external factors or initiated by a single phase to sheath fault in another cable. The sheath is always involved in any fault type as it encloses the core completely.

Faults in joints will at the moment of fault be shunt faults due to the contact between core and sheath. The core can either have connection to either the sheath of its own cable or to both its own sheath and the transposed sheath. Which sheaths are involved will depend on the type of fault and how it develops. The will affect the different fault location methods differently depending on the way the fault signals are analysed.

2.2 Current Fault Location Methods

In order to identify the most suited fault location methods for crossbonded cables, a review of existing fault location methods is conducted. The current fault location methods for cables can be divided into offline and online methods. The offline methods require special equipment, trained personnel and that the faulted cable is out of service before the methods can be used. The online methods utilise information in the current and voltage measured at the fault locator terminal (FLT) between fault incipience and fault clearance.

The online methods are the main focus in this thesis, but as a general background study, it is of interest to examine the existing offline methods and identify their advantages and weaknesses.

2.2.1 Offline Methods

The current offline methods are thoroughly described in Ref. [4]. The offline methods can be divided into two categories—terminal methods and tracer methods. The terminal methods do, as the name indicates, rely on analysing measurements performed from one or both ends of the cable. The tracer methods rely on the other hand on measurements performed by a trained person walking the cable route. These methods
are in general very accurate, but also very manpower- and time consuming. Some of the most common are bridge methods like the Murray-loop, acoustic methods, The Earth Gradient Method and the Magnetic Pickup Method [4]. The tracker methods are used when the online- or offline terminal methods fail.

Several fault location terminal methods are available. The usability of the methods depends on the value of the fault resistance at the fault location.

Most of the terminal methods require a low fault resistance in order to work. If the fault resistance is $5\,\Omega$ or below, both TDR and bridge methods can be used directly. The bridge method does not detect the fault and no waves are reflected at the fault location when using TDR methods. To solve the problem, a Surge Arc Reflection Method, Surge pulse reflection method or Burn arc reflection method must be used. These methods rely on temporarily converting the high resistance fault into a low resistance fault. However, IEEE recommends that “Fault-locating techniques that enable fault locating at the lowest possible voltage in the shortest amount of time should be selected” wherefore many of the offline methods are problematic to use [4].

### 2.2.2 Online Methods

The online fault location methods can be subdivided into two primary categories; Impedance- and travelling wave-based methods. As a subcategory of both, knowledge-based methods developed based on fuzzy logic, neural networks and expert systems are proposed. Some optical methods are presented in the literature as well.

Most fault location methods are developed for overhead line transmission systems and distribution systems. Very few publications exist, directly related to fault location on crossbonded cables [5–8]. In the following, the basic concepts for the most commonly used online fault location methods are described.

#### Impedance-Based Methods

The impedance-based fault location methods compares most often pre-known line parameters to the impedance measured in the case of fault. Based on this comparison the fault location can be estimated.

The line parameters can either be calculated or measured on the transmission line after installation. Often, a representation based on symmetrical components is selected because it can be difficult and time consuming to obtain all components in the series impedance matrix of the line.

Some of the more early single ended methods only utilise the imaginary part of the fault loop impedance for fault location estimation. This is done to omit the influence of the real fault resistance [9, 10]. However, for double sided infeed, the current from the far end source will contribute to the reactance measured by the fault locator (reactance effect) [11]. The impact of the fault resistance on single-terminal fault location methods is a key factor when evaluating their performance.
An early attempt to compensate for the influence of the fault resistance is proposed by Takagi et al. [12]. The line is decomposed into a pre-fault, a pure fault and a superimposed network using the Thevenin theorem. The method assumes the same angle of all line impedances that the line is transposed; that the line parameters are known and that the charging current can be neglected. This assumption is not valid for cables where the charging current can be 20–50 times higher compared to OHLs.

In more recent work, the capacitive effect of the cable is taken into account in for instance [13–15]. The latter two references depend on a commonly used assumption in fault location research; the modal decomposition can be calculated using a real modal transformation matrix (Clarke transformation, e.g.). The proposed real transformation matrix is only valid for fully transposed lines, and errors are introduced if the true frequency dependent modal transformation matrices are not used as the authors state [15].

The influence of the pre-fault load current is taken into consideration using an iterative process in Refs. [16, 17]. High load currents can be a problem for the single-ended fault location algorithms and must be taken into consideration [18, 19].

Phase coordinate based fault location methods are proposed by authors in Refs. [20, 21]. The methods take into account the unsymmetrical nature of some transmission lines, but require that all self- and mutual impedances are known exactly.

With the development of cheap communication between substations, the two-terminal fault location methods become more widely used [22–26]. Because more information is available for calculating the fault location, the performance of these methods is generally better than single-terminal methods.

The effect of the arc resistance can be eliminated. Often, distributed line models are used where these are based either on symmetrical components or are solved directly in the phase domain. In for instance [24], a two-terminal synchronised method that takes into account line asymmetry, shunt capacitance and fault resistance is setup. This method does, however, assume that all self- and mutual impedances and admittances are known exactly. The method performs well, but the authors point out that additional errors are most likely introduced by the transducers, hardware and errors in the assumed cable parameters.

Several publications discuss the problems associated with the use of current measurements for fault location due the current transformer (CT) saturation [22, 25]. CT saturation can introduce errors when the fundamental phasors are determined from the transient signals recorded at the fault locator terminals. These errors will reflect onto the calculated fault loop impedance and hence the estimation of the fault location.

Some parameter-free fault location methods are described in Refs. [27–29]. These methods rely on estimating the parameters using pre-fault voltages and currents. The methods estimate the line parameters well, but the verification is made with other calculated line parameters. The line parameters do not represent line asymmetry, but an average impedance and admittance is determined.

In Refs. [30, 31] and recently in [32], it is shown that the fault loop impedance of a crossbonded cable is not linear dependent on the fault location. This is due to discrete changes in the zero-sequence impedance at the crossbondings. Errors are introduced
for fault location purposes if the commonly used linear assumption between fault location and fault loop impedance is assumed. The references mentioned are based on a protection approach and the effect on fault location is not studied.

Min et al. presents in 2006 and 2007 an impedance-based method which takes into account the crossbonding of the sheath directly [5, 6]. Series impedance matrixes are formulated for each minor section and the fault location is calculated using a distributed representation of the line. The method is tested on a 154 kV 4.491 km underground cable system with five major sections. A maximum error of 0.2038% is found under the assumption that the faulted major sections as well as all line parameters for each minor section are known. The method is interesting and should be examined further if its assumptions can be proved valid.

**Discussion on Impedance-Based Fault Location Algorithms**

Several assumptions are made for most impedance-based fault location algorithms. The most common are:

1. The fault loop impedance is linear dependent on the fault location.
2. A sequence representation of the line can be used with no errors or the full series impedance matrix is available and represents the entire line.
3. The fundamental voltage and current phasors can be determined at either one or both cable ends.
4. The influence of the fault resistance, system loading and short circuit power can be eliminated.

The general behaviour of the fault loop impedance and influencing parameters on crossbonded cable systems are not well studied in the literature. References [30–32] give some discussions seen from a protection point of view, but fault location is not considered. In order to evaluate whether an impedance-based fault location method for crossbonded cables is feasible, what accuracy can be obtained and what limitations should be expected, more studies are needed. These are performed later in this thesis.

**Travelling Wave Methods**

When a fault occurs on a cable system, transient voltage and current waves will travel from the fault location in both directions towards the terminals to where the cable is connected [33]. The basic idea of the travelling wave fault location methods is to identify the arrival instance of one or more of these fault waves and estimate the fault location from the information extracted [34].

The most simple online travelling wave-based method is a single-terminal method. The method relies only on detecting the first and second wave from the fault location as the effective surge impedance of the substation is assumed to be different from the one of the line, such that an incoming wave is reflected back towards the fault. It
is also assumed that the fault arc is not extinguished at the fault location so the surge impedance is close to zero, and the wave is almost completely reflected back towards the fault locator terminal [35]. If the arrival instance of the first and second waves at the fault location is captured and the wave velocity is known, the fault location can be estimated as [35]:

\[ x = \frac{v_n \cdot \tau_d}{2} \]  \hspace{1cm} (2.1)

where \( v_n \) is the velocity of a wave of mode \( n \), and \( \tau_d \) is the time difference between the arrival instance of the two first waves from the fault for a mode \( n \) wave. If the fault occurs at more than 50% of the line length away from the fault location, then \( \tau_d \) in Eq. (2.1) is calculated as \( 2\tau_l - (\tau_2 - \tau_1) \) where \( \tau_l \) is the travelling time for a wave of mode \( n \) travelling the entire line length. The method does not rely on a working communication link between two terminals and is therefore a robust solution when it can be used.

A second type is the two-terminal online method where time synchronised data acquired from both ends is used to estimate the fault location. The data from these units can be sent to a common data handling point where the fault location can be determined using Eq. (2.2) [35].

\[ x = \frac{l - v_n \cdot \tau_d}{2} \]  \hspace{1cm} (2.2)

where \( v_n \) is the velocity of a wave of mode \( n \), \( l \) is the length of the transmission line, and \( \tau_d \) is the time difference between the arrival time of the waves at the two fault locator terminals (FLT).

The travelling wave methods rely as shown in Eqs. (2.1) and (2.2) only on knowledge about the wave velocity and on the arrival instance of one or two of the fault created waves at the fault locator terminals. The methods are immune to fault resistance, fault inception angle and network parameters. Furthermore, the same basic method is used for any fault type and works for overhead lines and cables [11].

The idea to analyse travelling waves for fault location on transmission lines was first proposed in 1978 [34]. The work carried out involving fault location on the transmission level is however mainly focused on overhead line systems—for instance [36–40]. Actual experience with travelling wave fault location on a 400 and 132 kV OHL system is presented in Ref. [41].

Travelling wave methods are also widely adopted for fault location on distribution systems [42–45] and to locate high impedance faults [46]. In a recent paper [47], it is suggested that the wave velocity can be eliminated from Eqs. (2.1) and (2.2) by combining the two methods.

The Wavelet Transform (WLT) has over the last years gained a lot of attention for solving fault location problems on transmission lines [48–54]. In for instance [55], the Wavelet Transform is used to detect the arrival instance of the fault created travelling wave for an OHL system. Both a method that requires two-terminal-GPS-synchronised data and a method which uses single ended recordings
only are proposed. Research studying different methods for singularity detection using Wavelets has been published [52, 56, 57]. The Lipschitz Exponent transform is a popular measure of singularities in transient signals and is used widely to detect the arrival instance of fault waves [52, 57].

Not much research has been published on fault location directly on crossbonded cables using travelling waves. In 2005 and again in 2007, Jung et al. published an article concerning with the issue of how to discriminate the fault generated travelling waves from the noise in a one ended fault location scheme for crossbonded power cables [7, 8]. The one terminal methods is, according to the authors, preferred because of the simple structure and because the errors associated with the GPS-synchronisation are avoided. The authors introduced a Wavelet-based filtering method that separated the reflections created at the crossbondings from the second wave from the fault location. The method is verified on a 6.284 km cable with six major sections, and errors between 0.08 and 1.8 % relative to the total cable length are obtained (5–111 m). The method seems promising, but it is verified only on a short cable.

**Discussion on Travelling Wave-Based Fault Location Algorithms**

The travelling wave-based fault location methods are interesting for crossbonded cables. The implementation is more expensive compared to traditional power frequency methods due to the requirements for high frequency data acquisition and a highly accurate common time reference at both line ends. However, the method is simple and independent of many of the system parameters which can affect other fault location algorithms negatively.

Fault location on crossbonded cables using travelling wave methods is not well studied, but is in general considered more complicated compared to fault location on overhead lines and non-crossbonded cables because additional reflections are created at each crossbonding [58–61]. How this affects the use of the single- and two-terminal fault location methods must be studied in further detail before a final evaluation of the method can be made.

**Application of Artificial Intelligence for Fault Location**

Generally, artificial neural networks (ANN) are used for pattern recognition. The ANN is trained through a number of training cases using a suitable system model to recognise certain behaviour. 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. The ANN type of algorithm is especially useful if no explicit solution can be formulated for the system (multi-ended transmission and distribution systems with laterals).

Fuzzy logic is a non-crisp type of logic that determines relations between objects by soft qualifications. This type of logic is useful for treating ambiguous, vague,
imprecise, noisy, or missing input information which can be available for fault location algorithms. Fuzzy logic is often combined with ANN in the fault location schemes proposed in the literature.

Different ANN’s must be used for different types of faults because of the different behaviour of the faults. This means that each ANN is trained according to the correct type of fault. The typical inputs for an impedance-based fault location algorithm using artificial networks are pre- and post-fault currents and voltages—also system parameters as loading, short circuit power, etc. can be used.

Most of the theories developed for power system protection and fault location are based on deterministic evaluation schemes [62]. This can give problems because of the complex system models, uncertain determined parameters, the large amount of data that must be processed and changing system configurations. For these reasons, several authors have proposed the use of Fuzzy logic, Neural Networks or a combination of the two to help make the correct decisions in various power system protection problems. In Ref. [63], a single ended fault location algorithm for a 400 kV transmission line is proposed based on neural networks. The input to the ANN are the pre- and post-voltages and currents phasors. The output is the fault resistance and distance to fault. The algorithm is compared to traditional fault location algorithms and it is shown that by correctly training the ANN, it can adapt itself to large variations in the fault resistance and source impedance.

In Ref. [64], a method of accurate fault locator for EHV transmission lines based on radial basis function neural networks is discussed. The locator utilises faulted voltage and current waveforms at one end of the line only.

In Refs. [65, 66], some discussions regarding the structure of neural networks for fault location is presented. In Ref. [65], several different structures are implemented and their performance evaluated.

In Ref. [67], the application of neural networks and Clarke’s transformation in fault location on distribution power systems is presented. The locator is able to identify and locate all types of faults with good results. In Ref. [68], application of wavelet fuzzy neural network in locating single line to ground fault (SLG) in distribution lines is discussed. The method is based on post fault transients and steady state measurements. Fuzzy logic and ANN are used to locate the fault. In Refs. [69, 70] fault location on hybrid systems is discussed. The fault locators estimate the fault location well for various hybrid lines. Neural networks are also used for distance protection schemes. The implementation of a neural networks for solving a protection problem is presented in Ref. [71]. Also, fault calcification using neural networks is proposed in the literature. Such a method is presented in Ref. [62] where neural networks are combined with the wavelet transform to classify the fault type. The algorithm is able to classify all types of faults.

Discussion on Application of Artificial Intelligence for Fault Location

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 fault location problems on crossbonded cables. Because the artificial network learns by example (supervised learning) it should, however, be possible to develop such a method using the methods already proposed. The problem is the extensive amount of data needed for training and to ensure that the models used to create the training data are good and reliable. None of the algorithms proposed in the literature are verified in real-life and if the models used to train the artificial networks are oversimplified, good results can be obtained when verifying the algorithm against the same model, but the results will not be useable in real life. How well the most advanced simulation models predict real fault behaviour on crossbonded cable systems must be examined before any final recommendation regarding artificial intelligence methods can be made.

Discussion on State of the Art

The state of the art analysis conducted shows that fault location on crossbonded cables is not a field which is studied in detail. Only few publications are available when considering both impedance and travelling wave-based methods. The publications which are available are centred on very short lines where the lines in the Danish grid will be considerable longer. The use of artificial intelligence for fault location is a relatively new area of research and is mainly focused on OHL systems. Furthermore, not much research that studies the special conditions for crossbonded cable system under faulted conditions is published.

References


32. Teruo Ohno, *Dynamic Study on the 400 kV 60 km Kyndbyvarrket Asnarsvarrket Line* (Energinet.dk, 1st edn, 2013)
52. S. Lin, Z.Y. He, X.P. Li, Q.Q. Qian, Travelling wave time-frequency characteristic-based fault location method for transmission lines. IET Gener. Transm. Distrib. 6(8), 764–772 (2012)
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