**Online Travelling Wave-based Fault Location on Crossbonded AC Cables in Underground Transmission Systems**

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**SUMMARY**

In this paper, a fault locator system specifically designed for crossbonded cables is described.

Electromagnetic wave propagation theory for crossbonded cables with focus on fault location purposes is discussed. Based on this, the most optimal modal component and input signal to the fault locator system are identified. The fault locator system uses the Wavelet Transform both to create reliable triggers in the units and to estimate the fault location based on time domain signals obtained in the substations by two fault locator units.

Field measurements of faults artificially created on a section of a 245 kV crossbonded cable system, connecting the newly installed 400 MW Danish offshore wind farm Anholt to the main grid, are obtained and used to verify the proposed system. Furthermore, extensive simulation data created in PSCAD/EMTDC is used in order to examine the robustness of the system to changes in the fault inception angle, fault resistance and fault location.

It is shown that the fault location can be estimated very accurately using the proposed system and the system will be used to monitor Danish crossbonded transmission cables in the future.

**KEYWORDS**

Online fault location - cable models – crossbonding - modal decomposition - cable transmission systems – Wavelet Transform.

# Introduction

A transmission grid is normally laid out almost purely as an overhead line (OHL) network. The introduction of transmission voltage level XLPE cables and the increasing interest in the environmental impact of OHL has resulted in an increasing interest in the use of underground cables on transmission level. In Denmark for instance, the entire 132 kV, 150 kV, 220 kV and parts of the 400 kV transmission network shall be placed underground before 2030.

To reduce the operating losses of a cable-based transmission system, crossbonding methods are normally used. The typical method used at transmission level is shown in Figure 1 for a two major section cable system.



Figure 1: Cable crossbonding scheme.

The minor sections are normally between 1 km and 1.4 km making the major sections between 3 km and 4.2 km. In Denmark, crossbonded cable systems between a few kilometres and close to 100 km will be constructed.

The propagation of electromagnetic waves on transmission lines is used for several different purposes. Of these, fault location is one of the more thoroughly studied as the ability to pinpoint the location of fault reduces the overall repair time of the transmission corridor. For crossbonded cables, the travelling waves fault location methods are superior to the impedance-based as they are to a much less degree sensitive to changes in the ground resistance, non-linear zero-sequence impedance, fault inception angle and fault resistance; parameters that affect the fault loop impedance significantly [1].

A tendency is seen on XLPE insulated cables where the fault does not burn solidly through the entire insulation. This renders the off-line travelling wave fault location equipment used today useless as no reflections are created at the fault location at all [2]. A solution to this problem is to use an online method that relies on capturing the waves generated at the instance of the fault. However, because the crossbondings cause discontinuities in the surge impedance along the cable line, the electromagnetic wave propagation is affected substantially [1]. In this paper, an online fault locator system that overcomes these difficulties is described.

# Electromagnetic wave propagation on crossbonded cable systems

The study of electromagnetic wave propagation on crossbonded cable systems is more complex compared to traditional wave propagation on overhead lines. Most research available in the field of fault location is focused on overhead lines and cannot be used directly on crossbonded cable systems without taking several precautions [1]. The general theory of wave propagation on crossbonded cables related to fault location and the necessary adjustments to the known methods are discussed in this section.

Because the conductors of a three-phase single-core cable system are electromagnetically coupled, a single wave velocity or attenuation constant for each conductor does not exist. A unique wave velocity is needed as input to most travelling wave based fault location methods. To simplify the analysis of transmission lines in general, the modal decomposition theory can, however, be used [3] [4]. This method utilises frequency dependent eigenvalues and transformation matrices allowing the *n* conductor transmission system to be represented by *n* independent modes [5].

The modal decomposition of a three-phase crossbonded cable system laid in flat formation will result in three coaxial, two intersheath and one ground mode. The modal attenuation and velocities of these modes are shown in Figure 2.

Figure 2: (left) Modal attenuation and (right) velocity as a function of frequency for a three single-core cable system laid in flat formation.

Both the coaxial and intersheath modal waves become frequency independent at high frequencies as shown in Figure 2 (b). This is a strong advantage for fault location purposes, as the initial fault wave to arrive at the fault locator terminal contains frequency components travelling at the asymptotical modal velocity and a single fixed velocity can therefore be used to determine the fault location.

However, the special design of the sheath system on a crossbonded system complicates the use of intersheath mode waves. As Figure 2 (b) shows, the coaxial waves are the fastest at any frequency. Therefore, they are also the first to arrive at any location after the occurrence of a fault. When a coaxial wave meets a crossbonding point, all modal waves including intersheath waves are created. The first intersheath mode wave to arrive at the fault locator terminals does therefore not contain unique information about the fault location as the wave was created at the closest crossbonding.

The coaxial wave is defined as a wave which at high frequencies propagates between the core and sheath conductors only. The magnetic field associated with the high frequency core current induces a current with equal magnitude, but opposite polarity on the sheath conductor (Lenz law). As a consequence, no magnetic field exists outside the sheath layer, and the coaxial modal velocity is only dependent on the relative permittivity and permeability of the insulation material. The permeability is equal to the vacuum permeability due to a none-ferromagnetic insulation material and the relative permittivity is constant in the frequency range of interest [6] [7].

The intersheath modal waves on the other hand propagate between sheath conductors and are therefore dependent on the ground resistivity and laying conditions for the cable system; both of which can vary. The ground mode wave is very frequency dependent and has high damping. The best choice for a modal component for fault location on a crossbonded cable system is therefore the coaxial mode.

The reflection and refraction of coaxial waves is of special importance for fault location purposes. In the case of a single core to sheath to ground fault, the healthy cables are unaffected by the fault wave propagating on the faulted cable due to the enclosed electromagnetic fields. However, because of the electrical interconnections of the sheath conductors at the crossbondings, a part of the initial coaxial fault wave that arrives at a crossbonding is reflecting onto the other two cables. As the fault wave meets an increasing number of crossbondings along the cable route, a larger part of the fault wave is observed on the two healthy phases. After 4-5 major section (12-15 minor section), the magnitude of the initial fault wave is divided almost equally between the three cables [1]. This can be a problem for accurate fault location especially in noisy environments, as the magnitude of the fault wave is reduced to one third of the initial value. A method to handle this problem is presented later in this article.

**Extracting the fault wave components**

As mentioned, it is common to use a decoupled domain to perform the necessary calculations involved in estimating the fault location with use of travelling wave theory. Voltage or current signals are recorded in the time domain where after they are transformed to the modal domain and by use of the modal components, the fault location is estimated. However, at high frequencies, the transformation from the time to the modal domain and vice versa is done by multiplications of real-number matrices [1]. As the coaxial waves are the fastest at any frequency of interest (see Figure 2 (b)), the first voltage or current change noticed in the time domain signals is caused by a coaxial wave. Thus, there is no need to calculate the modal transform before the fault location can be estimated.

By use of the coaxial wave velocity and the fact that the first wave noticed in the time domain is coaxial of nature, fault location on crossbonded cables in the time domain is possible.

**Choice of input signal**

The choice of input signal to any travelling wave fault locator system is important and will affect the accuracy. In most Danish 132-150 kV substations, inductive voltage transformers and current transformers are installed to monitor the high voltage signals. The use of these instrument transformers for fault location purposes can be problematic as the measuring transformers alter the high voltage signal in the secondary circuit by filtering the high frequency components and introducing a possible time delay. A method where capacitive voltage transformers are used is presented in [8]. This method requires, however, that the central point between the two main capacitors is available for signal extraction which is not always the case.

For fault location on crossbonded cables, a more attractive solution is available. The sheaths are bonded and grounded at each substation wherefore low voltage high bandwidth probes (for instance Rogowski coils) can be used to pick up the arrival instance of the coaxial wave travelling on the sheath conductor [9]. A further advantage is that a dedicated transducer can be used for the fault locator system as the influence of the secondary circuit on the electromagnetic wave response can be neglected.

# Field measurements

In order to verify the potential use of the coaxial modal wave for fault location purposes on crossbonded cable system, field measurements are carried out.

The 245 kV electrical connection to the Danish offshore wind farm Anholt is divided into three cable sections. The first section is a 59.6 km crossbonded land cable where it was possible to access all cable conductors at three locations for performing of field measurements. The locations were at the 400 kV substation Trige (Joint 0), at Joint 27 (31.4 km from Trige) and at Joint 33 (38.4 km from Trige). A sketch of the part included for measurements is shown in Figure 3.



Figure 3: Sketch of the 245 kV crossbonded cable system under study.

At Joint 27, all core and metal sheath conductors were accessible. This made it possible to apply faults at this location with an energised system from Trige. The travelling waves at Joint 0 and Joint 33 were then measured. In order to limit the influence of pre-strike, a Siemens 3AF 1532-4, 12 kV 1230 vacuum circuit breaker was used to apply the short circuit at the fault location.

All measurements were performed at reduced voltage (0.4 kV) as the voltage/current relationship of the cable system is linear, so the travelling waves created will be representative for waves created during a real-life fault situation. The system was fed though a 10 kVA 0.4/0.4 kV Dyn transformer setup at Trige. The set up in substation Trige is shown in Figure 4



Figure 4: Pictures from the measurements. (left) the setup in substation Trige and (right) at Joint 33.

The cable system consists of three single-core 2000 mm2 milliken Al cables with the layout shown in Figure 5. The cables have a 170 mm2 aluminium foil metal sheath.



Figure 5: Physical layout of the three phase 2000 mm2 aluminium single core 245 kV crossbonded cable system. *r1*=28.4 mm, *r2*=35.9 mm, *r3*=54.4 mm, *r4*=58.6 mm, *c*=3.547e-8 m, *s* =2.676 m,

*ECC*=1.724e-8 m,

The fault inception angle cannot be controlled with the Siemens vacuum breaker. Instead, the breaker was closed at several arbitrary instances and the fault inception angle in the simulation adjusted accordingly. At Joint 33, a 27  resistor is connected representing the coaxial surge impedance of a crossbonded cable system.

**Measuring System**

High bandwidth measuring equipment was used for capturing the arrival instances of the travelling waves on the cable system ends after the fault had been created. The three core voltages and currents as well as the three sheath currents were measured at both cable ends.

The minimum bandwidth of all used current probes was 20 MHz and 100 MHz for all voltage probes. The signals were recorded with Tektronix DPO2014 oscilloscopes set at a sampling frequency of 31.25 MHz. The vertical resolution of the oscilloscopes was 8 bits or 256 points. To synchronise the two measuring locations, synchronisation units based on the Rubidium frequency standard were used [10]. These units drift a maximum of 10 ns during the time the measurements were conducted (a coaxial wave will travel approximately 1.8 m in 10 ns).

# Field measurement results

Figure 6 shows the fault transient in the voltage of phase A at Joint 0 and 33 after a fault has been applied at Joint 27. The fault wave is first observed in the steady state signal at Joint 33 where after it appears at joint 0.



Figure 6: (a) Low resolution zoom of the core voltage at Joint 0 and 33 after a single phase to core to sheath fault is applied at Joint 27, (b) high resolution of the core voltage at Joint 33 and (c) at Joint 0.

Figure 6 (b) and (c) show that the exact arrival instances of the first coaxial wave at both joints can be identified within a precision better than a few samples based on a simple visual inspection of the time domain signals. This indicates that the two-terminal fault location method shown in Equation 1 may be used for crossbonded cables.

where *l* is the cable line length, *vc* is the asymptotical velocity of the coaxial mode and *A* and *B*are the coaxial fault wave arrival instances at the two terminals A and B, where the fault locator units are installed.

Using the time instances from the visual inspection and the coaxial wave velocity measured on the Anholt cable using an impulse test, the fault location is determined as 31.385 km; an error of -30 m (0.08%).

The sheath currents were measured only at Joint 33. The sheath current of sheath conductor A at the instance of arrival of the first coaxial wave is shown in Figure 7.



Figure 7: Measured sheath current of sheath conductor A at Joint 33.

Different signal types can be used at each cable end because coaxial waves travel both on the core and sheath conductors. Using the time extracted in the sheath current signal shown in Figure 7 at Joint 33 and the core voltage at Joint 0, the fault location is determined as 31.389 km; an error of -34 m.

# Design of a fault locator system for crossbonded cables

The main components in the proposed fault locator system are shown in   
Figure 8.



Figure 8: Components included in the proposed fault locator system.

The system consists of two similar units installed at each cable end and a centrally placed data processing system. The units installed in the substations are time synchronised using GPS and continuously monitor the cable by sampling the three chosen input signals at 10 MHz. In the case of a fault, the buffered data is saved and sent by WAN to the central data processing location.

The difficulty when performing online fault location on crossbonded cables when using travelling wave methods lies in making sure the fault transients are recorded in all cases by triggering the system and that the exact arrival instance can be determined correctly in the post-fault data processing routines.

**Trigger mechanism**

The fault transients can contain both very high and quite low frequency components depending on where the fault occurs relative to the fault locator units. This makes design of an effective and reliable trigger system challenging. A new method proposed for ensuring a reliable triggering is the ‘Online Wavelet Transform’ (OWLT).

Over the last years, the Wavelet transform (WLT) has gained a lot of attention for solving fault location problems on transmission lines [11]. The Wavelet transform offers the ability for multi-resolution analysis and therefore provides both high time and frequency resolution at the same time - a desirable feature for fault location studies.

The OWLT can determine the occurrence of a fault in a wide frequency range by calculating the wavelet coefficients at several scales instantaneously, and if a fault wave is picked up at any scale, a global trigger signal is set. This is an efficient method for ensuring a correct and fast trigger both for long and short crossbonded cables.

**Choice of mother wavelet and scale for the trigger system**

A study of which mother wavelet performs best for a trigger system is carried out using both the Anholt measurement and extensive simulated data created in PSCAD/EMTDC. In all cases, it is found that the Haar mother wavelet performs best. This is due to the square wave shape of the Haar wavelet combined with the shape of a voltage breakdown at the instance of fault. The 10 MHz signals recorded by the fault location units are downsampled 16 times to limit the amount of data to be analysed online. Scale 2, 4, 16, 32 and 64 are selected, thereby covering a frequency range from 62.26 kHz to 1.95 kHz. With these scales, all faults created are detected by the fault locator system.

**Central data processing system**

A fault locator system that does not require skilled operating personnel is preferable as faults on transmission lines are rare and the skillset of the operating personnel needs to be kept up-to-date. In the discussion of wave propagation on crossbonded cables, it was mentioned that the travelling fault wave is reflected onto the two healthy conductors as the fault wave propagates along the crossbonded cable. This causes a problem for detecting the edge of the wave, as the signal/noise ratio is reduced. It is therefore proposed to pre-condition the time domain signals before they are analysed by the WLT. This is done simply by adding the three phase signals point by point. This combines all the fault wave energy into one new signal and, furthermore, the power frequency signal is cancelled. The method can be used for both the core voltages and sheath currents as the fault wave is reflected positively onto the two additional conductors in all cases.

In Figure 9, the square of the Haar wavelet coefficients at Scale 5 are presented for the

Anholt core voltage signals with and without the proposed pre-conditioning. The threshold line (THL) value for each signal is calculated as an average of the 1000 pre-fault WLCs. The arrival of a fault wave is detected simply by comparing the THL to the wavelet coefficients point by point. For a coefficient lager than the THL, the fault wave is detected and the instance of occurrence is noted.



Figure 9: (a) Anholt Phase A voltage signals (b) the squares of the Haar WLC at scale 5 with the threshold line (THL), (c) Anholt conditioned signals (b) the squares of the Haar WLC at scale 5 with the threshold line (THL) for the conditioned signal.

In Figure 9 (b) which shows the WLCs calculated on the basis of a non-pre-conditioned signal (Figure 9 (a)), the wave arrival instance at Joint 33 is detected, but the wave at Joint 0 is not. The fault location cannot be determined in this case.

In Figure 9 (d), both the fault waves at Joint 0 and 33 are, however, detected. The use of scales enables a more precise estimate of the fault location and thereby a reduction in the overall repair time. The fault location is determined with an error of 37 m; very comparable to the results obtained using the visual inspection of the time domain signals presented in Section 4.

**Verification using simulation data**

To verify the proposed fault location method, three 150 kV crossbonded cable systems with lengths of 18 km, 36 km and 60 km are implemented in PSCAD/EMTDC. Single core to sheath to ground faults are applied at 5%, 35%, 60% and 90%. All minor sections are 2 km resulting in cable systems with three, six and ten major sections. The model details can be found in [1].

The fault resistance is varied from 0  to 10 and the fault inception angle set as 45°, 55° and 90°. The sheath currents measured at both ends are used as input to the fault locator system after they are pre-conditioned using the method presented in this section. As an example, the sheath currents at Bus A and B are shown in Figure 10 for a fault on the 60 km cable 6 km from Bus B with a fault resistance of 10  and a fault inception angle of 45°. The sample frequency of the fault locator system is 10 MHz and the signals are added white noise with double the magnitude as found in the Anholt field measurements.



Figure 10: Pre-conditioned sheath currents at (a) Bus A and (b) Bus B for a fault 6 km from Bus A on a 60 km crossbonded cable with 10 major sections, a fault resistance of 10 W and a fault inception angle of 45

The fault location is determined using the Haar wavelet at scale XX as 54.085 km; an error of 86 m.

In Table 1, several results are summarised for faults on the studied cables, at 5%, 35%, 60% and 90% of the cable line length.

Table 1Results obtained for the proposed fault location system for a fault inception angle of 45 degrees.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Fault resistance [] | Cable length  [km] | Fault location error at 5% [m] | Fault location error at 35% [m] | Fault location error at 60% [m] | Fault location error at 90% [m] |
| 0 | 18 | 37 | 30 | 28 | 43 |
| 36 | 56 | 50 | 41 | 61 |
| 60 | 85 | 75 | 60 | 81 |
| 10 | 18 | 39 | 31 | 28 | 42 |
| 36 | 60 | 54 | 43 | 63 |
| 60 | 86 | 85 | 61 | 84 |

As shown in Table 1, the fault locator performs well in all cases and is almost independent of the fault resistance. The largest absolute error is 86 m and occurs on the 60 km cable with a fault resistance of 10 and a fault inception angle of 45° (0.14% error).

The figures presented in Table 1 are obtained for a fault inception angle of 45°. However, the insulation tends to breaks down near peak voltage due to high stress and the inception angle will therefore be higher in practice. The result is fault waves with higher magnitudes and in general a better estimation of the fault location.

The fault locator system is realised by use of National Instrument equipment. A picture of the complete unit is shown in Figure 11. The system consist of a PXIe-8115 Core i5-2510E 2.5 GHz controller, a NI PXI-6682H IRIG-B,IEEE 1588 Sync and Time Module GPS module and a 60 MS/s, 12-Bit, 8-Channel Digitiser/Oscilloscope module.



Figure 11: National Instrument equipment used to build fault locator unit.

In the future, the fault locator system described in this article will be used to monitor all crossbonded cables in the Danish transmission network.

# Conclusions

In this article, the design of a fault locator system developed especially for crossbonded cables is described. The two-terminal method with use of coaxial modal waves detected directly in the time domain is used to estimate the fault location. Either core voltage or sheath currents are used as input signals to the fault locator. The wave arrival instance is determined using the Wavelet Transform with the Haar mother Wavelet. The trigger system in the fault locator unit is designed using the Online Wavelet Transform with use of the Haar mother wavelet as well. The system was tested using field measurements obtained on the 38.4 km 245 kV crossbonded cable section for the Danish offshore wind farm Anholt and extensive simulation data created in PSCAD/EMTPDC. In all cases, the fault locator estimates the fault location very accurately and will in the future be used for all Danish crossbonded cable lines.

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