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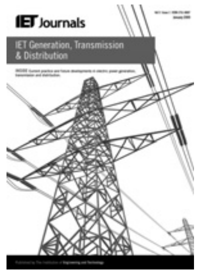

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Wavelet-based protection strategy for DC faults in multi-terminal VSC HVDC systems

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Abstract: A new protection algorithm for DC line faults in multi-terminal high voltage DC (MTDC) systems is proposed in this study. A four-terminal MTDC model is used to investigate fault behaviour and detection using the simulation program PSCAD/EMTDC. The simulation results are post-processed using Matlab. The fault clearing must be done very rapidly, to limit the effect of the fault on neighbouring DC lines because of the rapid increase in DC current. However, before clearing the line, the fault location must be detected as soon as possible. A rapid fault location detection algorithm is therefore needed, preferably without communication. The protection algorithm proposed in this study uses wavelet analysis to detect the fault location based on local measurements. The protection algorithm consists of three independent fault criteria, of which two use wavelet analysis. The third criterion is based on a detection method in the time domain. The latter is an additional detection method independent of wavelet analysis. Using a two out of three selection criteria results in an increased reliability of the whole protection algorithm. The final objective is to implement a protection algorithm which allows to detect a DC fault within 1 ms without using communication between the participating converter stations.

1 Introduction

Recent years have seen a strong and renewed interest in high voltage DC (HVDC) and specifically that of voltage source converter (VSC) HVDC. This relatively new technology offers several advantages: it is faster, offers control of both active and reactive power, and the power direction can be changed by changing the direction of the current and not by changing the polarity of the DC voltage. The latter allows the use of inexpensive cross linked polyethylene (XLPE) cables. Secondly, the constant DC voltage allows a common DC bus to be used. This makes it easier to build VSC HVDC systems with more than two terminals [1], this in contrast with the older line commutated converter (LCC) HVDC.

As such, the VSC HVDC system is considered to be the ideal building block for DC grids. The resulting DC system can be radial, meshed or a combination of both. In this paper, an example of a DC-meshed grid with four terminals is used to investigate a protection methodology for this type of grids.

The program used for the simulations is PSCAD/EMTDC, an electromagnetic time domain transient simulation environment [2], the post-processing is done using Matlab. The results proposed in this paper are based on a VSC HVDC system in an MTDC configuration.

2 Protection of VSC HVDC multi-terminal systems

The protection system may be the main problem when considering VSC HVDC multi-terminal configurations and a complete new method must be developed. First of all, the fact that the DC system does experience currents do not change in polarity makes it more difficult to extinguish the current arc. Furthermore, existing protection methods with LCC multi-terminal converters are not relevant in this case as the LCC converter is a current source converter with a fundamentally different operating principle. The existing VSC HVDC protection systems are also not suitable. They disconnect the entire DC system by activating AC switchgear (see Fig. 1). When a single line is considered, the difference between opening the faulted cable and removing the entire DC line is small from a system point of view. However, it is not acceptable to disconnect the entire DC system each time a single line fault occurs.

There are four main reasons why protecting a DC system is more difficult than protecting AC systems:

1. In VSC HVDC systems, cables are commonly used, higher rise times and higher steady-state short circuit currents.
2. DC converters are very sensitive to overloads and need to be protected against any overcurrent.

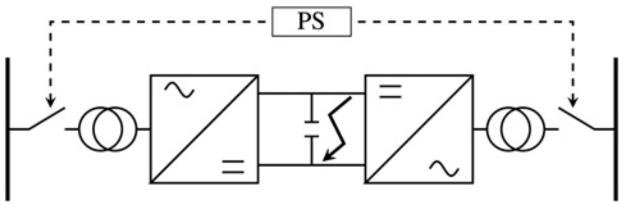

Fig. 1 *Protection system (PS) in existing VSC HVDC systems*

3. Switching DC currents is more difficult than switching AC.
4. Identifying the line in which a fault occurs is not trivial and traditional AC protection methods (e.g. impedance relays) cannot be used.

When a DC fault appears and a certain current level is reached, the insulated gate bipolar transistors (IGBTs) are blocked. In current VSC HVDC topologies, the anti-parallel diodes keep conducting during the fault and the converter operates as a rectifier bridge. As the viability of MTDC systems depends on the capability to survive DC faults, research has to be carried out on DC fault protection [3]. As such, a new protection system must be developed for short circuits in the MTDC transmission system, which has the following properties:

1. Detects the fault, insensitive to noise and normal operation patterns.
2. Identifies the fault location in a DC meshed system (faulted branch).
3. Triggers the correct DC breakers at both sides of the affected line in a selective manner within a few milliseconds.
4. Has sufficiently fast DC breakers.
5. Offers a backup in case the former fails.

The effects on the AC system performance must remain minimal during and after the fault. The protection system must also be insensitive to faults, which are outside the protection zone and to events that are part of the normal operation of the system. Lastly, the protection system must be able to handle the noise that is present in the system (e.g. from the converters).

The protection against DC faults in a VSC-based MTDC (multi-terminal HVDC) system has been addressed in previous works [4–6]. However, the main purpose of these studies was to develop a protection algorithm without using DC breakers. When DC breakers are not used, it becomes necessary to block all converter stations and to use the AC circuit breakers to clear the fault. After selecting and eliminating the faulted cable, the AC breakers are reclosed and the IGBTs are deblocked to perform a reorganisation of the power flow. This method is called the Handshaking method. Because of the temporary outage of the entire DC system, this method has a negative impact on the reliability of the combined AC and DC power systems.

This paper describes a new method that can be implemented in each breaker to take care of the first three requirements for the DC protection system. The proposed methodology can be locally implemented in each independent breaker and does not require communication. Of course, sufficiently fast DC breakers are not yet available and additional protection systems are needed to provide a backup method and to protect the converter and the substation itself.

3 Wavelet analysis

Wavelet analysis is a powerful signal processing method. This method is well suited to detect abrupt, local changes in a signal (e.g. short-time phenomena such as transient processes). Note that wavelet analysis does not use a time-frequency, but rather a time-scale region. The analysed signal is decomposed into different scales using a wavelet analysing function called 'mother wavelet'. This wavelet is scaled and translated to match an input signal locally. The subsequent calculated wavelet coefficients represent the correlation between the (scaled) wavelet and the signal.

3.1 Wavelet transform

The wavelet transform decomposes signals over dilated and translated wavelets. A wavelet is a function ψ with a zero average

$$\int_{-\infty}^{\infty} \psi(t)\,\mathrm{d}t = 0 \tag{1}$$

A wavelet transformation is characterised by a translation parameter u and a dilation parameter $\|s\|$. The dilation parameter determines the size of the window in which the wavelet transform is performed. The translation parameter determines the time corresponding to the centre point of each window.

A wavelet is normalised $\|\psi\| = 1$ and centred in the neighbourhood of $t = 0$. For each 'mother wavelet' ψ, a family can be obtained by scaling ψ by s and translation of ψ by u

$$\psi_{u,s}(t) = \frac{1}{\sqrt{s}}\psi\left(\frac{t-u}{s}\right) \tag{2}$$

Also, the scaled and translated wavelets remain normalised. The wavelet transform of a signal $f(t)$ at time u and scale s is calculated by

$$\mathrm{WT}(u,s) = \int_{-\infty}^{\infty} f(t)\frac{1}{\sqrt{(s)}}\psi^{*}\left(\frac{t-u}{s}\right)\mathrm{d}t \tag{3}$$

with ψ^{*} the complex conjugated of the wavelet function ψ. Wavelets can be an appropriate tool for detecting disturbances, for example, faults, in power systems [7–9].

3.2 Use of wavelets for fault detection

In general, three types of wavelet transforms can be distinguished, namely the continuous wavelet transform (CWT), the discrete wavelet transform (DWT) and the stationary wavelet transform (SWT). The CWT is the convolution of the signal multiplied by scaled and shifted versions of the mother wavelet. This continuous process results in many wavelet coefficients and a long calculation process. In fault detection applications, especially in VSC HVDC systems, a fast processing algorithm is essential. Therefore the CWT method is not considered suitable for this research.

In fault detection applications, it is of great importance that all data points are treated in the same way. For example, when a wavelet transform of a current signal in one cable is compared with one from another cable, it is crucial that both wavelet transforms are compared with each other without any shift in time. Therefore a translation invariant wavelet transform is necessary. A strategy for maintaining the translation invariance of a wavelet transform is to apply a wavelet transform where the scale $\|s\|$ is discretised but not the translation parameter u [10]. The calculation is carried out based on the window representations in Fig. 2. In this case, the window is each step shifted by one sample.

A wavelet transform with this property is the SWT. The SWT has been successfully applied in singularity detection in a noisy environment and is mainly applied in de-noising applications [11]. It is also known as the ϵ-decimated DWT [11], the undecimated DWT [12], the over-complete DWT [13], the shift-invariant DWT or the redundant DWT [14]. All these algorithms use the same concept: the signal is not downsampled at each decomposition level. In the different methods, this concept is implemented each time in a slightly different way. By this, the translation variance problem caused by decimation can be avoided [15].

An efficient way to implement this scheme is by using filters developed by Mallat (1988). This practical filtering algorithm, called 'algorithme à trous', described in [10], yields a fast wavelet transform by using a window into which the signal passes and out of which the wavelet coeffcients quickly emerge. When using dyadic scales to reduce the processing time, this scheme is called the fast dyadic wavelet transform (FDWT). The FDWT is a translation-invariant wavelet representation.

To calculate the dyadic wavelet transform of a function $f(t)$, the scale is sampled along a dyadic sequence to simplify the numerical calculations. The dyadic wavelet transform based on the more general calculation of (3)

$$\begin{aligned}\mathrm{WT}(u, 2^j) &= \int_{-\infty}^{\infty} f(t)\frac{1}{\sqrt{2^j}}\psi^*\left(\frac{t-u}{2^j}\right)\mathrm{d}t \\ &= f \otimes \bar{\psi}_{2^j}(u)\end{aligned} \tag{4}$$

with

$$\bar{\psi}_{2^j}(t) = \frac{1}{\sqrt{2^j}}\psi\left(\frac{-t}{2^j}\right) \tag{5}$$

In this paper, all signal processing results will be based on Mallat's FDWT algorithm. The main applications of the dyadic wavelet transform are texture discrimination (2D) and edge detection (1D) [10].

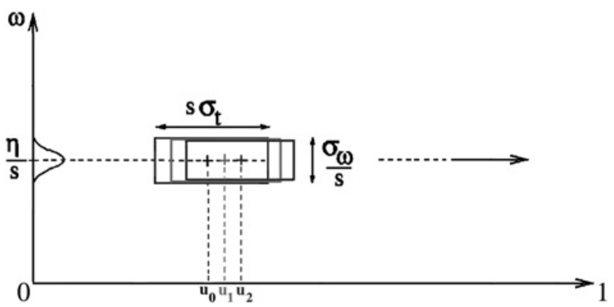

Fig. 2 *Window positions at scale s without discretisation of the translation parameter u*

4 Protection strategy

4.1 Fault detection

In the proposed protection setup, each line is equipped with a DC breaker. With(in) the breaker relay, the necessary voltage and current measurements can be done and locally processed where needed. In such a setup, different inputs signals can potentially be used as a basis for the protection system. Examples are direct measurement of voltage (V) and current (I) signals and their derivatives (($\mathrm{d}V/\mathrm{d}t$) and ($\mathrm{d}I/\mathrm{d}t$)), signal processing in the frequency domain (e.g. through Fourier analysis), in the frequency and time domain (e.g. wavelet transform) or through combinations such as done in impedance relays. These different methods all have their advantages and disadvantages. Time measurements of voltage and current (derivatives) are straightforward and do not require any processing, but are subjective to noise and incorrect data samples. Signal processing in the frequency domain was found to be troublesome with respect for analysing the low frequency content in the travelling wave. Wavelet transform does allow a detection of rapid changes without loosing the time aspect as in Fourier analysis [16, 17].

4.2 Protection algorithm

After extensive testing, no measurement signal was found to give satisfactory results in all circumstances. Therefore the proposed protection strategy for VSC-based HVDC systems in this paper uses a combination of three detection criteria. These criteria are based on the following signals:

1. Module M1: fault detection by using the voltage wavelet coefficients (criterion 1),
2. Module M2: fault detection by using the current wavelet coefficients (criterion 2),
3. Module M3: fault detection by using the voltage derivative and magnitude (criterion 3).

These three criteria are needed because the measurements vary with fault location.

In comparison to point-to-point VSC HVDC systems, an additional difficulty appears in an MTDC system. When a cable fault occurs, the DC bus voltage of the two nearest converter stations will be affected. But, since it is a common DC bus, the voltage in the other cables throughout the DC grid are strongly affected. This can result in the fault detection in a healthy cable. To overcome this problem, each detection criterion is divided into two parameters:

1. Parameter 1: fault detection,
2. Parameter 2: fault confirmation + selection of the faulted cable.

Based on voltage and current measurements in each cable separately, parameter 1 detects a fault using a threshold value for each fault criterion. This parameter needs to be determined through simulations in order to obtain selectivity with AC and DC faults outside the protection zone.

Parameter 1 is not in all cases sufficient to correctly identify the faulted cable. In certain cases, a fault will be recorded in multiple cables. Especially, when a fault appears near the converter station, a fault might be detected in the other cables connected to the same DC bus.

To avoid this selectivity problem, a second parameter is taken into consideration. This parameter confirms whether

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the fault appeared indeed in that cable. If a fault appeared, parameter 2 decides in which cable the fault occurred. Parameter 2 is only taken into account when parameter 1 detects a possible fault in order to make a distinction with external faults.

4.3 Triple modular redundancy (TMR)

The idea of using three fault criteria is to achieve a two-out-of-three majority system improving the reliability of the signal processing. When a cable fault appears, the correct line has to be switched off as fast as possible. On the other hand, when there is no fault, it is required that no breaker trips.

To meet both assumptions, the reliability of the protection strategy has to be improved.

Together, the three criteria can forma redundant structure using a majority voting system. Here, the static TMR technique was implemented shown in Fig. 3 [18, 19]. The TMR method is needed as the independent criterion are not sufficient to correctly identify all possible faults.

If the fault is very close to a terminal, independent detection by all three parameters cannot be guaranteed. In this case, a large voltage wavelet coefficient is not sufficient to select the faulted cable. Hence, a comparison of the voltage derivative and magnitude in all three DC cables is necessary. If the fault is far from the terminal (cable end), the current wavelet coefficients will cause a selectivity problem with external faults. One possibility to solve this problem is by increasing the threshold value of parameter 1. This solution contributes to an increase in time at which a fault in a cable between two substations (e.g. $Cable_{12}$ in Fig. 4) is detected by the converter station (e.g. VSC_1 in Fig. 4). By increasing this threshold value, this criterion is not able to detect a remote cable fault applied at the end of $Cable_{12}$ within 1 ms. Owing to the fact that the latter case has a higher priority than the selectivity towards external faults, this possibility cannot be taken into consideration. A two out of three criterium will solve this non-selectivity using the voltage wavelet coefficients, voltage magnitude and derivative. Therefore to detect a fault, at least two criteria should be positive to avoid an unexpected switching-off, even when this is theoretically not possible in this model (real phenomena cannot always be predicted). As mentioned before, the third criterion is sensitive to noise and incorrect data samples.

The advantage of the TMR technique can be explained by two examples:

1. Suppose there is no fault and one of the criteria gives an incorrect interpretation of the measurements. This will result in a high input signal. The voter makes the decision whether a fault occurred. In this case, only one of the input signals is high. Therefore, the voter provides a low output signal (logic 0) and no clearing signal is sent to the DC breaker. Hence, the voter masks an incorrect input.
2. Suppose a fault occurred and one of the criteria does not detect a fault either by an incorrect input or by criterion 2 which does not cover 100% of all fault cases, the voter will mask this misapprehension because the other input signals are high.

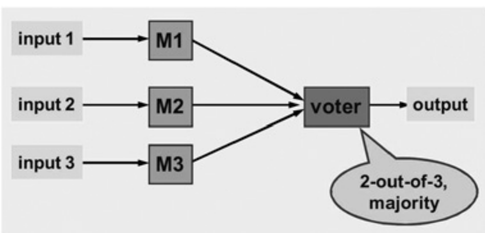

Fig. 3 *Representation of a static TMR-system*

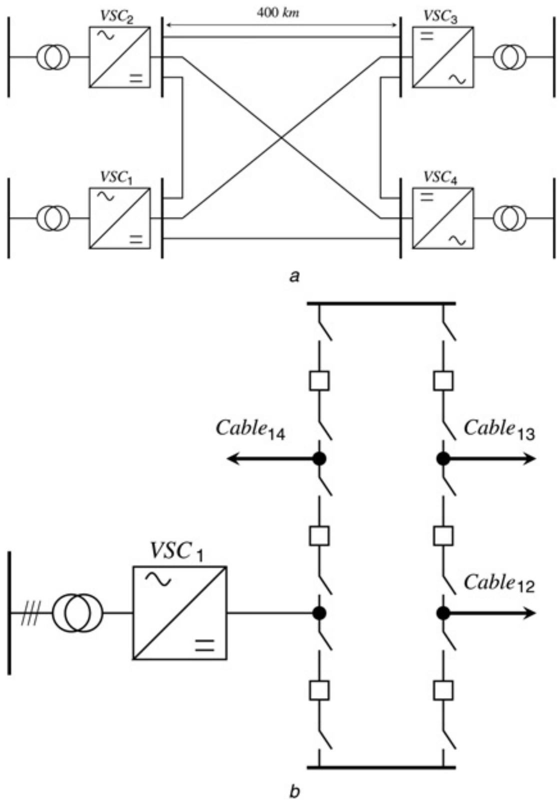

Fig. 4 *Configuration of the four-terminal VSC HVDC system used in this paper*

a 4-terminal MTDC system
b Single line or single pole DC breaker-and-a-half scheme

4.4 Threshold value determination

Essential for the operation of the proposed methodology is a correct determination of the used thresholds to determine whether an event is a fault or not. The search of the correct threshold values can be done through a systematic search using multiple simulations. By focusing on the worst case situations (fault at the far end of a cable and fault at the near end of the cable), this determination can be done in a relatively fast and straightforward manner. In case very large and very meshed DC grids would be used, other computational methods to determine the threshold might be needed.

5 Implementation and results

5.1 DC system

To test the protection methodology, a four-terminal MTDC system implemented in PSCAD is used [20, 21]. The four converters are each connected to a strong (In protection systems, contrary to control systems, a high short-circuit power is more challenging than a weak system.) and independent AC voltage source (V_{AC} = 400 kV, $I_{SC,AC}$ =

53 kA). At the DC side, each DC substation is connected to the other three substations, using bipolar DC cables with a length of 400 km. Together, these converter stations form a meshed HVDC network shown in Fig. 4. Each DC substation is equipped using a breaker and a half topology and solidly grounded. The converters and their controls are modelled using the proprietary positive sequence model of ABB, using a 20 kHz sampling rate.

Although the inverter controls are modelled in the used system, they do not interact with the protection equipment.

In PSCAD only specific simulation blocks for power systems are present. This limits the possibility for signal processing purposes. Therefore the simulation results are post-processed using Matlab. In the base configuration, active power is transported from the rectifier stations VSC_1 and VSC_4 to the inverter stations VSC_2 and VSC_3. Converter station 2 provides DC voltage control. The other converter stations are operating in active power control mode. At the AC side, all converter stations create a AC grid voltage, controllable in amplitude and in phase, at their terminals.

The system is represented by the parameters given in the appendix.

5.2 Implementation of the protection strategy

The proposed protection strategy is applied to all breakers in Fig. 4. Each breaker is equipped with the algorithm. The wavelet transform on the measurements can in practice be done by dedicated microprocessors in the breaker. The simulations performed below focus on the protection of converter VSC_1. The protection zone of VSC_1 includes the cables $Cable_{12}$, $Cable_{13}$ and $Cable_{14}$.

5.3 Fault simulations

Each converter station is connected to a strong AC grid. At the AC side, faults at the point of common coupling (PCC bus) are applied, as well as faults at the filter bus of each VSC terminal. DC faults are applied at both the ends and the middle of each cable. At a DC fault in a cable system, the conductor will be short-circuited between conductor and screen, with only small fault impedance. The fault impedance for the simulations is set to 0.01 Ω.

For the different fault locations, the three fault criteria with their two parameters are examined. The first detection criterion (parameter 1) is based on the wavelet coefficients of the voltages measured in each cable connected to VSC_1. Fig. 5 shows the pole-to-pole faults FLT-12-m-PP applied in $Cable_{12}$ and the external fault FLT-43-3-PP applied in $Cable_{43}$. For each cable, the wavelet coefficients at scale 2^1 are shown.

A distinction has to be made between faults appearing in the protection zone of VSC_1 and external faults. When the detection level is set to a threshold value of 2, a distinction can be made between internal and external faults. The case of fault FLT-12-m-PP is shown in Fig. 5. The fault is detected at $t = 1.05$ ms. FLT-12-m-PP is a fault applied in the middle of $Cable_{12}$. For a correct interpretation of the result presented, the traveling time, that is the time the wave needs to affect the voltage measured at VSC_1, is taken into account being 1.0125 ms. Making the simple subtraction (1.05 ms − 1.0125 ms), the real fault detection time is 37.5 μs.

By looking closer into a number of exceptional cases, the cable selection parameter can be determined (parameter 2).

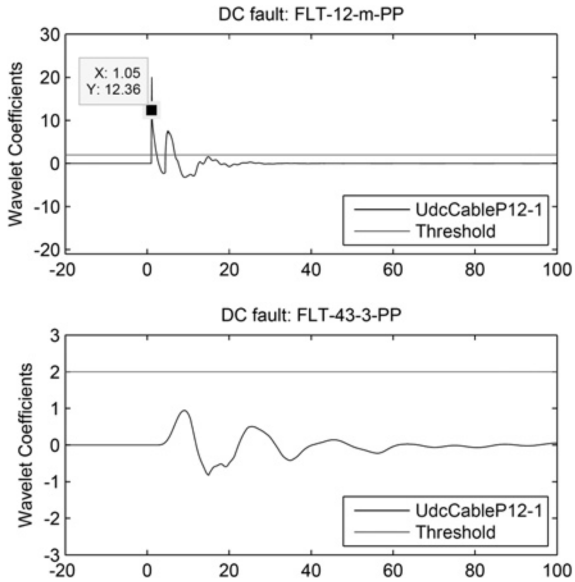

Fig. 5 *Wavelet coefficients of cable voltages at VSC_1 for FLT-12-m-PP and FLT-43-3-PP*

Fig. 6 shows the pole-to-pole faults FLT-13-1-PP applied near VSC_1. These fault is in the protection zone of VSC_1.

It can be seen that in both cases, either in $Cable_{13}$ and $Cable_{14}$, a fault is detected. In $Cable_{14}$, a high wavelet coefficient appears because of the fact that the fault occurred nearby in a $Cable_{13}$ connected to the same DC bus. Both faults are detected by the measurement in $Cable_{13}$ and by the measurement in $Cable_{14}$ at the same time. It is noted that this system is reciprocal.

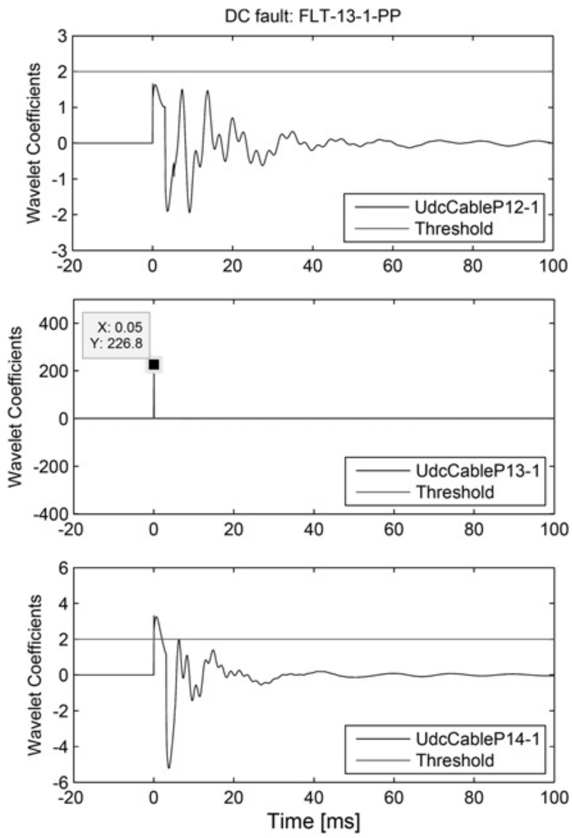

Fig. 6 *Wavelet coefficients of cable voltages at VSC_1 for FLT-13-1-PP*

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One way to overcome this problem is by setting a higher threshold. However, also remote cable faults have to be detected within an acceptable time span. This selectivity condition is the first priority of the protection strategy. Therefore it was not possible to implement this option.

Another possibility to select the faulted cable is achieved by comparing the magnitude of the wavelet coefficients in $Cable_{12}$, $Cable_{13}$ and $Cable_{14}$. For example when a fault is detected in $Cable_{12}$ by parameter 1, the protection algorithm compares the wavelet coefficients with those in $Cable_{13}$ and $Cable_{14}$. If the coefficients from $Cable_{12}$ are the highest, the fault is confirmed and $Cable_{12}$ is selected as faulted. This process is performed each time a potential fault is detected.

As expected, the DC protection algorithm does not operate for faults on the AC side.

Table 1 shows the detection times for DC cable faults near the converter station and for faults applied in the middle and at the other end of each cable. The values in Table 1 take into account the fault distance and hence the travelling time.

In the worst case scenario, namely a remote cable fault at 400 km using the current wavelet coefficients, the fault is detected after 675 μs. It is observed that the proposed protection algorithm is selective with faults at the AC side.

5.4 Selectivity with load fluctuations

Under normal operation conditions, a change of the operation voltage angle at any of the AC terminals is possible. In this situation the selectivity with DC faults must be guaranteed. A variation of 20% in the active power was applied at VSC_1. The active power flow from the AC grid through the rectifier station VSC_1 is abruptly reduced with 20% from 1100 to 880 MW. The positive-to-ground voltage in $Cable_{12}$ is shown in Fig. 7. The wavelet coefficients at the first decomposition level are presented.

Table 1 Detection times for the fault criteria for different fault locations (see Section 5.3)

Fault location	Criteria 1, μs	Criteria 2, μs	Criteria 3, μs
at 0 km (near VSC_1)	50	50	100
at 200 km	50	150	100
at 400 km	225	675	225

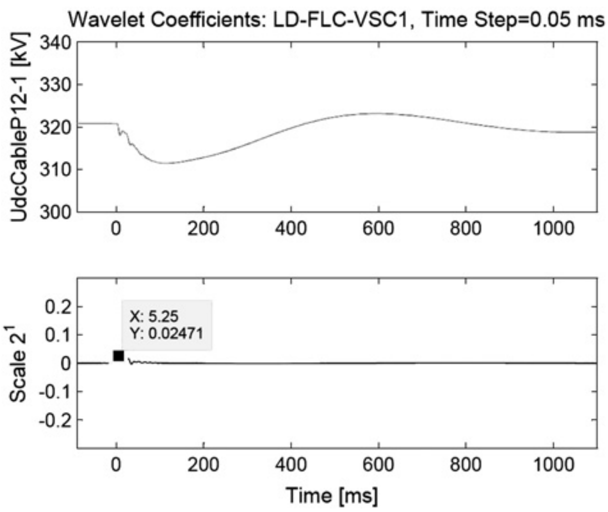

Fig. 7 *Voltage wavelet coefficient at level 1 for a 20% load variation at VSC_1*

The threshold value for the voltage wavelet coefficients was set on 2. In Fig. 7 it is observed that the load fluctuations results in a maximum wavelet coefficient of 0.02471. Therefore load fluctuations cause no selectivity problems.

5.5 Selectivity with AC faults

For calculating the wavelet coefficients in criteria 1 and 2, the Haar-wavelet is used as mother wavelet. Suppose a three-phase-to-ground fault appears at the filter bus of converter station 1. This fault induces high fluctuations in the AC bus voltage in the three phases and is therefore the worst case for an AC fault. Fig. 8 shows the results for the Haar-wavelet applied to the DC cable voltages at VSC_1. The selectivity of the Haar-wavelet is sufficient, the wavelet coefficients remain under the threshold value.

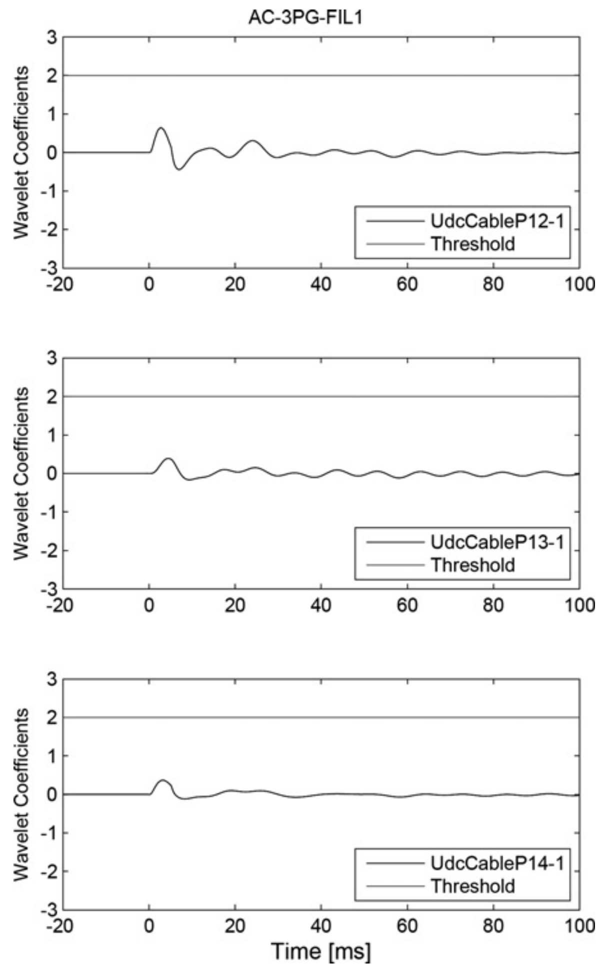

Fig. 8 *Wavelet coefficients of cable voltages at VSC_1 for an AC three-phase-to-ground fault using Haar-wavelet*

Table 2 Parameters for calculation of the DC ripple voltage

Parameter	Value
modulation index	0.82
carrier frequency	1050 Hz
AC line-current (RMS)	1.5 kA
DC pole-to-ground voltage	320 kV
DC capacitor	47 μF

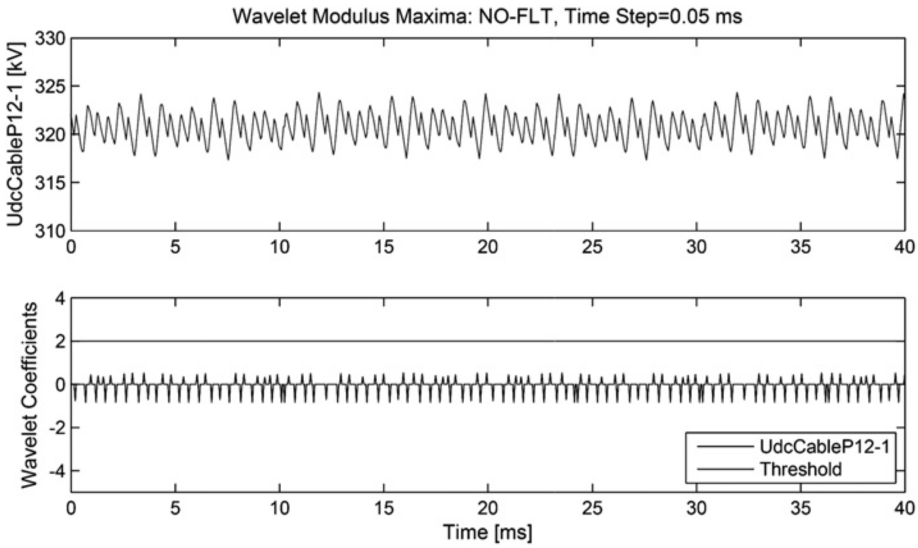

Fig. 9 *Voltage wavelet coefficient at level 1 for a 20% load variation at VSC_1*

5.6 Influence of converter switching

A special remark has to be made concerning the converter unit. In the used model, the electronic switches (IGBTs) are not separately implemented. The converter unit acts as one identity. Thereby, higher harmonic components in the DC bus voltage because of pulse width modulation (PWM) switching are not present in the simulation results.

Since the presence of noise has an important influence on the calculated wavelet coefficients, its influence is examined. The parameters of the used noise signal can be found in Table 2.

This ripple voltage was added to the non-faulted case. The result for the wavelet coefficients and the wavelet threshold value is shown in Fig. 9 where the maxima of the wavelet coefficients are presented.

It is seen that no fault is detected by the protection system, therefore the method is selective with the higher harmonics because of PWM switching.

6 Conclusions

In fault detection, a fast and correct detection of faults is of utmost importance. In order to achieve the required detection times for meshed DC systems, the traditional methods cannot be used. Therefore a methodology using wavelets is presented which allows a fast and reliable detection of DC cable faults. The FDWT is used to select the faulted cable in a meshed DC grid in a timely manner. This wavelet transform offers a time-invariant solution for the wavelet coefficients. It can also be concluded that for fast fault detection only compactly supported wavelets are useful. These wavelets need the lowest number of data samples in order to make a quick decision [16].

The proposed protection strategy offers a high reliability. By the combination of different fault detection and cable selection criteria, 100% selectivity is obtained without the use of communication between the participating converter stations. Using only current wavelet coefficients for fault detection causes a lack of selectivity. This problem is solved by introducing the redundant TMR technique. By evaluating the influence of converter switching noise and the influence of load variations, it is proven that with the proposed protection strategy the selectivity is retained. In addition, the proposed reliable configuration has the capability to mask an accidental mistake of the protection algorithm.

Simulations show that a detection time of less than 1 ms is obtained with the proposed protection scheme, when taking into account the travel time of the fault.

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9 Appendix: simulation data

System parameters	
AC voltage V_{AC} (line–line)	400 kv
frequency f	50 Hz
resistance R_{AC}	3.7853 Ω
inductance X_{AC}	43.2658 Ω
short circuit ratio (SCR_{AC})	35.5
DC voltage V_{DC} (line-ground)	320 kV
DC cable resistance	0.0121 Ω/km
DC cable capacity	0.2961 μF/km
DC cable inductance	0.1056 H/km
DC cable surge impedance	18.9 Ω