LOCATING SINGLE PHASE-TO-EARTH FAULTS IN COMPENSATED AND ISOLATED DISTIBUTION NETWORKS APPLYING TRAVELLING WAVE TECHNOLOGY

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ABSTRACT

The paper presents the experiences with travelling wave technology for fault location in compensated and isolated power grids. Moreover, the installed pilot monitoring system as well as the background of the fault location with travelling waves is presented in detail. Some typical cases of successful fault locating and the potential of collecting additional information from the captured records are discussed. This is the first time the travelling wave technology is applied successfully for the localization of short term single phase-to-earth faults in a compensated network.

INTRODUCTION

The reliable fault localization in a power system network is one of the main criteria for the successful and safe operation of power grids. In many typical, solidly grounded networks, available technologies already provide a sufficiently accurate fault location. In this case, the location is performed by the evaluation of the short circuit reactance at the fundamental frequency component. An improvement of the location result can be achieved by a two-sided algorithm. However, both of these methods require an effective measurement window of at least one period, which is a relevant limitation and can cause errors in the case of very short-term faults. In addition, transient distortions of current and voltage signals can cause significant deviations in the fault location results.
For single phase-to-earth faults in compensated or isolated medium- and high-voltage networks, there are no ready-to-use products on the market offering proper solution for locating the fault. It is only possible to detect the affected line branch, but not an accurate fault location. For locating the fault, e.g. in case of single phase-to-earth faults (110-kV-overhead line), long sections of the line (up to 50 km) have to be partially inspected. For many areas, e.g. mountains, access is challenging. Well-equipped and experienced employees have to inspect the lines on foot, resulting in high costs.
The standard equipment for detecting and locating single phase-to-earth faults and applying methods is not sensitive enough. The measured voltage in the ground fault loop is approximately zero and the magnitude of the fault current is in the range of the load current. In addition, current and voltage signals contain transient distortions which slowly fall off until the electric arc is extinguished. Another difficulty for the conventional method is the necessity of setting the earth factor $\underline{k}_0$, which is not easy to measure and changes with environmental conditions. A high mesh-degree in distributed networks with often applied intermediate feed also contributes to the failure of conventional fundamental component based locating methods.
Therefore other methods, which are not based on the fundamental component in voltage and current, need to be developed and tested in respect to accuracy and reliability of the fault location.
In this paper the experiences with travelling wave technology as one possible way for the fault location under the mentioned difficulties are reported.

IDEA OF FAULT LOCATION WITH TRAVELLING WAVES

Figure 1 shows the typical short-term phase-to-earth fault recorded in a compensated network. The duration of this transient fault was about 45 ms. The moment of inception for the fault can be recognized by the rapidly growing current and strongly dropping voltage in the faulty phase B. After 45 ms, the voltage recovers to a nominal value. Unfortunately, both the fault current and voltage do not exhibit a pronounced fundamental component. As a result, it can be concluded that fault location using the fundamental component is not possible in this case. This example presents clearly that conventional methods are not sufficient to localize all short-term ground faults.

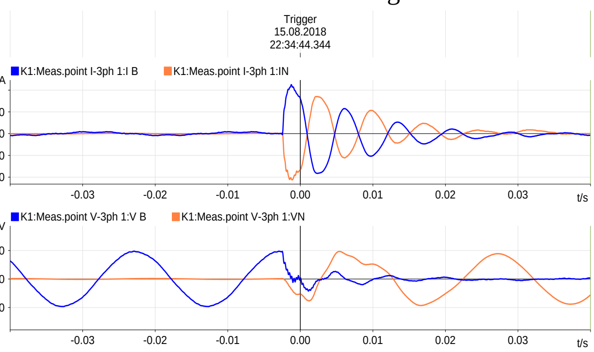

Figure 1: Recorded short-term phase-to-earth fault in a compensated network from figure 5 (Station ST)

There are qualified approaches based on transient analysis which can detect the direction of the short-term ground faults, but often it is just sufficient to localise the affected network branch. The direction of such faults can be computed from the product of the ground current and ground voltage. Detected forward direction on both ends of the line points to the affected network branch. This entire line then needs to be inspected by special qualified personal.

Independent on the network type, each fault can be mostly associated with a rapid drop in voltage. Such an event provides the high frequency components which propagate with a velocity close to the speed of light. The occurrence time of the events is strongly dependent on the distance from the event location. Since the conventional protection and recording devices do not dispose of the appropriate time resolution these effects cannot be observed in common recordings.

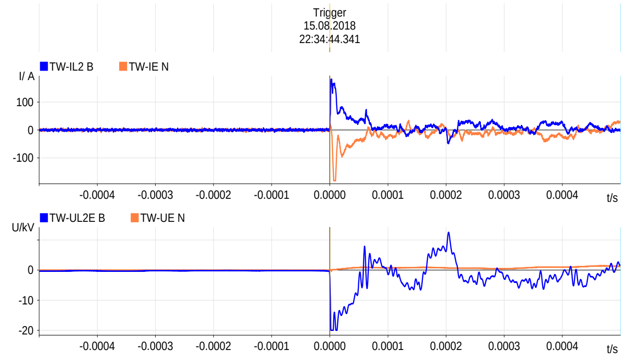

Figure 2: Travelling wave captured by travelling wave fault recorder (Station ST)

The phenomena of wave propagation [1] and wave capturing in the power system network is a complex topic, so in this paper the consideration will be restricted to some particular effects only. For the simple understanding of the travelling wave phenomena it can be imagined that each fault current or fault voltage measured by conventional protection is a superposition of impacts coming from propagated waves generated after the event. Following properties of travelling waves are valid: If propagating waves in one medium meet another medium with different characteristics, the waves will reflect and transmit. The most significant splitting of the travelling waves often takes place on the bus bar, where a large amount of feeders are present. Since each propagation medium has a frequency dependent damping factor, the shape of the travelling wave is smoothed during the travel time. This means that the captured waves coming from distant event locations do not have sharp edges. In practice, the travelling wave phenomena can be clearly recognized after a very short time after the event. For example, for a location of 50 km, the event can be recognised within 170 µs. Most of the time, only the first wave can be effectively used for the fault location. An example of the travelling wave captured by the appropriate device for this goal is presented in figure 2. Extraction of the travelling wave both for current and voltage takes place by high-pass filtering. As can be seen by the trigger time stamp, this is the same fault as in figure 1. The first arriving travelling wave has very pronounced sharp edge and thereby can be relatively simply marked with an accurate time stamp. The accuracy of this time stamp is essential for the accuracy of the fault location.

It can be assumed that wave propagation takes place with constant speed resulting from the overhead line configuration. In practice, this speed is about 97 % of the speed of light for overhead lines. The fault location can be performed by comparison of the arrival times of the captured waves from both sides of the line involving the following expression:

$$FL = \frac{l + \Delta t \cdot \upsilon}{2} \qquad (1)$$

where l is the line length, υ is propagation speed of the wave and $\Delta t = t_1 - t_2$ is the time difference between arriving waves. FL denotes the result of the fault location. This formula is valid for the sending side with the arrival time t_1. For the receiving side, the fault location can be computed according to the assumption: $\Delta t = t_2 - t_1$.

In figure 3, the captured travelling waves occurring in the real field for both sides of the overhead line are presented. Additionally, the captured times for arriving waves from sending and remote side were marked. Knowing the speed of the wave υ=97% c as well as length of the line l=40,61 km fault location can be carried out:

$$FL = \frac{40{,}61km - 81{,}12\mu s \cdot 290.798km/s}{2} = 8{,}51km \qquad (2)$$

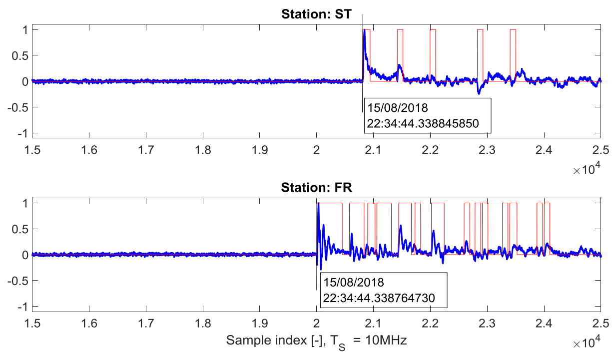

Figure 3: Captured current travelling waves from both side of the line

In figure 3, reflections from the fault place as well as from sound feeders can be recognized. The reflected wave edges are not sharp and reflections from different feeders cannot be simple distinguished from the reflection occurring from the fault.

In some cases, the reflection effect can be also used for fault location. In this case, the so called travelling wave single sided principle can be carried out. Unfortunately, for applications of this type of fault location, detailed data about the network structure around the line affected by the fault is necessary. Otherwise, the fault location can only be carried out in very close proximity to the measurement device. The impact of non homogenous lines can cause significant deviations in this approach. In practice, the single fault location approach can perform the result up to the distance of one half of the path to the first reflection place (e.g. first nearest station). From expression 3 the single ended *FL* result can be obtained:

$$FL = \frac{\Delta t \cdot v}{2(k-n)} \qquad (3)$$

where Δt is the time difference between first (n=1) and second reflection (k=2).

For the transient ground fault from figure 3 the time difference between both considered reflections could be determined. This time is approximately 57,7 µs. Using equation 3, the following is obtained:

$$FL = \frac{57{,}7\mu s \cdot 290.798 km/s}{2(2-1)} = 8{,}38km \qquad (4)$$

The result from expression 4 confirms the fault location performed with a double sided approach from equation 1 with a deviation of 0,13 km. Based on the captured reflection, the distances to the neighbouring stations could be also determined. Since the first neighbouring station is far away, it is more than twice the distance to the fault, the result from single sided fault location can be considered as secure in this case.

From this consideration, it could be concluded that both double sided and single sided travelling wave fault location can be used for the localisation of the short term ground faults with very high accuracy. For the single ended fault location the challenge consists in the distinction of the reflection cause – only reflections from the fault site are important. In contrast, the double ended fault location needs a highly accurate synchronisation between devices for the determination of time differences for arrival waves. However, for a reliable fault location, the double sided fault location approach is preferred.

REQUIREMENTS OF DEVICES

Conventional protection or recording devices are not able to aquire travelling waves. In order to capture the high frequency components contained in travelling waves, devices with sampling rates above several hundred kilohertz are necessary. A high sampling rate guarantees a high time resolution, which is essential for accurate fault location. Siemens developed a travelling wave recorder for this goal, running with a sampling rate of 10 MHz. The sampling process is coordinated by a very accurate clock synchronized to the Global Navigation Satellite System (GNSS). The device has its own GNSS receiver. The resolution of the clock equals 5 ns, which results in a minimal location error of 1,5 m in ideal conditions. The high sampling rate allows for more accuracy in the case of the travelling wave with very sharp edges. This is mostly the case for faults close to the line end.

By itself, the high time resolution is not enough to detect the travelling waves with appropriate accuracy. A suitable magnitude resolution in high frequency range is required. In order to capture the travelling wave the fundamental component is eliminated from the measured signals. The measurement range can be set in a range of 40dB for both the current 0,3 A-30 A and the voltage 2.4 V-240 V. The developed prototype allows for measuring both four currents and four voltages. These inputs can be wired with conventional primary instrument transformers. The non-conventional instrument transformer can also be connected to device over the BNC inputs. It is of interest, if the connection cannot be done by using existing instrument transforms cores.

For data recording, the COMTRADE 2013 format was chosen. It means that the analysis of the event can be performed in the common software applied in protection area. The maximum length of the record is 50 ms with flexible parameterized pre-trigger and post-trigger intervals. However, a recording interval in the range of some millisecond is enough for the capturing of travelling waves. The devices can be triggered over external as well as an internal trigger. The internal trigger is the simple threshold value referenced to the measurement range of each measured quantity. The threshold for voltages and currents can be set separately. The devices cannot perform a fault location by themselves. The records can be transfer by http-protocol to the server where the fault location can be performed using special developed PC software. The trigger time already saved in the records can be used directly for the fault location.

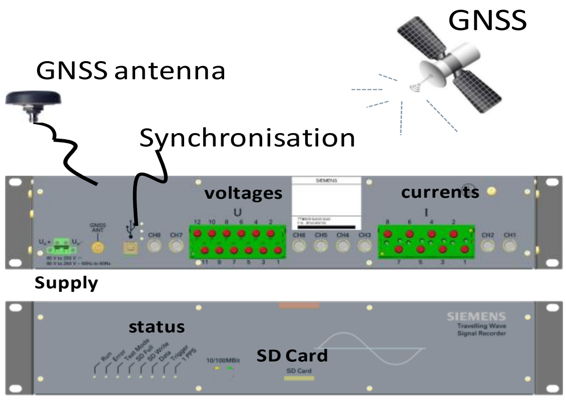

Figure 4: Travelling wave recorder 7TW800

Since the recording is started after exceeding the parameterized constant threshold, it is not sure that the created time difference is accurate enough for the fault location. The deviation of 1 µs already results in an error of 300 m in the fault location. For an improvement of the results, some numerical methods involving a higher amount of samples were applied. The computation of the corrected time stamps takes place offline in the software. Although, many investigation in this field have been performed [2] - [4], experience based on the real recordings need to be gained. For simulated cases, the accuracy achieved with developed devices resulted in the range of some meters.

FIELD INSTALLATION AND FIRST TEST

For data acquisition three travelling wave pilot prototype devices, GNSS-synchronized with sampling rate of 10 MHz were installed at the ends of two 110-kV-overhead lines with a total length exceeding 60 km. The installation was made in stations: ST, FR, TK (see figure 5). These create 3 particular configurations with 40,61 km, 20,85 km and 61,46 km lines. As can be observed, the considered system also contains a parallel line which connects other stations with one of the monitored ones: station TK. The parallel line is split into two parts 162/5D or 162/5E with middle station UA. A characteristic feature of the monitored part of the network is a split ground wire. This occurs on the tower M358. This aspect contributes to enormous difficulties, if the fault location is attempted using method based on the fundamental component. The main purpose of the installation was to see if such a configuration is a challenge for fault location with travelling wave technology.

Conventional instrument transformers were used to measure the currents and voltages. The trigger for picking-up of TW-recorders was set based only on the high frequency components. Since the travelling wave recorders only capture the high frequency components, conventional recording devices with a sampling rate of 16 kHz were installed for the full spectral analysis of the events. These devices are triggered by the travelling wave recorders. The goal of this additional installation was to differ between transient phase-to-earth fault and other events in the network.

The devices save the recordings locally in the “Comtrade” format. After a new event has been captured, the server of the DSO transfers the data to a central network drive for further processing. The absolute time stamp of the event is already included in recordings. Related records from each device are used for analyzing differences in wave arrival times caused by earth-to-phase faults. Based on computed differences in arrival times, the distance of the fault from either end of line can be calculated.

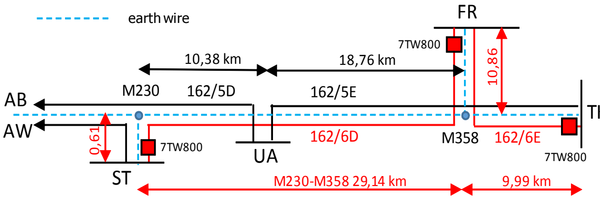

Figure 5: Field installation in a compensated network for the testing of the reliability of the travelling wave technology

The following current range was parameterized for the measuring of travelling waves:

$$
\begin{aligned}
RangeCurrent &= F_{attenuation} \frac{\sqrt{2} U_N}{\sqrt{3} Z_C \cdot CT_{ratio}} \\
&= 0{,}5 \frac{\sqrt{2} \cdot 110kV}{\sqrt{3} \cdot 250\Omega \cdot 600} \\
&\approx 300mA
\end{aligned} \tag{5}
$$

where Z_C is the characteristic impedance of the line, U_N is the nominal voltage of the power network and CT_{ratio} is the ratio of the current instrument transformer. $F_{attenuation}$ denotes the assumed attenuation factor of the current transformer and wiring. The original parametrized threshold was 10 % of the current range. Since the transfer function for the voltage instrument transformer has a significantly worse attenuation characteristic for high frequencies, the voltage range was parameterized to 30 % of the voltage magnitude. Also in this case the threshold level was set to 10 % of the range. Some field experiments were performed to test the settings. One of these was switching on the transformer in idle state. This procedure was carried out for the transformer in the station FR. It was observed that all devices triggered on this event. From the timings in all stations and under consideration of a wave speed of 97%c the lengths of 162/6D and 162/6E were confirmed with an accuracy of some tenth meters. Moreover the performed fault location on the route ST-TK delivered the exact position of station FR, where the event was initiated.

EXPERIENCES

The first short term phase-to-earth fault was captured with all travelling wave recorders about one week after the installation. Based on the information from other measurement instruments installed in the network it could be simply concluded that the fault was on the parallel line 162/5D or 162/5E. However the location was unknown. Since the installed devices on own line picked it up, it was interesting to find out if the fault location on parallel line is possible as well. Standard formula from 1 applied to the captured arrival times at ends ST, TK, and FR delivers the values contained in figure 6. Captured times of the first arrival wave by all devices indicate internal fault. Since the station FR is located directly on the path between stations ST and TK, each fault appeared in area of segment 162/6D or 162/6E should be confirmed over the full path 162/6D +162/6E. At the first view the results seemed to be implausible. Therefore the carefully interpretation of this record was necessary. Assuming that the earth fault occurred on the parallel line, somewhere in area of the station ST, it could be simple to imagine that one part of the wave travels in direction of station ST and another part in direction of FR and TK on segments of the parallel line. The travelling wave cannot arrive at the stations FR and ST at the measured times. The wave must over-couple on the own line during the propagation. It is supposed that the coupling on the own line occurs on the place where the ground wire is split. There were following points: tower M230 (in direction of ST) and tower M358 (in direction of FR). Due to this fact, the waves were received in both stations which are not electrically connected with a parallel line. The confirmation of this assumption can be found in the result of location in the segment 162/6E. The result pointed to the tower M358, where the splitting of the wave occurred. It is typical behavior in case of star- or T- form structure. If the fault did not occur on the segments between both ends, the obtained result from fault location points to the split node. Since the first arrival wave in the station TK did not take the route over the station FR, the result of location between ST and TK is reasonably wrong. Correcting the path between ST and TK taking into account the over-coupling on tower M358 the result of location as the distance of 20,96 km from ST could be confirmed over the other path as well.

Trigger time ST	02:49:04.888326290	4,888326290
Trigger time FR	02:49:04.888321620	4,888321620
Trigger time TK	02:49:04.888319010	4,888319010

calculation with equation 1							
162/6D			162/6E			162/6D + 162/6E	
ST-FR	FR - ST		FR - TK	TK - FR		ST - TK	TK - ST
20,98	19,63		10,80	10,05		31,79	29,67

Figure 6: Fault location results performed by Austrian DSO (Netz OOE GmbH) for the first acquired phase-to-earth fault with travelling wave recorder

The result of the location was confirmed by special qualified service personnel (see Figure 7) inspecting the line as well as the overhead line tower located close to the result. It was discovered that on the tower in the surrounding of the expected fault, the bird's nest was settled. The distance to this tower was 21,28 km. So location was performed with accuracy of about 0,3 km, which is an extremely accurate result for such network types.

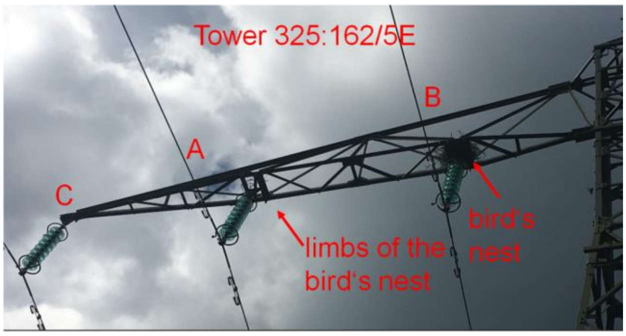

Figure 7: Picture of the tower with bird's nest. The distance to the tower corresponds to fault location result

Within 6 months more than 300 events were recorded. Most of these recordings were captured with all three installed devices. Within these events about 10 % internal phase-to-earth faults were located. Among these recordings there are several types of other event causing transients like: other fault types, faults outside the monitored area, CB-switching, or even disturbances from medium voltage grids.

CONCLUSIONS

From collecting records with this very first single line fault locating system applying the travelling waves method, the following conclusions were drawn:

- with travelling wave technology and a double ended approach, accurate fault location results were achieved
- single sided fault location based on secondary reflection of the wave could confirm the result of the double ended approach
- repeatable results pointed to the same towers
- the fault location could also be carried out for the parallel line using the measurements from the own line
- for the fault inside the monitored area, the over coupling effects were discovered; the primary event waves took the different routes with different lengths, the timings of the waves were comprehensible
- visible coupling effects appeared for the events which involved ground only
- the location of the faults outside the monitored area with single ended principle was not successful; in most cases the magnitude of the travelling waves was not strong enough because they were too far away
- the myth of voltage transformers not transferring the travelling wave could be rejected in this case; the primary reflections could be captured with very high accuracy, however the response time of the voltage transformer caused secondary reflections overlapping the signal which could not be used for the single ended fault location or result confirmation

REFERENCES

[1] R. Ruedenberg, 1962, *Wanderwellen auf der Leitungen*, Springer, Berlin, Germany, 4-113.

[2] X. Bustamante-Mparsakis, J.-C. Maun, C. Dzienis, A. Jurisch, 2017, "Travelling wave fault location based on pattern recognition", *IEEE Manchester PowerTech*, 1-6.

[3] A. Jezierska, C. Dzienis, Y. Yelgin, H. Eberhardt, 2018, "Fault location on distributed an transmission lines based on travelling wave arrival time determination using resonance filter", *PSCC Conference*, 1-7.

[4] C. Dzienis, T. Hensler, M. Kereit, 2018, "Wanderwellen und Fehlerortung", *OMICRON AWT*, Berlin, 34-44.