EVALUATION OF TRAVELLING WAVE BASED PROTECTION SCHEMES FOR IMPLEMENTATION IN MEDIUM VOLTAGE DISTRIBUTION SYSTEMS

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ABSTRACT

This paper investigates travelling wave based protection schemes developed for high voltage transmission systems and their adaptation to medium voltage distribution networks in order to enable ultra high speed relaying (within a quarter of a cycle of the power frequency) on a medium voltage level. After different travelling wave algorithms are evaluated using simple test systems, they are applied to an industrial power system where fault detection within one millisecond is required. Difficulties that arise from typical characteristics of medium voltage distribution systems are outlined and requirements to measurement and signal processing systems are discussed.

INTRODUCTION

Automatic detection and removal of faults have been requirements for operating a power system since the early days of power system development. Early methods were based on electromechanical devices and relatively complex schemes could be implemented by passing the fault currents and voltages through a combination of coils. The next step of the development was the so-called solid-state relay that implemented fault detection through electronic circuits. Nowadays the fault detection is performed in numerical relays that in many cases consist of a digital signal processor (DSP) with additional measuring circuits and output circuits.

The improvement of computers with respect to speed and processing power seems to continue in the future. A sampling rate of 1 kHz that was considered high a couple of years ago is now considered rather low. In this paper a sampling speed of 1 MHz would seem appropriate for some applications and as long as the amount of calculations that will be performed between each sample is not too high, it will be manageable.

There are numerous methods available for fault detection (see for example [1]). Many of them are based on Fourier filters that extract the fundamental frequency component from the measured current and thus have a “dead-time” of typically 16-20 ms (depending on the power frequency 50/60 Hz) before a change in the current can be detected. There are power systems were the need for speed is considerably higher. An example is the industrial power system that is used in this paper as a test system. The reconnection of a generator to an existing busbar was studied. In case of a fault in the reconnected system, the fault current would be larger than the equipment is designed for. A solution that was investigated was to install a fault current limiter. The fault current limiter that was investigated was based on power semiconductors and thus needed a reliable fault detection signal for its operation. The requirement on the speed of the fault detection for the reconnected system is in the order of 1 ms. Hence, methods using travelling waves (sometimes used in high voltage (HV) systems) have been investigated to determine whether they could be suitable to use for this purpose also in medium voltage (MV) systems.

Electrical disturbances on lines result in propagating voltage and current transients. Figure 1 demonstrates how travelling waves are initiated by faults.

Figure 1: The pre-fault voltage $U_{pf}$ appears at the fault location in normal operation mode. When the fault occurs at $t_f$, $-U_{pf}$ is superimposed resulting in traveling waves. Solid line: forward wave $u_+$, dotted line: reflected wave $u_-$.

During normal operation, the pre-fault voltage $U_{pf}$ appears at the fault location. The effect of a fault can be modelled as switching on a negative pre-fault voltage at fault inception time $t_f$. The resulting superimposed quantities are travelling along the line with a certain speed that is dependent on the line characteristics. Reflection takes place whenever the waves arrive at impedance discontinuities, for example at line terminals, junctions, or the fault itself.

METHODS

A number of different fault detection and fault location
methods based on fault induced travelling waves have been published [2]. Some techniques that have been investigated in this paper for implementation in medium voltage distribution systems are outlined in the following.

Fourier/spectral methods

The spectra of fault-induced travelling waves are discussed in [3]. The frequency band of fault transients depends on the line characteristics (distributed parameters) and the line length.

The frequency content of fault-induced travelling waves contains information about the distance to the fault. So-called spectrum analysers are used to build the power spectrum via Fast Fourier Transformation (FFT). Also combinations of correlation and spectral methods can be used [4].

Correlation based methods

Fault detection and location on transmission lines are possible using correlation algorithms [2]. Both autocorrelation and crosscorrelation functions are used for single- and both-end measurements respectively. Normally, the filtered modal components of the phase quantities are used in these algorithms. From the correlation function, the time difference between the arrivals of the transient signals can be estimated. Together with the modal velocity, the fault location can then be determined.

The accuracy of correlation methods depends on the resolution, i.e. the sampling frequency of the measurements. For long high voltage lines, travelling times are long as well, and sampling speed is not an issue. In medium voltage distribution systems lines are normally not longer than a few kilometres, but the travelling speed of the waves is the same as in high voltage systems (close to the speed of light). Therefore a very high sampling rate is needed in order to get adequate results for the fault location.

Another issue with correlation methods is the transient behaviour of current and voltage transformers. Especially the latter ones show a transfer function far from the ideal behaviour that results in a significant change of the signal shape and complicates the use of correlation methods.

Directional wave method

Directional wave relays can be used to determine the fault direction with respect to the relay location [5]. With voltage and current measurements on both ends of a line it is possible to detect whether the fault is between the relays or not, i.e. the faulted line section can be identified. This directional comparison method requires communication between the two relays at the line terminals.

The fault direction can be determined by the use of discriminant functions, which are dependent on the modal voltage and current signals [5].

In medium voltage distribution systems it is very often sufficient to know the section of a line that is faulted. Since lines are not too long, the fault can be located and repaired from the operational staff after the corresponding feeder is disconnected.

Wavelets

Many papers have been written on wavelets and how to use them in power systems (see for example [6]). One way to implement wavelet transforms is through filter banks implementing Multi Resolution Analysis (MRA) in which the analysed signal is filtered through a sequence of filter banks so that the result is a set of signals in the time-domain. Each set represent a band pass filtered version of the original signal. In this way it can be analysed how the frequency content of the studied signal varies with time. Quite a few applications of wavelet transforms are based on feature detection. Such applications could be worthwhile to use when trying to use wavelet theory for the detection of travelling waves. There are discrete versions of the wavelet transform that are suitable for computer implementation. For each sampling instant, the wavelet-transform is performed or updated and when a travelling wave is present it should be possible to detect it in one or a few of the band pass filtered outputs from the filter bank. It should also be possible to distinguish a travelling wave from a transformer energization or a capacitor energization because the frequency content of such events can be determined. In [7] a correlation based method and a wavelet based method are analyzed and it is shown that under some assumptions, the correlation method is nothing more than a wavelet transform.

STUDIED SYSTEMS

Three simple power systems have been modelled and implemented in the simulation software PSCAD/EMTDC [8]. Power system shunt faults (1-, 2-, and 3-phase) have been simulated at different locations, with different fault resistances (5, 50, and 500 Ω) and different fault inception angles (5°, 45°, and 90° after voltage zero crossing). Phase voltages and currents have been recorded at different locations using ideal transducers. For a few of the voltage recordings a model of a capacitive voltage transformer (CVT) has been used. The recorded data have then been exported to Matlab for further evaluation.

Simple HV system

This system (Figure 2) consists of an infinite source representing a high-voltage transmission grid with a short-circuit power of 3 GVA at 250 kV.
The infinite source is connected to a load through a transmission line that has a length of 200 km. The transmission line is represented as a distributed parameter model so that travelling wave effects will be apparent. The load was selected to 66 MW and 22 MVAr. A busbar capacitance has to be included in the model in order to represent the high-frequency properties better. Its value was selected to 0.1 \( \mu \)F (see for example [9]).

Faults have been applied at five locations along the line and with different fault resistances and fault inception angles. Two periods of data have been recorded for each fault case – one period before the fault and one period after the fault. Three-phase voltages and phase currents have been recorded at each line end.

An example of a recorded phase voltage due to a three-phase fault is given below (Figure 3).

![Figure 2: A small test system. The labels F1 through F5 represents different fault locations along the line.](image)

**Simple MV system**

Essentially, this is the same system as the simple HV system (Figure 2). The parameters of the infinite source has been adjusted to represent a 12 kV system with a short-circuit power of 416 MVA. The line model was substituted for a cable model with a length of 4 km and the load was modified to 10.4 MW and 7.5 MVAr at 10.5 kV. Since the length of the cable was shorter than the line length in the HV system, the sampling frequency had to be adjusted to 1 MHz.

**Industrial system**

The third system has been used in previous studies [10]. This system illustrates the connection of a generator to a weak system. As an alternative to upgrading the system a solution with fault current limiters was studied [11]. In such a system, the need for fast fault detection is apparent, thus it was of interest to study possible travelling waves in this system and if they could be used for fast fault detection. The system is described in detail by [10] but some important parameters are repeated here for convenience. One important modification is that where [10] used a lumped impedance to represent a cable, the distributed parameter cable model available in PSCAD/EMTDC is used instead.

An infinite source of 2250 MVA at 135 kV is used to represent the connection to the transmission grid. A power transformer (135 kV/10.5 kV – 55 MVA) connects the transmission grid to the medium voltage distribution system. From the power transformer a cable of length 1 km connects to the medium voltage busbar under study. To the busbar a generator rated 81.25 MVA at 10.5 kV is connected. Its parameters are selected so that it produces approximately 10 MW when the system is in steady state.

![Figure 4: An industrial system. The labels F1 through F3 represents different fault locations in the system.](image)
From simulation results of the simple HV and MV systems it was concluded that the directional wave relay is the most promising method to work in the industrial system. Therefore simulations were carried out for this system using the directional wave method.

CONSIDERATIONS FOR IMPLEMENTATION

Many of the methods that are described in this paper have originally been used in transmission systems. Since the aim of this paper is to study whether it is possible to use those methods in medium voltage distribution systems one must consider that a transmission system in many ways is different from a distribution system. A few items that are important to consider are found below.

Sampling

One consideration for travelling wave based methods for fault location is that the sampling speed has a clear relationship to the accuracy of the estimated fault location. For MV distribution systems the message is twofold – first the cables/lines are short, the travel time for a travelling wave is in the order of 10 \( \mu \)s which indicates that a sampling period time of about 1 \( \mu \)s should be used. Second it is not always necessary to locate the fault, just detect that a fault has occurred. For such a case the requirement on the sampling time period will probably be lower.

Line/Cables

Especially in densely populated areas (urban districts and cities) cables are often used for electricity distribution. In terms of transients, cables and lines show different characteristics. The major difference between lines and cables is their shunt capacitance. Due to closer conductors and different insulation materials, cables have usually a much higher shunt capacitance compared with overhead lines of the same rating and voltage level. Also the series inductance differs, normally it is slightly lower for cables. The travelling wave propagation velocity depends on both parameters, and is usually lower for cables than for overhead lines.

Measurement Transformers

The current transformers (CTs) that are used in MV distribution systems are built up in the same way as those intended for use in HV transmission systems. Of course there are substantial differences in size, isolation and even location (indoors/outdoors) but the principle remains the same. A voltage transformer (VT) intended for use in a MV distribution system is typically a pure magnetic voltage transformer. At higher voltage levels the common practice is to use capacitive voltage transformers (CVTs) that consists of a capacitive voltage divider in series with a magnetic voltage transformer. These two types of voltage transformers have different bandwidths and the CVT is furthermore tuned to one frequency so its behaviour is unknown for other frequencies.

When comparing the bandwidth of a CT with that of a VT (or CVT) it is well documented that a CT has higher bandwidth than a VT (or CVT) [12]. Thus it would be more suitable to detect travelling waves in measured current signals than in measured voltage signals.

Topology

The implementation and performance of travelling wave based protection depend very much on the grid topology. Topology characteristics of medium voltage distribution systems are not very beneficial for the implementation of travelling wave based protection schemes. Table 1 compares typical properties of high voltage transmission and medium voltage distribution networks.

The main complicating factors for distribution systems are:

- Short travelling times due to short lines require fast sampling
- High number of reflections due to T-junctions (customer connections etc.) have to be regarded in the algorithms
- High damping of transients due to comparatively high resistive part of line impedance
- High frequency of travelling waves due to shorter lines [3].

<table>
<thead>
<tr>
<th></th>
<th>HV transmission</th>
<th>MV distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical nominal voltage</td>
<td>&gt; 100 kV</td>
<td>&lt; 50 kV</td>
</tr>
<tr>
<td>Typical line impedance</td>
<td>almost inductive (imp. angle 90°)</td>
<td>resistive and inductive (imp. angle 45°)</td>
</tr>
<tr>
<td>Typical line length</td>
<td>up to several 100 km</td>
<td>few km</td>
</tr>
<tr>
<td>Typical topology</td>
<td>meshed</td>
<td>radial, open ring</td>
</tr>
<tr>
<td>T-junctions</td>
<td>rarely</td>
<td>frequent</td>
</tr>
</tbody>
</table>

SUMMARIZING DISCUSSION

As reported in previous studies [13], the use of travelling wave based methods in distribution systems is more complicated than in transmission systems. Shorter lines and therefore shorter travelling times represent the main challenge for an implementation.

The attempts to implement correlation based and wavelet based methods worked for some of the recorded signals but not for all. One issue with these methods is insufficient sampling speed what corresponds to a low resolution of the
It was earlier mentioned that it is sometimes sufficient to have a crude fault detection/localization, i.e. whether a fault is inside a system or outside a system. The directional wave method can provide such a criterion which was demonstrated using the fault records from the industrial system.

However, further studies are required to investigate how the method responds to other transients than faults such as capacitor energization, transformer energization, or opening of a circuit-breaker.

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REFERENCES


