A NOVEL TRAVELLING WAVE BASED FAULT DETECTION SCHEME FOR SERIES COMPENSATED TRANSMISSION LINES USING WAVELET TRANSFORMS

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ABSTRACT

Series compensated transmission lines have serious protection problems due to the lumped nature of the capacitor bank and due to Metal Oxide Varistor (MOV) operation. In this paper, an Ultra High Speed (UHS) solution for series compensated transmission line using Wavelet Transform is presented. The synthetic relaying signals are transformed using Wavelet Transform instead of conventional filtering. Digital simulation results are obtained for different types of short circuit faults simulated at different locations on the series compensated transmission line. As the scheme is not an impedance based protection scheme, it is unaffected by the location of capacitor bank with respect to the fault location. Also, the proposed scheme is unaffected by the change in impedance caused by the MOV operation. The scheme is able to detect close-up faults as close as 10 km from the relay as well as faults with fault incipient angle approaching 0°.

KEYWORDS: Power system protection, EHV transmission lines, Capacitor compensated transmission lines, Wavelet Transforms.

1. INTRODUCTION

Transmission lines are series compensated to improve power transfer capability. Capacitor banks are installed in the transmission line at appropriate locations to reduce the series reactance of the transmission line which is mainly inductive. Due to the lumped nature of the capacitive reactance, the impedance of the transmission line is not uniformly distributed throughout the length of the transmission line. This causes a myriad of problems for the impedance based protection relays, e.g., if a short circuit occurs before the capacitor bank, the impedance seen by an impedance relay installed before the capacitor bank is actually higher than the impedance seen by the relay if the same short circuit would have occurred after the capacitor bank. Also, the inclusion of MOV causes the transmission line impedances to change by bypassing the fault current through the capacitors. The complications introduced by series compensation render the impedance measurement as an unreliable fault detection method for the series compensated transmission line. An example of protection system failure was the grid utility system rotating blackout in north eastern Canada and United States in 2003.

As conventional relaying solutions are unreliable for series compensated transmission line, many novel solutions have been proposed such as the UHS distance protection scheme by Crossley and McLaren [1], Christopoulos et al. [2], and the UHS direction protection scheme by Johns [3], Takagi et al. [4]. But, there are shortcomings in the proposed schemes, e.g., inability to detect close-up faults, inability to detect faults incipient at 0° of the sinusoidal wave.

Wavelet Transform is a new kind of orthogonal transform. Unlike the conventional Fourier Transform, the time information is not lost in the Wavelet Transform. Consequently, it is suitable to study non-stationary processes having sharp discontinuities. Wavelet Transform can efficiently extract the discontinuity from the input signal along with the time information.

A Wavelet Transform based solution is presented in this paper. The proposed method is based on travelling waves direction protection [3]. The synthesized relaying signals were processed using Wavelet Transform instead of conventional digital signal processing. The travelling waves signals are extracted from the fault signals which are further processed to obtain the relaying signals. The proposed direction protection scheme falls under the category of unit-protection schemes as the local and remote relays work in tandem to detect the fault.

2. WAVELET TRANSFORMS

Wavelet Transform is being used in this paper to process the synthetic relaying signals. Unlike Fourier Transform which uses sinusoids as basis functions, Wavelet Transform uses localized waves [5] owing to which it is able to preserve the time information naturally, without any windowing method. Today, Wavelet Transforms are employed in a variety of applications, from detecting High Impedance arc type faults [6, 7] to compression of fingerprint files. A brief overview of Wavelets is given below [8].

Consider a signal $x(t)$, with bandwidth 0 to π. Let $\phi(t)$ be another selected function defined as

$$\phi_m(t) = \phi(t-m). \qquad (1)$$

$\phi(t/2)$ is a dilated version of $\phi(t)$. $\phi(t)$ and the translated version of $\phi(t)$ expressed as $\phi(t-m)$ can be used to completely represent $\phi(t/2)$ as follows

$$\phi\left(\frac{t}{2}\right) = \sqrt{2}\sum_{m=0}^{N} h'(m)\phi(t-m), \quad (2)$$

where $h'(m)$ are some specified coefficients. The function $\phi(t)$ in (2) is called the "scaling function". For $\phi(t)$, (2) becomes,

$$\phi(t) = \sqrt{2}\sum_{m=0}^{N} h'(m)\phi(2t-m). \quad (3)$$

The equivalent "wavelet function", $\psi(t)$, is obtained from the scaling function as

$$\psi(t) = \sqrt{2}\sum_{m=0}^{N} -(-1)^m h'(N-m)\phi(2t-m), \quad (4)$$

3. Travelling Waves

For a single phase AC system, the post fault voltage and current waveforms are given as [9]

$$v(t) = v_p(t) + \Delta v(t), \quad (5)$$
$$i(t) = i_p(t) + \Delta i(t), \quad (6)$$

where $v_p(t)$ and $i_p(t)$ are the pre fault voltage and current respectively while $\Delta v(t)$ and $\Delta i(t)$ denote the incremental voltage and current respectively.

The incremental voltage and current after fault are given by the "wave equation" [9] as,

$$\Delta v(t) = \frac{1}{2}(a'(t) + b'(t)), \quad (7)$$

$$\Delta i(t) = \frac{1}{2Z_s}(a'(t) - b'(t)), \quad (8)$$

where Z_s, $a'(t)$, and $b'(t)$ are the line surge impedance, forward, and backward travelling waves respectively. Replacing Z_s by the replica resistance R_s and replacing $a'(t)$, and $b'(t)$ by the new relaying signals $a(t)$, and $b(t)$ respectively in (7) and (8), and solving for $a(t)$ and $b(t)$ gives

$$a(t) = \Delta v(t) + R_s \Delta i(t), \quad (9)$$

$$b(t) = \Delta v(t) - R_s \Delta i(t). \quad (10)$$

where R_s is the replica resistance while $a(t)$ and $b(t)$ are the new relaying signals. For three phase, the fault voltage and current are transformed using modal analysis [10] as follows. The modal components are obtained from phase quantities by using the following equations,

$$v_{0\alpha\beta}(t) = S^{-1} v_p(t), \quad (11)$$

and

$$i_{0\alpha\beta}(t) = Q^{-1} i_p(t). \quad (12)$$

There are two "aerial" modes, α mode and β mode, propagating at a velocity close to c ($c = 2.99 \times 10^8$ m/s), and a "ground" or "0" mode propagating at a relatively lower velocity. The transformation matrix used is given in Appendix A.

4. Power System

The single line diagram of the sample EHV, meshed transmission interconnected power system is shown in Figure 1. The local source is a 13.8 kV, 2000 MVA generating station and is modelled by an equivalent 60 Hz, 13.8 kV Thevenin's source in series with a 0.2437 mH inductance and a 0.025 Ω resistance. The source voltage is stepped up to 500 kV using a Δ-Y transformer bank. The remote source is a 500 kV, 3200 MVA system and is modelled by an equivalent 60 Hz, 500 kV Thevenin's source in series with a 207 mH inductance and a 7.8 Ω resistance. The phase difference between the local source and the remote source is 10°.

The transmission line is a single circuit, 322 km (200 miles) 'Long Transmission Line'. It is transposed at 80 km (50 miles), 161 km (100 miles), and 282 km (175 miles) intervals. Conductors are bundled with 3 conductors per bundle per phase. The transmission line is modelled using the frequency dependent José Marti Model [11] using EMTP-ATP [12].

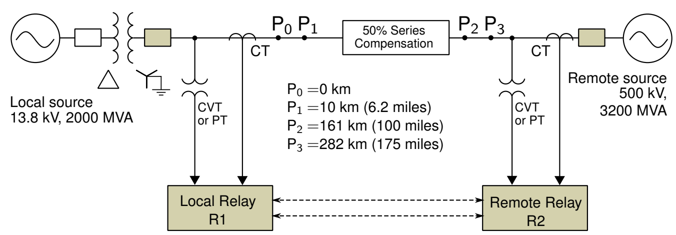


Figure 1: Single Line Diagram of the Meshed, 500 kV, 322 km (200 miles) Transmission System.

5. Short Circuit Faults

For the sample study system, bolted faults are modelled by a 0 Ω resistance and linear faults are modelled by a 50 Ω resistance.

6. Proposed Scheme

The novel UHS relaying algorithm, shown in Figure 2, is explained as follows:

- As per Saleem and Sharaf [13], the measured phase voltages and currents are decoupled to obtain the modal components from which the incremental voltage and current signals are obtained using cycle subtraction. The incremental voltage and current signals are processed to obtain the relaying signals $a(t)$ and $b(t)$. Wavelet Transform of the relaying signals is obtained to remove the high frequency travelling waves from the relaying signals. The resultant signals are denoted as $\widehat{a(t)}$ and $\widehat{b(t)}$.

- The fault direction is determined by monitoring the relaying signals. Let the forward direction be from the local relay toward the remote relay. A forward fault is indicated if $\widehat{b(t)}$ crosses a set threshold before $\widehat{a(t)}$ does. A reverse fault is indicated if $\widehat{a(t)}$ crosses the set threshold before $\widehat{b(t)}$ does. A fault would exist on the transmission line if the local relay indicates a forward fault and the remote relay indicates a reverse fault.

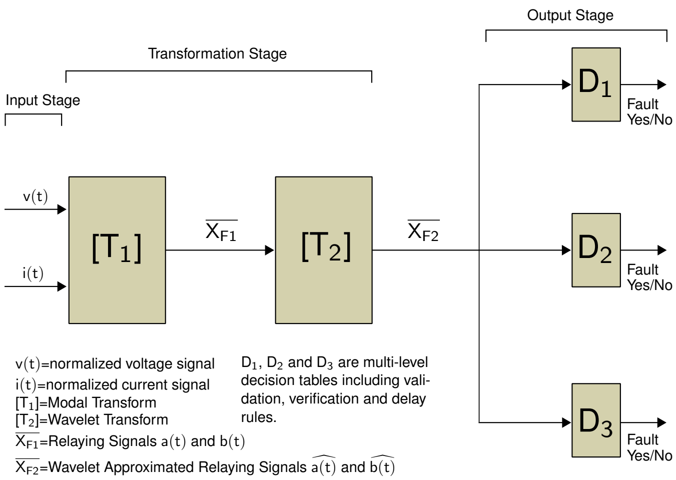


Figure 2: General Structure of the Multi-level High Speed DSP Relaying Scheme.

7. Test Cases

A series of short circuit tests were simulated at 10 km, 161 km, and 282 km as shown by points P1, P2, and P3 respectively in Figure 1.

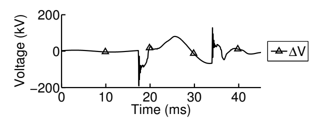
Table 1: Test Cases (5 Cases)

Case #	Type	Dist. km.	Angle deg	Modal Transform
1	a-g, single line-ground bolted fault	10	0 °	α
2	c-g, single line-ground linear fault	282	30 °	β
3	a-c, double line-ground bolted fault	161	90 °	0
4	a-b-g, double line-ground bolted fault	10	30 °	α
5	a-b-c, three phase bolted fault	161	90 °	α

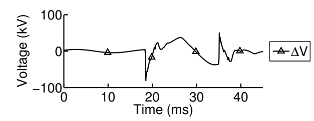
8. Digital Simulation Results

The digital simulation results using EMTP-ATP [12] are shown in Figure 3 and Figure 4. The simulation results of selected cases given in Table 1 are given in the Figure 3 and Figure 4.

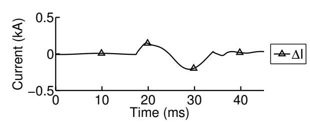
The Wavelet Transform of the synthesized relaying signals was obtained using Matlab Wavelet toolbox [14]. Daubechies's "db3" was chosen as the "Mother Wavelet" to obtain the Wavelet Transform of the relaying signals. The final relaying signals were reconstructed using the 3^{rd} level "approximate" coefficients. The final relaying signals, $\widehat{a(t)}$ and $\widehat{b(t)}$, are shown in Figure 3(g) and Figure 3(h) for the local and remote ends respectively.



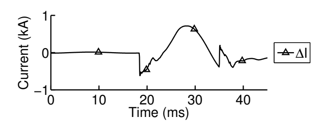
(a) Incremental Voltage at the Local End for Case 1.



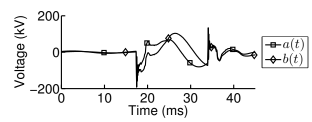
(b) Incremental Voltage at the Remote End for Case 1.



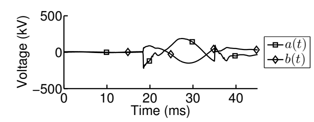
(c) Incremental Current at the Local End for Case 1.



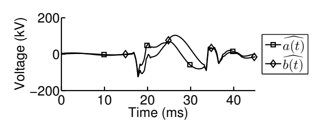
(d) Incremental Current at the Remote End for Case 1.



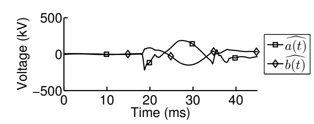
(e) Relaying Signals at the Local End for Case 1.



(f) Relaying Signals at the Remote End for Case 1.



(g) Wavelets Approximated Relaying Signals at the Local End for Case 1.

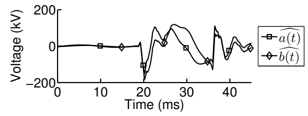


(h) Wavelets Approximated Relaying Signals at the Remote End for Case 1.

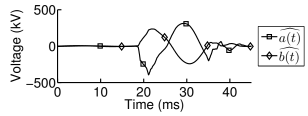
Figure 3: Simulation Results for Case 1 using α Transform.

9. Conclusion

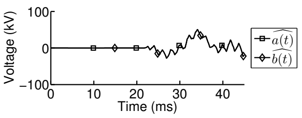
In this paper, a novel direction type UHS relaying scheme using Wavelet Transforms is presented. The relaying signals were processed using the Wavelet Transform instead of conventional signal processing methods. The relaying signals approximated by Wavelet Transform were able to correctly detect short circuit faults on the sample study system. The proposed scheme is unaffected by the location of capacitor bank. Also, the independent of the fault impedance and is immune to change in impedance caused by the MOV operation. The scheme is able to detect close-up faults as well as faults approaching 0°. Results for arcing short circuit faults are presented by the authors in another paper [15].



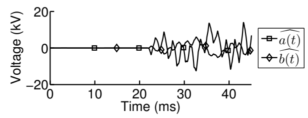
(a) Wavelets Approximated Relaying Signals at the Local End for Case 2.



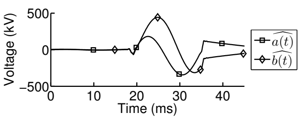
(b) Wavelets Approximated Relaying Signals at the Remote End for Case 2.



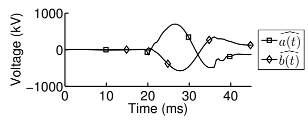
(c) Wavelets Approximated Relaying Signals at the Local End for Case 3.



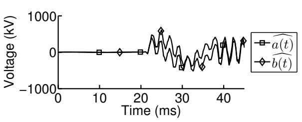
(d) Wavelets Approximated Relaying Signals at the Remote End for Case 3.



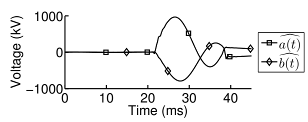
(e) Wavelets Approximated Relaying Signals at the Local End for Case 4.



(f) Wavelets Approximated Relaying Signals at the Remote End for Case 4.



(g) Wavelets Approximated Relaying Signals at the Local End for Case 5.



(h) Wavelets Approximated Relaying Signals at the Remote End for Case 5.

Figure 4: Wavelets Approximated Relaying Signals.

A. Modal Transformation Matrix

The modal transformation matrices [S], [Q] defined in equations (11) and (12) are defined as,

$$[S] = [Q] = \begin{bmatrix} 1 & 1 & 1 \\ 1 & -2 & 1 \\ 1 & 1 & -2 \end{bmatrix}. \qquad (13)$$

B. Transmission Line

The EHV transmission tower is shown in Figure 5. ACSR and ACAR cables data is given in Table 2.

Table 2: Characteristics of Conductors

Code	Use	Cross Section kcmil	Cond. Dia. in.	Core Dia. in.	DC Resis. Ω/Mile (25° C)	GMR ft.
ACSR	Phase	1590.0	1.504	0.376	0.059	0.0497
ACAR	Sky wire	248.7	0.572	0	1.118	0.0031

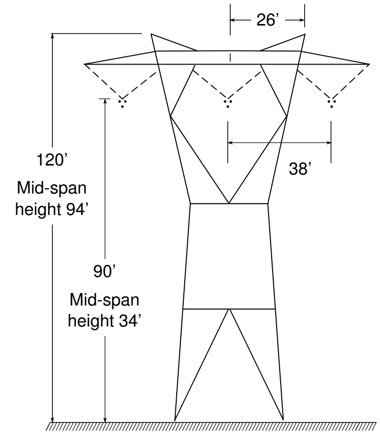


Figure 5: Overhead Transmission Line Tower.

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