Fault Localization using Wavelet Transforms in 132kV Transmission Lines

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Abstract: Fast fault clearance and fault localization is of great interest in the context of power systems operations and economics. Conventional distance protection schemes provide adequate information in fault isolation but do not provide sufficient information for fault localization and characterization in required accuracy. This study develops a distance relay observer model using fault transient analysis to be used in radial and in branched networks. Wavelet analysis together with traveling wave behavior of fault transients obtained from wide band substation voltage transformers are used to retrace the fault transient history. Modal transform associated with Daubechies filtration of fault transients identifies successive impulses. The resulted fault transient voltage graph together with network topology is used to calculate the fault distance and fault category. The polarity, magnitude and timing of the reflections originated from network boundary discontinuities and from the fault are analyzed to locate the fault. Simulation studies in MATLAB/SIMULINK environment demonstrate that this scheme is capable of locating and characterizing the faults accurately.

1. Introduction

Electric power systems are susceptible to various types of faults caused by transient weather or animal induced situations as well as maintenance circumstances with human and asset related failures. The fault locating, fault clearing and power restoring functions have more expert systems based control than human decision based control.

The conventional distance protection schemes used in transmission and primary distribution networks employ impedance based fault identification techniques using pre fault and post fault power frequency signal analysis. It provides the combination of fast fault clearance with selective tripping. But it will not reveal the accurate information about fault location since calculated line impedance based on relay measurements is influenced by harmonics and DC components when fault occurs. Further distance relay is normally set at 80% of the length of the line to ensure the relay reliability due to overreaching and under reaching effects.

Thus once receiving the feeder circuit breaker trip information, the fault clearing teams have to identify the faulty feeder for fault localization and remedial action. It can be a rigorous and time-consuming task and the reconnection time primarily depends on the fault localizing duration than the remedial duration.

Among the presently available fault localizing techniques, Impedance based fault location

algorithms [1,2] make use of voltage and current signals at pre-set locations to calculate the line impedance. [1] uses an apparent impedance based technique for multiple fault location predictions by continuously updating the voltage and current vectors, extracting the fundamental components and then determination of fault type and phasors. But it does not address the ranking of multiple fault locations and the compensation for modeling errors.

Knowledge-based techniques [3-5] often rely on external information such as SCADA alarms, substation and feeder switch status, feeder measurements, load voltage sensors, etc. These approaches may not be feasible since measurements are usually only available at the substation and information about the operation of feeder protective devices is normally unknown.

[6,7] Describe methods based on integration of disturbance fault recorder data with network topology characteristics. [6] consists of calculating the complex power at each node during the fault by modeling its behavior according to the voltage variations and then fault distance in a recursive algorithm. [7] calculates the faulted regions based on

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probabilistic modeling and analysis to deal with uncertainties in system modeling and phasor estimation.

Travelling wave based fault detection techniques [8-14] based on fault transient analysis can address the fault location problem for power networks more accurately. Selection of accurate fault point among multiple fault location predictions, fault distance calculation to a higher degree of accuracy and fault type clarification can be easily obtained through a proper algorithm developed.

Information for fault localization is mostly available in the fault transient waveforms. Thus the fault localization by fault transient analysis is a preferred scheme. This approach is more viable due to the rapid growth of microprocessor power and hence improved digital relaying techniques.

Thus this research focuses on analysis of fault transients to develop an observer model for distance protection relay agent in fault localization.

2. Proposed fault location scheme

The proposed research work has developed a fault transient based fault locating scheme which can act as an observer model to the microprocessor based distance relay. The principle of the proposed fault location scheme is based on the identification of successive high frequency travelling waves arriving at the substation end relay. The faulted voltage records rich with non periodic signals containing both high frequency oscillations and impulses apart from power frequency are converted by modal transforms to eliminate significant electromagnetic coupling. The modal signal with sufficient transient information is processed using Wavelet Transform [8,16] in mapping transients in to time - magnitude - frequency plane to produce high frequency notch analysis of fault characteristics. Fault distance is calculated by using an algorithm which retraces the processed transient signal history subjected to Wavelet analysis.

The fault transient information is obtained by simulating different types of faults on a 132kV power transmission network model developed in MATLAB/SIMULINK environment. The Modal analysis and Wavelet analysis are built

into the model by SIM Power systems signal controls block set available.

The resulted fault transient graph provides basic information for fault distance calculation together with the power network's physical characteristics. Further a modified fault location algorithm is presented to look after the faults in a branched power network.

2.1 Fault Transient Analysis using Wavelet Transformation (WT)

Wavelet Transform is a multi resolution analysis based technique which provides non stationary signal analysis at different frequencies with different resolutions to give a good time resolution with poor frequency resolution at high frequencies and good frequency resolution with poor time resolution at low frequencies. A key part in fault transient based algorithms is the detection of transients and extraction of their magnitude, time and frequency information.

2.1.1 Continuous Wavelet Transform (CWT)

In mathematical terms, the WT of a continuous signal $X(t)$ is given by $W_s(a, b)$;

$$W_s(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} X(t) h^* \left(\frac{t-b}{a} \right) dt \dots \dots (1)$$

- a - scale parameter defining the support width of the wavelet
- b - Translation parameter localizing the wavelet functions in the time domain.
- $h(t)$ - Mother wavelet (a finite window function)

The mother wavelet ($h(t)$) is short and oscillatory having zero average and decay quickly at both ends. This restriction is to ensure that the integral in (1) is finite and gives the name wavelet or 'small wave' to the transform.

CWT is a correlation between a wavelet (mother wavelet) at different scales and the signal with the frequency being used as a measure of similarity. It is computed by changing the scale of the analysis window, shifting the window in time, multiplying by signal and integrating over all times.

2.1.2 Discrete Wavelet Transform (DWT)

Since the computation of CWT requires a significant amount of computation time and resources, DWT is introduced to provide sufficient information for both analysis and

synthesis of the original signal with a significant reduction in computational time.

In DWT, a time-frequency representation of a digital/ sampled signal is obtained using digital filtering techniques. The sample signal is passed through a series of high pass and low pass filters to analyze high frequencies and low frequencies respectively. Therefore implementation of DWT involves successive filtering of the signal at each scaling stage using low pass and high pass filters whose coefficients are determined by the shape of the mother wavelet.

In mathematical terms, DWT of a sampled signal is given by,

$$DWT(m, k) = \frac{1}{\sqrt{a_0^m}} \sum_k X(n) h^* \left[\frac{(k - na_0^m)}{a_0^m} \right] \dots (2)$$

Where $h(n)$ is the mother wavelet and scaling and translation parameters a and b in (1) are functions of an integer parameter m , in such a way; $a = a_0^m$ and $b = b_0^m$.

The equation in (2) can be represented in a different format to show the similarity in between general equation for finite impulse response for digital filters with the DWT as follows.

$$DWT(m, n) = \frac{1}{\sqrt{a_0^m}} \sum_k X(k) h^* (a_0^{-m} n - k) \dots (3)$$

Finite impulse response is;

$$y(n) = \frac{1}{c} \sum_k x[k] h[n - k] \dots \dots \dots (4)$$

Equations (3) and (4) suggest that $h^*(a_0^{-m} n - k)$ is the impulse response of a low pass digital filter for a given transfer function.

2.2 Wavelets for Power System Transient analysis

Fault transients are difficult to analyze with conventional time domain analysis as well as with traditional Fourier transform analysis as their frequency response varies with time.

It has been shown that wavelet coefficients [8, 12, 13] can be successfully used for the classification of different power system transients such as faults, capacitor switching and load switching by selecting a proper mother wavelet function. But this study does not investigate that aspect, but assumes the availability of a technique such as the one proposed in [13] to discriminate fault transients from the others. Thus, among those wavelets, Daubechies is the most widely used mother wavelet in the analysis of fault transients in electrical networks and found to be well suited for power system applications. In addition, the higher number of wavelet levels used, the closer the reconstructed function is to the original. Therefore proposed scheme uses Daubechies 4 wavelet where number 4 represents the number of wavelet coefficients. Sampling frequency selected is 200 kHz to extract the transient travelling waves in 40 - 80 kHz [8,9] frequency range.

2.3 Modal Measurements for Fault characterization

Three phase power lines are characterized by their mutual coupling effects. Modal Transform is used to transform a group of coupled quantities into decoupled ones. Thus the solution of three phase quantities will be simpler since the decoupled equations can be treated as equivalent single phase line model. So it is convenient to analyze the transients in Modal domain in identification of correct fault configuration.

Figure 1. Wavelet decomposition for travelling wave sampled at 200 kHz

For a three phase system, the relationship between phase and modal quantities is given by,

$$[V_m] = [T][V_p]$$

Where $[V_p]$ - Phase quantity matrix

$[V_m]$ - Modal quantity matrix

$[T]$ - Modal transformation matrix.

Transformation matrix can be selected considering the characteristics of power network. For non transposed multiphase lines, an eigen vector based matrix which is frequency dependent would be preferred, for balanced or equally transposed multiphase lines, a matrix can be easily chosen to one of the different real value transformation matrices such as wedepohl, karrenbauer and Clarke transformation.

Clarke Transformation is used in this study assuming 132kV power line is well balanced and transposed.

For the Clarke transformation [17], the relationship between modal and phase quantities is given by,

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = [T] \begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} \quad \text{Where } T = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \end{bmatrix}$$

V_A, V_B, V_C - Phase voltages

V_0 - Ground mode component

V_α - Aerial mode 1 (Mode α)

V_β - Aerial mode 2 (Mode β)

2.3.1 Appropriate mode selection according to fault type

For Clarke transformation used, mode α is valid to deal with all type of faults except the fault of B-C. In such a case it is appropriate to take fault distance of β modal. The transients observed in ground mode components are sufficient only for the faults involved with ground. Therefore either single component or combination of modal components can be used to identify the fault type with the transients observed [9,10].

In this study, a trial and error based approach is used to find the most suitable mode at the time of fault simulation to accommodate all types of faults.

3. Fault location approach

Assume a fault occurs at a point F, x distance away from the substation end of the radial line as shown in figure 2.

Figure 2. Simulated faulted line

During a fault, system voltage and current will experience in transients, in which way they propagate in both directions subjected to transmissions and reflections at every discontinuity point [15]. The initial values of these surges depend on the fault position, fault path resistance and instance of fault occurrence. Transmission and reflection coefficients at every discontinuity point depend on the line's characteristic impedance.

Collection of these successive voltage surges at the substation end relay makes the base for calculating fault distance as these transients reflect fault characteristics uniquely once they are processed with Modal and Wavelet transforms. The processed information in voltage transient graph provides a distribution of significant voltage pulses for different frequency scales.

'Scale 1' plot in figure 3 contains high frequency components of (50 - 100) kHz which is fallen into the range of fault characteristic frequencies of (40-80) kHz. Thus it is used for further analysis.

Figure 3. Scale 1 plot of Transient voltage graph resulted from 3 phase fault.

The impulse distribution is subjected to retrace back in time to find out the origins of these waves by analyzing their traveling wave history. Thus a hypothetical time axis of τ_1 period (equal to the line transit time) is considered and the impulse record is placed on

it in reverse order assuming time $t=0$ s point corresponds to far end of the line as impulse record is fed to the line from the far end of the line (not substation end) as shown in figure 4.

Figure 4. Placement of impulse record over time axis

For the radial line configuration, all the surges arriving at the substation are resulted from consequent reflections at the fault point. Thus the successive surges change their polarity in alternate way.

Therefore signal history is retraced back with 'Scale 1' plot as shown in table 2 to calculate the fault distance as follows.

Net time of intersecting 2 impulses on the time axis $= \tau_1 - \frac{t_1}{2}$ s

Equivalent fault distance (From far end of the line) $= (\tau_1 - \frac{t_1}{2}) \times C$ km

Equivalent fault distance (From substation end) $= [\tau_1 - (\tau_1 - \frac{t_1}{2})] \times C = \frac{t_1}{2}$ km

Where C is the velocity of light.

3.1 Fault location algorithm

Flow chart arrangement for the proposed fault location algorithm is shown in figure 5.

All three phase voltage measurements are transformed to modal domain containing three new voltage components, namely ground mode, aerial mode 1 (mode α) and aerial mode 2 (mode β). Depending on the fault type, more significant modal voltage component is passed through wavelet filters to extract high frequency components of desired frequency ranges. When a fault situation is detected, 'scale 1' plot of the transient graph is used for further derivations.

$t=0$ s		P1, P2 start travelling along the forward direction.
$T=t_1$ s		P2 is still in forward direction motion since $\tau_1 > t_1$.
$T=\tau_1$ s		At the line end, P2 reflects backwards.
$T = (\tau_1 + t_1/2)$ s		P1, P2 meet up at the fault point and proportion al distance given by net time period along time axis ($t = \tau_1 - t_1/2$)

Table 2. Signal retracing procedure

As the first step, surge magnitudes are expressed as a ratio of the first impulse magnitude to identify the pulse generation or check whether it's resulted from which reflection or transmission. Then they were retraced on the hypothetical time axis equivalent to line transit time to find out the crossover point of original surge with reflected surge at fault point. That provides the fault distance.

Figure 5. Proposed fault location algorithm

3.2 Modified fault location algorithm for a branched network

Figure 6. Simulated branched network

In this scheme, detailed analysis of surge magnitude and polarity provides more ground information for verifying fault location. Once impulse record is traversed along the power line in reverse direction starting from all line ends, reflected surge at a branched point will meet the original surge at the respective branched point. That location can be verified as a branched point since the network topology is already known. Further reflected surges from the fault point will meet up with the original surge on the same point.

This will lead to identify healthy branches and faulty branch separately. Once faulty branch is found, pulse track can be fed from the end of that line to verify the fault point accurately.

4. Simulations

132kV, 50HZ power line is simulated in MATLAB/SIMULINK environment for developing the proposed fault location algorithm. DWT required for the algorithm described in section 2.1.2 was incorporated in the same model by modeling a wavelet filter bank with required parameters.

4.1 Feeders

Simulated 132kV, 3 phase power line is in double circuit line configuration. All the relevant data about these lines were offered by the Ceylon Electricity Board and are given in Table 3. and figure 7. Calculated RLC line parameters are amended in Appendix i.

Table 3. Transmission line data

Conductor type	ACSR Zebra
No. of phase conductors	06
No. of Ground wires	02
Conductor size	428mm ²
Conductor DC resistance at 20 °C	0.069Ω/km
Ground resistivity	100Ωm
Earth wire	GS 7/3.25
Earth wire size	58 mm ²
Conductor sag	9.5m
Tower span	335m

Figure 7. Double circuit line configuration

4.2 Discrete wavelet filter bank

DWT described in section 2.1.2 is achieved by implementing specified low pass and high pass Finite Impulse Response (FIR) filters.

Table 4. DWT filter characteristics

Data sampling rate	200kHz
Filter selected	Daubechies
Wavelet order	04
No. of levels	04

Scale 1 output provides the transient information which contains high frequencies in between 50 kHz - 100 kHz range and that transient graph is used for identification of fault locations.

5. Results

5.1 Modal Analysis

Scale 1 plot of voltage transient graph for different modes resulted from fault simulations are shown in below.

3 Phase fault

Figure 8. 'Scale 1' plot of modal voltages resulted from 3 phase fault

For a three phase fault, α - modal voltage impulse distribution is more significant than that of other two modes. Mode 0 voltage is insignificant compared to other two since the simulated fault is not involved with ground. Therefore with the Clarke transformation matrix selected mode α is valid to deal with three phase faults.

3- Phase Ground fault

Figure 9. 'Scale 1' plot of modal voltages resulted from 3 phase ground fault

All the modal components contain considerable voltage impulse distribution for a three phase

ground fault. Mode 0 voltage is significant as the fault is involved with ground and α -modal shows good impulse distribution since all three phases are short circuited. Thus mode α or mode 0 voltages can be processed for fault distance calculations for three phase ground faults.

Phase B- C fault

Figure 10. 'Scale 1' plot of modal voltages resulted from Phase B-C fault

For a phase B-C fault, β -modal voltage is more significant than other two components.

Therefore with the Clarke transformation matrix selected, based on the above analysis mode α is valid to deal with all types of faults except the fault of B-C. In such a case β modal is considered. The transients observed in ground mode components are sufficient only for the faults involved with ground.

5.2 Fault distance calculation

Simulation results shown in figures 11 and 12 are used to calculate the fault distance illustrating the performance of proposed fault location algorithm.

Case 1: Radial transmission line - 100km length
3 phase fault at 50km distance - mode

Figure 11. 'Scale 1' plot of α - modal voltage resulted from 3 phase fault

Table 5. Details of simulated 3 phase fault

Simulated fault description (For branched power network)	Fault distance (km)	Error %
3 phase fault at 30km-branch 1- mode 0	31.5	5
3 phase fault at 60 km-branch 2- mode α	60.5	0.83
A-B Phase fault at 80 km-branch 3- mode α	78	2.5
B-C Phase fault at 50 km - branched point- mode β	51	2

Time duration between 2 pulses = 0.00034s
Calculated fault distance= km

$$\frac{0.00034}{2} \times 3 \times 10^5 = 51 \text{ km}$$

Actual fault distance = 50 km.

Case 2: Branched 132 kV transmission line - 100km length. Branch point is at 50 km
Three phase fault at 60 km distance along the main feeder (branch 2) - Mode α

Figure 12. Scale 1' plot of α - modal voltage resulted from 3 phase fault

Resulted impulse record listed in table 5 is traversed over the line model from both branch ends to locate faulty branch first and then fault location is found as the crossover point of two surges excluding known discontinuity points of the line.

Faulty branch = branch 2;
Impulse crossover point (1 and 2) = 10.5 km away from junction point along branch 2.
Calculated fault distance = 60.5 km (from substation end)
Actual fault distance = 60 km

Tables 6 and 7 present a summary of fault calculation details for different types of faults. According to it, proposed technique gives the fault point accurately within 0.5 – 2.0 km faulty region irrespective of the fault type.

Table 6. Summary of fault calculation details- radial power line.

Im pulse	Receiving time (s)	Distance from 1 st impulse	Polarity	Comment
1	0.02053	-	-	Original surge from fault point.
2	0.02060	21 km	Same as original	Reflected surge at load end or subjected to 2 consequent reflections at junction and fault point.
3	0.02066	39 km	Same as original	
4	0.02087	102 km	Opposite to original	Reflected surges at junction
5	0.02094	123 km	Opposite to original	

Table 7. Summary of fault calculation details - branched power network

Simulated fault description (For radial power line)	fault distance (km)	Error %
3 phase fault at 50km, mode α	51	2
3 phase ground fault at 80 km, mode 0	81.5	1.9
A-B Phase fault at 40 km, mode α	39	2.5
B-C Phase fault at 10 km, mode β	9.5	5
3 phase ground fault at 60 km, mode 0	60.5	0.83

6. Summary and Conclusions

Proposed study has presented a fault transient analysis based fault location algorithm which

can be incorporated as an observer function into a microprocessor based distance relay application. New scheme is intended to be used in radial as well as in branched networks with single relay agent located at the substation end.

It is developed using transient voltage recordings through wide frequency response voltage transformer installed at the supply end of the feeder. The voltage signals are analyzed in modal domain for fault characterization and further investigated using wavelet transform. Daubechies 4 wavelet is used to discriminate fault transients from other types of power system transients. Simulations were carried out by modeling a 132kV transmission line using SIMPOWER SYSTEMS block set available in MATLAB / SIMULINK environment. Simulation results have proved that this scheme is capable of locating faults to an accepted degree of accuracy irrespective of the fault type. Calculated fault distances provide up to maximum of 1.5 km boundary as the faulty region in case of radial power line and it has been extended to 2.0 km span for the branched network configuration.

Though multi relay agent based protection schemes can process synchronized information at different locations to give more precise results in fault localization, this technique performed in single relay agent is also provides quite accurate results.

As a further study, applicability of this proposed concept in fault localization can be investigated for power distribution networks with high degree of branching and diverse network topology.

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Appendix

132kV radial transmission line - RLC line parameter calculation-Report generated by running 'RLC line parameter computation tool' available in SIMPOWER SYSTEMS control block set

132kV line

Double circuit configuration

1L1

R, L, AND C LINE PARAMETERS:

Resistance matrix R_{matrix} (ohm/km):

```
0.0558 0.0207 0.0206
0.0207 0.0558 0.0207
0.0206 0.0207 0.0558
```

Inductance matrix L_{matrix} (H/km):

```
1.0206e-003 4.7511e-004 4.1121e-004
4.7511e-004 1.0793e-003 4.7511e-004
4.1121e-004 4.7511e-004 1.0206e-003
```

Capacitance matrix C_{matrix} (F/km):

```
1.6473e-008 -4.0756e-009 -2.5778e-009
-4.0756e-009 1.5989e-008 -4.0756e-009
-2.5778e-009 -4.0756e-009 1.6473e-008
```

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