Abstract: Of all available relays, distance relay attracted more attention for transmission line protection. Whenever fault occurs in power system the actualizing quantities contains harmonics, decaying dc components and noise. Faults have to be cleared rapidly in order to prevent damage to the operating devices and personnel. So many filtering algorithms are available for the protection of transmission line but all are having their own merits and demerits. To obtain exact fundamental frequency components for relaying purpose, Smart Discrete Fourier Transform (SDFT) algorithm is proposed. On 17-bus power system, proposed algorithm is tested for speed, accuracy, frequency response, computational burden and capability to distinguish among different types of faults. The results are compared with available filtering algorithms. The power system testing is done with MATLAB and PSCAD/EMTDC environment. The test results shows that proposed SDFT algorithm is better that existing relaying algorithms.

Key words: Filtering Algorithms, Faults, Distance relay, Decaying Dc offset, Harmonics, Power system Protection.

I. INTRODUCTION

According to the historical records, many large scale system-wide blackouts involve relay misoperations. Evaluation and improvement of existing relay algorithms and settings as well as investigation of new techniques for relaying are very important for understanding and mitigating relay misoperations. The most common approach used by many researchers for studying relay algorithm performance is using a simple two-machine system and limited fault scenarios. An algorithm for comprehensive study of different relaying actions and fault analysis under variety of system-wide disturbances is needed.

Numeric transmission line distance protection systems have been widely applied in recent years primarily because of their monitoring and communications capabilities rather than for improved performance of the protection functions. Typical tripping times for digital distance relays range from one to 3 cycles, with state of art filtering algorithm it can offer trip times of one-quarter to one cycle. Recent developments in adaptive algorithms and the use of higher sampling rates combine to provide secure high speed protection not available with previous implementations. The fast and accurate determination of fault location on electric power transmission line is utilized as an aid in the fault analysis and power restoration. At the same time, the fault destination adversely impacts service reliability, operation cost and the quality of power delivery.

Distance relaying techniques have attracted considerable attention for the protection of transmission line. The principle of these techniques measures the impedance at a fundamental frequency between the relay location and the fault point thus determining if a fault is internal or external to a protection zone. Voltage and current signal are used for this purpose and they generally contain the fundamental frequency component in addition to harmonics and the dc offset. With digital technology being ever increasingly adopted in power substation more particularly in the protection field, distance relays have experienced some improvement mainly related to efficient filtering method. During last two decades remarkable work has been demonstrated in the area of distance protection. Many filtering algorithms have been proposed numerical relaying actions. Every algorithm has its own merits and demerits

The aim of most of these filtering algorithms is to extract the fundamental frequency component from the complex post fault voltage and current signals containing a transient dc offset component and harmonic frequency components in addition to the power frequency component. The exponentially decaying dc offset present in the relaying signal gives rise to large errors in the pharos estimates unless the offset terms are removed prior to the execution of the algorithms.

This paper presents a novel Smart Discrete Fourier Transform (SDFT) algorithm with capability to estimate exact fundamental frequency components during faults, that operating signals contain fundamental frequency components in combination with decaying dc components and harmonics. Proposed SDFT algorithm performance is compared in terms of distance relay with existing filtering algorithms regarding their speed, accuracy, computational burden and frequency response.

A 17-bus power system is taken to test the effectiveness of proposed SDFT algorithm. Different types of faults like single line to ground, double line to ground and three lines to ground faults are simulated at different lengths of selected transmission line. The distance relay characteristics are generated using MATLAB and PSCAD/EMTDC output files containing the values of the apparent impedances seen by faulted input

**II. PROPOSED SDFT FILTERING ALGORITHM**

The voltage and current signals may contain serious harmonics and decaying dc components during fault interval. The decaying DC seriously decreases the precision and convergence speed of fundamental frequency signal from DFT. In order to overcome the above problems, the proposed digital multifunction relay with SDFT algorithm can estimate the DC offset frequency and phasor from a faulted input
operating signals. Since there are several components in a fault current signal, the algorithm first takes DC offset into consideration and uses smoothing windows to eliminate other components in a fault signal.

Consider any fault signal \( f(t) \) with fundamental frequency components and decaying DC offset set can be expressed as

\[
f(t) = F \sin(\alpha t + \phi_1) + F \sin(\phi_2) e^{-\alpha t}
\]

Where

\( F \) is the amplitude of the faulted signal

\( \phi_1 \) is the phase angle of the faulted signal

\( \phi_2 \) is the fault angle of the signal

\( \alpha^{-1} = \tau \) is the time constant of the signal

Suppose \( f(t) \) is sampled with a rate of sampling (50*N) Hz to produce the sample set \( \{ f(k) \} \)

\[
f(k) = F \sin \left( \frac{k \alpha}{50N} + \phi_1 \right) + F \sin(\phi_2) e^{-\alpha \frac{k}{50N}}
\]

The signal \( f(t) \) is conventionally represented by phasor complex number \( \hat{f} \)

\[
\hat{f} = F e^{j\phi_1} = F \cos \phi_1 + j F \sin \phi_1
\]

Then \( f(t) \) can be expressed as

\[
f(t) = \frac{\hat{f} e^{j\phi_1} - \hat{f}^* e^{-j\phi_1}}{2} + F \sin(\phi_2) e^{-\alpha \frac{k}{50N}}
\]

Fundamental frequency components of Discrete Fourier transform of \( \{ f(k) \} \) is calculated from the following equation

\[
\hat{f}_r = \frac{2}{N} \sum_{k=0}^{N-1} f(k + r) e^{-j2\pi \frac{k}{N}}
\]

Taking frequency deviation \( \omega = 2\pi(50 + \Delta f) \) into consideration

\[
\hat{f}_r = \frac{\hat{f}}{N} \sum_{k=0}^{N} e^{j2\pi(50 + \Delta f) \frac{k}{N}} e^{-j2\pi \frac{k}{N}}
\]

\[
= \frac{\hat{f}}{N} \sum_{k=0}^{N} e^{j2\pi(50 + \Delta f) \frac{k}{N}} e^{-j2\pi \frac{k}{N}} + \frac{2F \sin(\phi_2)}{N} \sum_{k=0}^{N} e^{-j2\pi \frac{k}{N}} e^{-j\frac{\alpha k}{50N}}
\]

We can rearrange the Equn. (6) as

\[
\hat{f}_r = \frac{\hat{f}}{N} e^{j2\pi \frac{\Delta f}{50N}} \sum_{k=0}^{N} e^{j2\pi \frac{k}{N}}
\]

\[
- \frac{\hat{f}^*}{N} e^{-j2\pi \frac{\Delta f}{50N}} \sum_{k=0}^{N} e^{-j2\pi \frac{k}{N}}
\]

\[
+ \frac{2F \sin(\phi_2)}{N} e^{-j\frac{\alpha k}{50N}}
\]

Above Equn. (7) can be solved by the following identity

\[
\sum_{k=0}^{N-1} e^{j\theta k} = \frac{N \theta}{\sin \theta} e^{j \frac{N-1}{2} \theta}
\]

We can rearrange the Equn. (7) as

\[
f_r = \frac{\hat{f}}{N} e^{j2\pi \frac{\Delta f}{50N}} \sum_{k=0}^{N} e^{j2\pi \frac{k}{N}}
\]

\[
- \frac{\hat{f}^*}{N} e^{-j2\pi \frac{\Delta f}{50N}} \sum_{k=0}^{N} e^{-j2\pi \frac{k}{N}}
\]

\[
+ \frac{2F \sin(\phi_2)}{N} e^{-j\frac{\alpha k}{50N}}
\]

We can rearrange the Equn. (7) as

\[
f_r = \frac{\hat{f}}{N} e^{j2\pi \frac{\Delta f}{50N}} \sum_{k=0}^{N} e^{j2\pi \frac{k}{N}}
\]

\[
- \frac{\hat{f}^*}{N} e^{-j2\pi \frac{\Delta f}{50N}} \sum_{k=0}^{N} e^{-j2\pi \frac{k}{N}}
\]

\[
+ \frac{2F \sin(\phi_2)}{N} e^{-j\frac{\alpha k}{50N}}
\]

So far the development of the algorithm of SDFT is the same as the traditional DFT method. So the SDFT can keep all advantages of DFT such as recursive and half-cycle computing manner. But in the DFT, it doesn’t take DC offset into consideration and it assumes that the frequency deviation is small enough to be ignored. It always considers \( \hat{f}_r = A_r \), so traditional DFT based methods incur error in estimating frequency and phasor when frequency deviates from nominal frequency (50 Hz) or DC offset is present. If we want to obtain exact solution, we must take \( B_r \) and \( C_r \) into consideration. Then we define

\[
a = e^{j \frac{\pi}{50N} (2N + 100)}
\]
From Eqn (10) following relations are obtained
\[ A_{r+1} = A_r \alpha \]
\[ B_{r+1} = B_r \alpha^{-1} \]
\[ C_{r+1} = C_r \]

Then
\[ \hat{f}_{r+1} = A_{r+1} + B_{r+1} + C_{r+1} = A_r \alpha + B_r \alpha^{-1} + C_r \]
\[ \hat{f}_{r+2} = A_{r+2} + B_{r+2} + C_{r+2} = A_r \alpha + B_r \alpha^{-1} + C_r \]

Eqn. (14) is multiplied both sides with ‘b’ and subtract from Eqn (20) gives

\[ \hat{y}_r = \hat{f}_{r+1} - \hat{f}_r b = A_r (\alpha - b) + B_r (\alpha^{-1} - b) \]
\[ \hat{y}_{r+1} = \hat{y}_{r+1} - \hat{f}_r b = A_r (\alpha - b) + B_r (\alpha^{-1} - b) \]
\[ \hat{y}_{r+2} = \hat{y}_{r+2} - \hat{f}_r b = A_r (\alpha - b) + B_r (\alpha^{-1} - b) \]

We can rearrange Eqn. (22), (23) and (24) as

\[ \tilde{y}_r = \hat{y}_r - \hat{y}_r a - \hat{y}_{r+1} \]
\[ \tilde{y}_{r+1} = \hat{y}_{r+1} - \hat{y}_r a - \hat{y}_{r+2} \]
\[ \tilde{y}_{r+2} = \hat{y}_{r+2} - \hat{y}_r a - \hat{y}_{r+1} \]

Put Eqn. (23) & Eqn. (24) in Eqn. (27)

\[ \left[ \hat{f}_{r+2} + \hat{f}_{r+2} - \hat{f}_{r+1} \left( \hat{f}_{r+1} + \hat{f}_{r+3} \right) \right] b^2 + \left[ \hat{f}_{r+3} + \hat{f}_{r+2} - \hat{f}_{r+1} \left( \hat{f}_{r+2} + \hat{f}_{r+2} \right) \right] b + \left[ \hat{f}_{r+3} + \hat{f}_{r+2} - \hat{f}_{r+1} \left( \hat{f}_{r+2} + \hat{f}_{r+3} \right) \right] = 0 \]

Solve Eqn. (28) to obtain ‘b’. From the definition of ‘b’ in Eqn (16) we can obtain the exact solution of the time constant.

\[ \tau = \frac{1}{50N \log b} \]

Eqn. (27) can be rearranged as

\[ \tilde{y}_r a^2 - (\tilde{y}_r + \tilde{y}_{r+2}) a + \tilde{y}_{r+1} = 0 \]

Solve Eqn. (30) to obtain ‘a’. From the definition of ‘a’ in Eqn. (15) we can get the exact solution of the frequency.

\[ f = 50 + \Delta f = \cos^2 (\text{Re}(a)) \frac{50N}{2\pi} \]

From Eqn. (29) and Eqn. (31), it is observed that SDFT can provide exact time constant and frequency using \( \hat{f}, \hat{f}_{r+1}, \hat{f}_{r+2}, \hat{f}_{r+3} \) and \( \hat{f}_{r+4} \) in the absence of noise. Moreover, we can estimate both the phasor and fault angle after getting exact time constant and frequency by the following equations:

\[ A_r = \frac{\tilde{y}_r a - \tilde{y}_r}{(a^2 - 1)(\alpha - b)} \]
\[ F = \frac{\alpha \sin \theta}{\sin(N \theta)} \]
\[ \phi = \angle (A_r e^{i\theta (N-1)}) \]

The relations of Eqn. (17), Eqn. (18) and Eqn. (19) are still kept in Eqn. (32). Therefore, the same steps from Eqn. (20) to Eqn. (33) can be used in Eqn. (39). Hence we can estimate time constant and frequency without modifying equations, but we have to do some change in Eqn. (32) and Eqn. (35) when we estimate phasor and fault angle.

\[ A_r = \frac{\tilde{y}_r a - \tilde{y}_r}{(a^2 - 1)(\alpha - b)(s_r + s_r a + \ldots + s_r a^{m-1})} \]

Where

\[ \tilde{y}_r = \tilde{y}_{r+1} - \frac{\tilde{y}_{r+2}}{\tilde{y}_r a} \]
\[ \tilde{y}_{r+2} = \tilde{y}_{r+1} - \frac{\tilde{y}_{r+3}}{\tilde{y}_r a} \]
\[ C_r = \frac{a^2 \tilde{y}_r - a(\tilde{y}_r + \tilde{y}_{r+2}) + \tilde{y}_{r+1}}{(\alpha - b)(s_r + s_r b + \ldots + s_r b^{m-1})} \]

The phasor obtained from Eqn. (40) and fault angle obtained from Eqn. (41) will allay the phase shift and amplitude decay caused by smoothing windows.

III. FILTERING ALGORITHMS AVAILABLE

i) Infinite Impulse Response Algorithm

In traditional method, transfer of analog filter to digital filter is practiced to get the desired requirements.
Transformation method used is impulse variance that uses s-plane conversion to z-plane of differential equations to difference equations and then to direct synthesis.

Analog prototype low pass filter is given as

\[ H(s) = \frac{1}{s^2 + \sqrt{2}s + 1} \]  

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Analog prototype can be converted into digital by bilinear transformation, it can be expressed as

\[ s \rightarrow \frac{2Z - 1}{T + Z^2} \]  

---43

T is sampling time

The bilinear transformed equation that is 's' replaced by right hand term of equation results in

\[ H(z) = (1 + 2Z^{-1} + Z^{-2}) \left[ \frac{4}{T^2} \frac{2\sqrt{2}}{T} + 1 \right]^{-1} \left[ \frac{-2}{T} \right] \]  

\[ + (1 + 2Z^{-1} + Z^{-2}) \left[ \frac{4}{T^2} \frac{2\sqrt{2}}{T} + 1 \right]^{-1} \]  

The fundamental component present in the signal \( x(t) \) will be extracted by designing band pass filter at 50Hz frequency can be obtained from below expression

\[ Y_s(N) = 0.523X(N-1) - 0.365X(N-2) + 0.734X(N-3) - 0.649X(N-4) + 0.632Y(N-1) - 0.643Y(N-2) + 0.879Y(N-3) - 0.369Y(N-4) \]  

---44

\[ \text{ii) Least Square Curve Fitting Algorithm:} \]

Here it is assumed that the inrush current contains decaying DC and no more than five harmonics, then in a certain time interval, the signal current can be represented as

\[ x(t) = P_0 e^{-\lambda t} + \sum_{k=1}^{5} P_k \sin(k \omega_0 t + \theta_k) \]  

---45

Where \( x(t) \) is instantaneous differential signal sampled at a time \( t \)

\( P_0 \) is decaying DC component.

\( \lambda \) is inverse time decay time constant of DC component

\( P_k \) is peak component of the \( k^{th} \) harmonic differential signal

\( \omega_0 \) is fundamental frequency

\( \theta_k \) is Phase angle of \( k^{th} \) harmonic

\[ x(t) = P_0 - P_0 \lambda t + \sum_{k=1}^{5} P_k \cos \theta_k \sin(k \omega_0 t) \]  

\[ + \sum_{k=1}^{5} P_k \sin \theta_k \cos(k \omega_0 t) \]  

---46

In matrix form the above equation can be written as

\[ [x] = [a][y] \]  

---47

Least square components obtained from

\[ [Y]([A^T]A)^{-1}A^T] = [B][X] \]  

---48

It can be shown that

\[ [B] = (A^T)^{-1}A^T \]  

---49

As the matrix \( A \) has known elements, matrix \( B \) can be found easily. Matrix \( b \) can then be used to compute the vector \( X \) from the sampled signal. The Fourier sine and cosine components of fundamental frequency can be obtained from

\[ C_i = P_i \cos(\theta_i t) = \sum_{n=1}^{16} B(3,n)x(t_n) \]  

---50

\[ S_i = P_i \sin(\theta_i t) = \sum_{n=1}^{16} B(4,n)x(t_n) \]  

---51

\[ \text{iii) Kalman Filtering Algorithm:} \]

The Kalman filtering algorithm has been proven to be the optimal linear estimator even in noisy environment once a signal is represented by a state variable equation of the form

\[ X_{k+1} = FX_k + W_k \]  

\[ Z_k = HX_k + V_k \]  

The covariance matrices for \( W_k \) and \( V_k \) are given as follows.

\[ E[W_k^T W_i] = Q \quad i = k \]  

\[ = 0 \quad i \neq k \]  

\[ E[V_k^T V_i] = R \quad i = k \]  

\[ = 0 \quad i \neq k \]  

\[ E[W_k^T V_i] = 0 \quad \text{for all } k \text{ and } i \]  

---52

Where \( E \) denotes the expected values.

Having a prior knowledge of the initial estimation error covariance matrix \( P_0 \), the Kalman gains can be computed recursively as follows.

\[ K_k = P_k H^T (HP_k H^T + R)^{-1} \]  

\[ R_k = (I - K_k H)P_k \]  

\[ R_{k+1} = F R_k F^T + Q \]  

---53

Where \( K_k \) is the Kalman gain matrix at time \( tk \).

\( P_{k+1} \) is the estimation error covariance matrix at \( t_k \);

\( P_k \) the error covariance matrix for the updated estimate at \( t_k \)

\( I \) is the identity matrix.

Having an initial state estimate \( X_0 \), the Kalman filter equation, which recursively estimate new values of the state vector, is as follows.

\[ \dot{X}_k = X_k + K_k (Z_k - HX_k) \]  

\[ X_{k+1} = FX_k \]  

---54

Where \( X_k \) is the estimate of \( X_k \). The discrete time state space representation of periodic signal having harmonic components on to nth order with samples \( Z_k \) at time \( t_k \) can be given.

\[ X_{k+1} = FX_k \]  

\[ Z_k = HX_k \]  

---55

\[ w = \omega T, \omega \text{ is the fundamental supply frequency in rad/s and is the sampling interval, } s \text{ and } \]  

\[ H = [1, 0, 1, 0, ............1, 0, 1] \]  

---56
iv) Block Pulse Functions Algorithm:

A set of block pulse functions on a unit time interval (0,1) with N number of samples per cycles defined as

\[ \phi_a(t) = 1 \quad \text{for} \quad \left( \frac{n-1}{N} < t < \frac{n}{N} \right) \quad \text{-----58} \]
\[ = 0 \quad \text{otherwise} \quad \text{for} \quad n=1,2,3, \ldots, N \]

If there is a function f(t), which is integrable in (0,1) can be approximated using BPF as,

\[ f(t) = \sum_{n=1}^{N} a_n \phi_n(t) \quad \text{-----59} \]

where the coefficient an are block pulse function coefficients determined so that the integral square error is minimized.

\[ \xi = \int f(t) - \sum_{n=1}^{N} a_n \phi_n(t)^2 \quad dt \quad \text{-----60} \]

For such a square fit an is given by

\[ a_n = \frac{1}{N} \int f(t) \phi_n(t) \quad dt \quad \text{-----61} \]

\[ = \text{average value of } f(t) \text{ in the interval } (n-1)N < t < n/N \]

v) Wavelet Transforms Algorithm:

The wavelet transform translate the time domain function into a representation localized not only in frequency but also in time. Wavelet theory is the mathematics associated with building a model for a non-stationary signal, with a set of components that are small wave called wavelets. There are some conditions that must be met for a function to qualify as a wavelet. They must be oscillatory and have amplitudes that quickly decay to zero. The product of an oscillatory function with a decay function yields the wavelet. A number of different wavelets are used to approximate any given function with each wavelet generated from one original wavelet called a mother wavelet. The new elements, called daughter wavelet are nothing but scaled and translated mother wavelets. Scaling implies that the mother wavelet is either dilated or compressed and translation implies shifting of the mother wavelet in the time domain.

Let a function for a mother wavelet follows.

\[ g(t) = e^{-at^2} e^{iat} \]
\[ g^\dagger(a,b,t) = \left( \frac{1}{\sqrt{a}} \right) \phi\left( \frac{t-b}{a} \right) \quad \text{-----62} \]

Where

- a is a constant;
- b is the time translation factor
- a is the scaling factor.

The energy of the scaled daughter wavelet is normalized to keep the energy same, as the energy in the mother wavelet.

For computer implementation, the discrete wavelet transform is used. A discrete wavelet transform results in a finite number of wavelet coefficients depending upon the integer number of the discretization step in scale and translation denoted by m and n, respectively. So any wavelet coefficient can be described by two integer, m and n. If \( a_0 \) and \( b_0 \) are the segmentation step sizes for the scale and translation respectively, the scale and translation in terms of these parameters will be \( a = a_0^{-m} \) and \( b = nb_0a_0^{-n} \).

After discretization in terms of the parameter \( a_0, b_0, m \) and \( n \) the mother wavelet can be written as,

\[ g(m,n,t) = \left( \frac{1}{\sqrt{a_0}} \right) \phi\left( \frac{t-nb_0a_0^{-n}}{a_0^{-m}} \right) \quad \text{-----63} \]

\[ g(m,n,t) = a_0^{-m/2} \phi(ta_0^{-m} - nb_0) \quad \text{-----64} \]

After discretization, the wavelet domain coefficients are no longer represented by a simple a and b instead they are represented in terms of m and n. The discrete wavelet coefficient \( Wfg(m,n) \) are given by

\[ Wfg(m,n) = a_0^{-m/2} \int f(t) \phi(ta_0^{-m} - nb_0) dt \quad \text{-----65} \]

The transformation is over continuous time but the wavelets are represented in a discrete fashion like the continuous wavelet transformation these discrete wavelet coefficients represent the correlation between the original signal and wavelets for different combination of m and n.

**DISTANCE RELAY**

In general thirteen input signals, namely, three line-to-ground voltages, three line-to-line voltages, three line currents. Three differences in line currents and residual current are required to obtain phasor quantities necessary for an impedance relay. In this work all the 13 signals are obtained from simultaneously taken samples of 6 signals, namely, three line-to-ground voltages and three line currents using following relations

\[ V_{L1-L2} = V_{L1} - V_{L2} \quad \text{-----66} \]
\[ i_{L1-L2} = i_{L1} - i_{L2} \quad \text{-----67} \]
\[ i_k = i_{L1} + i_{L2} + i_{L3} \quad \text{-----68} \]

The ground impedance seen at the relay point is calculated as

\[ Z_g = \frac{V_{L1}}{I_{L1} + K \frac{1}{3} I_k} \quad \text{-----69} \]

\( V_{L1}, I_{L1} \) are the RMS values of the relay voltage and current \( I_k \) is the RMS value of the residual current.

K is the degree of compensation, being a ratio of zero to positive sequence impedance of the line that remains constant for all fault locations within the protected line.

The phase impedances at the relay point are calculated as

\[ Z_{L1-L2} = \frac{V_{L1-L2}}{I_{L1-L2}} \quad \text{-----70} \]

The Function logic supports two commonly used operating Circular and Quadrilateral characteristics of conventional impedance relays. The Function Logic implements a three stepped distance protection by accepting three such characteristics, one for each zone.
TEST SYSTEM AND RESULTS

Proposed filtering algorithm was tested with 17 bus system as shown in fig.1

Generator G_1 is rated at 2GW and generator G_2 is rated at 1GW, both are at 15KV, 0.866 power factor lagging with transient reactances of 0.14p.u. Load-1 is rated at 30462 MVA and Load 2 is rated at 30577 MVA.

Transformers Data

<table>
<thead>
<tr>
<th>Transformer</th>
<th>MVA rating</th>
<th>Voltage ratio KV/KV</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>2500</td>
<td>15/500</td>
</tr>
<tr>
<td>T2</td>
<td>1800</td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td>500</td>
<td>500/15</td>
</tr>
<tr>
<td>T4</td>
<td>600</td>
<td>500/230</td>
</tr>
<tr>
<td>T5</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>T6</td>
<td>1000</td>
<td>500/230</td>
</tr>
<tr>
<td>T7</td>
<td>1000</td>
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<tr>
<td>T8</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>T9</td>
<td>1000</td>
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</tr>
</tbody>
</table>

Each transformer has reactance of 0.1p.u. Each transmission line has shunt conductance of 1.0e-10 mhos per meter. Load connected at bus-14 is 200MW at 500KV, bus-15 is 150MW at 230KV, bus-16 is 150MW at 500KV and bus-17 is 150MW at 500KV.

Zones and Reach adjustment of Distance relay

The adjustment of zone-1 was set to protect up to 80% of the impedance of the protected line. Zone-2 was set to protect up to 50% of the shortest impedance of the lines T_6 and T_13, emanating from the remote bus. Zone-3 was set to protect up to 100% of the remote line T_6. Distance relay was placed at bus-3 for the proposed simulation.

Case-1: Simulation of faults at 10% of Line L_5 :

Different types of faults like single line-to-ground, double line-to-ground and three-phase-to-ground faults were simulated at 10% of transmission line L_5 from bus 3. Fault impedances from relay location are calculated by distance relay at 10% of line L_5. The corresponding characteristics are as shown below.

Single line-to-ground faults at 10% of Line L_5 from Bus 3

Double line-to-ground faults at 10% of Line L_5 from Bus 3

Three-phase-to-ground fault at 10% of Line L_5 from Bus 3

Case-2: Simulation of faults at 50% of line L_5 :

Single line-to-ground, double line-to-ground and three-phase-to-ground faults were simulated at 50% of transmission line L_5 from bus 3. Fault impedances from relay location are
calculated by distance relay at 50% of line \( L_5 \). The corresponding characteristics are as shown below.

Single line-to-ground faults at 50% of Line \( L_5 \) from bus-3

Double line-to-ground faults at 50% of Line \( L_5 \) from bus-3

Three phase-to-ground fault at 50% of Line \( L_5 \) from bus-3

CONCLUSIONS

A number of algorithms for numerical distance protection have been compared with proposed novel SDFT algorithm to calculate the apparent impedance of the line between the relay’s location and the fault point by using digitized samples of voltage and current signals. Each algorithm has certain merits and demerits regarding computational simplicity, speed, accuracy and frequency response. The selection of any particular algorithm depends on the protection requirement. All the various schemes of algorithms proposed advocate a family of wide spectrum of techniques to determine the impedance of the transmission line under fault condition. Different fault types were simulated in two different locations of transmission line \( L_5 \). The distance relay’s correctness in fault identification, the time of the event they were monitoring and exhibition of required discrimination in their operation were compared between proposed Smart Discrete Fourier Transform algorithm (SDFT) and above said filtering algorithms. The distance relay calculated the apparent impedance of the transmission line, and the plotted apparent impedances in R-X plane supported the correct operation of the relay with the proposed algorithms are compared.

In the Kalman filtering algorithm uses only present sampled signals and does not require any past data to be stored in the memory. The major difference between the Kalman filter and proposed SDFT algorithm is evaluation of filter gains. In SDFT there is no need of evaluating gains but case of Kalman filter requires it. The gains of Kalman filter vary with time as the gains are non-stationary. Being recursive in nature, even though Kalman filter is computationally more efficient but it has limited capability for modeling the decaying dc component. In addition, statistical properties of the signal to be processed are needed for calculating the Kalman gains. So it is concluded that proposed SDFT algorithm is efficient and more acceptable.

One of the most prominent advantages of algorithms using Blocked Pulse Function Algorithm coefficients is that the sampling rate can be any positive integer, whereas in other method like in Haar and Walsh transform, one is compelled to use sampling rates that are equal to integral powers of 2. In other algorithms generally 16 samples/cycle are used to give the satisfactory results. For distance protection however, the BPF algorithm uses 12 samples, which requires less multiplication, so less memory space and time but obtained samples contains errors as it is not handling decaying dc component properly. This drawback is completely eliminated in proposed SDFT algorithm.

Least Square Curve Fitting Algorithm can also handles decaying dc offset components to filter from operating signals as it is in proposed SDFT algorithm but it is suffering from drawback that it can only work for the harmonics of order 5. Above which this algorithm outcomes suffers from large errors. But there is no restriction on order of harmonics in SDFT algorithm.

Being recursive in nature, an Infinite Impulse Response Algorithm is an accurate and error free algorithm but it needs to transform differential equations from s-plane to z-plane frequently and feedback is desired. Probability of errors in transformation will result with less knowledge in z-transforms. But this feedback and interrelating output with input is not required in SDFT algorithm.
Non-stationary signals, where the interest is only for what spectral components exist in the signal but not interested where these occur, can be easily handled with wavelet transforms. It provides the time frequency representation. Although the discretized Continuous Wavelet Transform (CWT) enables the computation of required CWT by the computer, but it is not a true discrete transform. As a matter of fact, the wavelet series is simply a sampled version of the CWT and the information it provides is highly redundant for the signal concerned. This redundancy, on the other hand, requires a significant large amount of computation time and resources. Time of fault clearance based on fault amplitude computation is more important than the instant where the fault has occurred. Computation time of Wavelet is more than proposed SDFT. More than that, in some limit, SDFT can handle non-stationary signals as wavelets.

The discrete Fourier transform algorithm was used to extract real and imaginary components that involves number of multiplication operations, in addition to summation/subtraction operations, it is less time consuming algorithm. Based on the experimental results, proposed SDFT algorithm is found to be the best algorithms in terms of accuracy and computing time when compared some of existing filtering algorithm.

REFERENCES


