On Line Fault Detection and an Adaptive Algorithm to Fast Distance Relaying

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Abstract-- **This paper presents the design of an hybrid scheme of wavelet transforms and an adaptive Fourier filtering technique for on line fault detection and phasor estimation to fast distance protection of transmission lines. The wavelet transform is used as a signal processing tool. The sampled voltage and current signals at the relay location are decomposed using wavelet transform-Multi Resolution Analysis (MRA). The decomposed signals are used for the fault detection and as input to the phasor estimation algorithm. The phasor estimation algorithm possesses the advantage of recursive computing and a decaying dc offset component is removed from fault signals by using an adaptive compensation method. Fault detection index and a variable data window scheme are embedded in the algorithm. The proposed scheme provides capability for fast tripping decision, taking accuracy into account. Extensive simulation tests and comparative evaluation presented prove the efficacy of the proposed scheme in distance protection.**

Index Terms-- **Adaptive filtering, decaying dc offset, digital distance protection, discrete Fourier transform (DFT), discrete wavelet transform (DWT), wavelet transform.**

I. INTRODUCTION

THE Rapid interconnectivity existing among modern Power systems make them highly unstable when faults are not cleared rapidly. Hence the growth of power systems in both size and complexity enhances the need for high-speed relays to protect major equipments and maintain system stability.

Distance protection is one of the most common methods used to protect transmission lines. Recently, distance relays have seen much improvement due to the adoption of digital relaying. With the advancements of digital signal processors (DSPs), the development of more complex algorithms can be implemented for high-speed distance protection.

Signal processing is one of the most important parts of the operation of the digital distance protection. When a fault occurs, the voltage and current signals are severely distorted. In addition to the fundamental frequency signals, these signals may contain harmonics and decaying dc components [1][2]. This makes the fundamental phasors very difficult to be fast and accurately estimated and affects the performance of a distance relay.

We can find a number of advanced techniques proposed for the phasor estimation in literature to meet the high speed and accuracy in distance protection [3]-[12]. Even though the Discrete Fourier Transform (DFT) algorithm is most popular and standard in Industry, its performance results to erroneous estimates due to the adverse effect of decaying dc component in the fault transients [3]-[5]. The distance relay mal operates (overreach/underreach) due to the decaying dc offset. Digital mimic filter is proposed to eliminate the dc offset in current waveforms [3].But the method gives the best performance when the time constant of both the mimic filter and dc offset is same. DFT based dc offset removal algorithm proposed in [4] and [5] can not achieve high speed because of long window length of the filters. Algorithm proposed in [6] cannot achieve high speed because of fixed data window. A new adaptive data window approach which can overcome the speed and accuracy problems, which cannot be solved by a fixed data window algorithm, is proposed in [8].However the speed can be further increased by pre processing the fault signals.

A wavelet-based signal processing technique is considered to be an effective tool for power system transient analysis and feature extraction [9]-[12]. One of its major applications in power system protection is in fault detection. With MRA technique of wavelet transforms pyramid algorithms are proposed [9]-[12] for fault detection and phasor estimation. Since the phasors are estimated using approximate coefficients at higher levels, the speed and accuracy will be affected by larger window lengths and also steps should be taken for dc component elimination. Further a combined techniques such as wavelet transforms and Artificial neural network is proposed in [12] for fault detection and classification.

Keeping in mind the above aspects, in this paper, a hybrid scheme is proposed which is embedded with wavelet transform and an adaptive DFT algorithm for high speed and accuracy. Theoretical basis and design of the scheme are described.

In the proposed hybrid scheme the fault voltage and current signals will be decomposed at level one of wavelet transform-MRA and the coefficients at level one are taken to the relaying algorithm. The developed Relaying Algorithm is the Adaptive data window DFT embedded with the fault detection index and variable data window scheme. The algorithm also possesses the advantage of recursive computing and the decaying dc offset component is removed from fault signals

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using an adaptive compensation method [7].

The proposed technique is computationally efficient and no statistical information concerning the signals is required. It provides capability for fast detection and tripping decisions taking accuracy account. Extensive simulation tests are conducted and comparative studies of the scheme with the resent method proposed in [7] are explored and sample results are presented.

II. PROPOSED HYBRID SCHEME FOR ONLINE FAULT DETECTION AND PHASOR ESTIMATION

Figure 1.0 shows the procedure steps of proposed hybrid scheme.

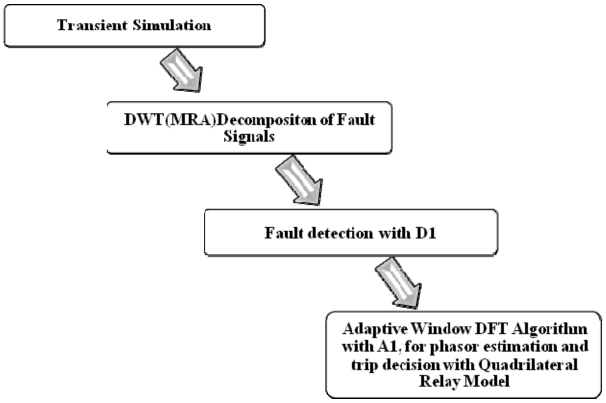

Fig. 1. Sequence of operation of the proposed hybrid scheme.

In the present work, wavelet transform concept is introduced. The property of multiresolution in time and frequency provided by wavelets is described.

As shown in Fig, 1 ,The detail coefficients of level one decomposition is D1 which is between Fs/4 and Fs/2 ,where Fs is the sampling frequency .D1 is of high frequency coefficients generally used for the online fault detection and fault classification [10][11]. The Approximate coefficients at level one A1, which is between 0 to Fs/2 and has the fundamental component details, will be used by the phasor estimation algorithm for the fundamental phasors estimation to calculate the impedance.

A. Wavelet Transform- Discrete Wavelet Transform (DWT): MRA

DWT is a time frequency analysis technique that is most suited for non stationary signals. DWT also has other desirable properties such as providing a substantial amount of data reduction and having a simple and fast algorithm.

DWT analyses the signal at different frequency bands by decomposing the signal into detail information and coarse approximations called wavelet function and scaling function.

The decomposition of the signal into different frequency bands is simply obtained by successive high pass and low pass filtering of time domain signal, which is achieved by Wavelet Filter Banks (WFB) [9] [10]. The DWT technique is indicated in Fig. 2.

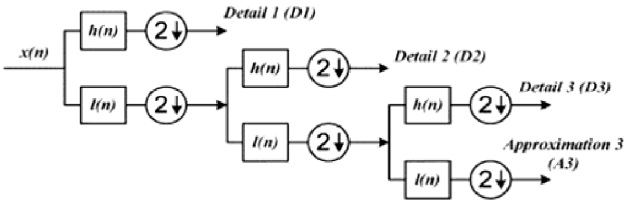

Fig. 2. DWT analysis (MRA).

The original sampled signal x (n) is passed through a high pass h (n) and low pass filter l (n). After the filtering the half of the samples eliminated according to Nyquist's rule, the signal therefore is decimated by 2, simply by discarding every other sample. This constitutes the level one decomposition of original signal. D1 and A1 are the detail coefficients and the approximation coefficients at level one, respectively. This procedure called subcoding is repeated for further decomposition. At every level the filtering and subsampling result in half the time resolution and double the frequency resolution. Each level of decomposition analyses the signal at different frequency ranges at different resolutions, hence the name Multi Resolution Analysis (MRA).

As shown in Fig. 2, if the original Sampling frequency is **Fs,** in **level one** the signal information captured by **D1,**output of high pass filter, is between **Fs/4** and **Fs/2** of the frequency band. **A1,** output of low pass filter, has the signal information between **0 to Fs/2**.similarly in **level two**, **D2** captures information between **Fs/8** and **Fs/4,** and **A2** between **0** and **Fs/4** of the frequency band. The decomposition process can be repeated up to the required level. The information of original signal is clearly represented at each frequency band.

Generally the D1 are used for fault detection and classification [10]. Approximate coefficients having the fundamental components will be taken for phasor estimation.

B. Fault Detection Index

The technique used for the fault detection Index is as mentioned in [7], originally proposed by J.A Jiang et al [8] based on a fault detection/location index for a single phase. An adaptive PMU-based fault-detection/location technique is developed using two-terminal synchronized phasors and distributed line model [1][2].

The following equations will lead to the fault detection index.

$$N = \frac{1}{2}\left[V_r - Z_c I_r\right] - \frac{1}{2} exp(\gamma L)\left[V_s - Z_c I_s\right] \tag{1}$$

$$M = \frac{1}{2}\left[V_S + Z_C I_S\right] \exp(-\gamma L) - \frac{1}{2}\left[V_r - Z_C I_r\right] \tag{2}$$

$$D = abs\left[\ln\left(\frac{abs(N)}{abs(M)}\right) 2\gamma L\right] \tag{3}$$

Where D is the suggested fault location/detection index and L is the total length of the transmission line. γ is the propagation constant and Zc is the surge impedance of the transmission line. Vs, Is, Vr and Ir are the sending and receiving end voltages and currents respectively.

Under healthy conditions, the absolute values of N and M will be ideally held at zero and thus the index D would be very high. But, even a couple of fault samples are enough to ensure that D changes drastically enough so that by means of a threshold, the fault can be detected very fast. In the simulation studies, since only single end data are obtained, the above equations are modified to exclude the receiver end terms like Vr and Ir. This will introduce a bias even under healthy conditions. However, the change in the value of D when a fault occurs remains unaffected. To remove the bias, the index is slightly modified as

$$D_m = D - D_{pre} \tag{4}$$

Where D is the value of the index for the current sample and D_{pre} is the same for the previous sample. D_m is zero under healthy conditions and increases very fast with even a couple of samples of fault data. A threshold (Th_D) is employed for fault detection.

C. Adaptive compensation for decaying dc offset [7]

The main component of the fault current is expressed as

$$x(t) = X\cos(\omega t + \phi_1) + X_d \exp(-\alpha t) \tag{5}$$

X	Amplitude of the current signal
$\omega = 2\pi * 60$	Fundamental angular frequency of the current Signal
ϕ_1	phase angle of current signal
$X_d \exp(-\alpha t)$	Decaying dc offset
$1/\alpha = \tau$	time constant of current signal

The sample set obtained by sampling the signal for N samples per cycle is

$$x_n = X\cos(\omega n/50N + \phi_1) + X_d \exp(-\alpha n/50N) \quad n = 1,2,3,\ldots,N-1. \tag{6}$$

$$X_r = \frac{2}{N}\sum_{n=0}^{N-1} x_{n+r} e^{-jnq} \tag{7}$$

Where N = Samples per cycle of data

r = Index of the moving window

θ = 2π / N

Considering (6) and (7) the fundamental current phasor is expressed as

$$\hat{x}_r = A_r + B_r \tag{8}$$

where,

$$A_r = Xe^{j(\phi_1 + r\theta)} \tag{9}$$

$$B_r = \frac{2}{N} X_d e^{-\alpha r/50N} \sum_{n=0}^{N-1} e^{-\alpha n/50N} e^{-jn\theta} \tag{10}$$

The fault current signal mainly consist decaying dc components .But a full cycle DFT will not eliminate the decaying dc component if present. To get exact solution Br is taken for consideration, thus by defining

$$a = e^{j2\pi/N} = e^{j\theta}, \quad d = e^{-\alpha/50N} \tag{11}$$

Considering 3 moving window DFT estimates, after some algebraic solutions [7], we obtain

$$d = \frac{\hat{x}_{r+2} - a\hat{x}_{r+1}}{\hat{x}_{r+1} - a\hat{x}_r} \tag{12}$$

$$A_r = \frac{\hat{x}_{r+2} - d\hat{x}_r}{(a-d)} \tag{13}$$

Where d is the decaying dc component

Then, the accurate current fundamental phasor can be estimated by,

$$X = abs(A_r) \tag{14}$$

$$\phi_1 = angle(A_r e^{-j2\pi(r-1)/N}) \tag{15}$$

Specifically (12)-(15) can be applied to the case of an arbitrary window length K with modifications so that it satisfies the least square error criterion [7].

The computation for the phasor estimation for an arbitrary length K is

$$\begin{bmatrix} X_c \\ X_s \end{bmatrix} = \begin{bmatrix} M_1 & M_2 \\ M_2 & M_3 \end{bmatrix} \begin{bmatrix} \sum_{n=0}^{K-1} x_n \cos(n\theta) \\ \sum_{n=0}^{K-1} x_n \sin(n\theta) \end{bmatrix} \tag{16}$$

where $\theta = \frac{2\pi}{N}$

$$M_1 = \frac{1}{\Delta}\sum_{n=0}^{K-1} \sin^2(n\theta) \tag{17}$$

$$M_2 = -\frac{1}{\Delta}\sum_{n=0}^{K-1} \cos(n\theta)\sin(n\theta) \tag{18}$$

$$M_3 = \frac{1}{\Delta}\sum_{n=0}^{K-1} cos^2(n\theta) \qquad (19)$$

$$\Delta = \sum_{n=0}^{K-1} cos^2(n\theta) \sum_{n=0}^{K-1} sin^2(n\theta) - \left[\sum_{n=0}^{K-1} cos(n\theta)\, sin(n\theta)\right] \qquad (20)$$

Further, the DFT computations for a moving window scheme [1] and recursive estimation procedure for the implementation of Fourier filtering [2][7], to estimate the phasor, is adopted so that the numbers of computations are significantly reduced.

From (16), real and imaginary part of the complex phasor is given by

$$\begin{bmatrix} X_{c,r} \\ X_{s,r} \end{bmatrix} = \begin{bmatrix} M_1 & M_2 \\ M_2 & M_3 \end{bmatrix} \begin{bmatrix} Y_{c,r} \\ Y_{s,r} \end{bmatrix} \qquad (21)$$

The right hand side of (21) can be calculated by

$$Y_{c,r} - jY_{s,r} = \left[\left(Y_{c,r-1} - jY_{s,r-1}\right) + x_r \times e^{-jK\theta} - x_{r-K}\right].e^{j\theta} \qquad (22)$$

Where r denotes the index for the moving data window

Thus the complex phasor can be expressed as

$$\hat{x}_r = X_{c,r} - jX_{s,r} \qquad (23)$$

D. *Adaptive Window Fourier Technique*

The technique developed consists of three stages as proposed by Chen et al in [7] .The technique will be initiated by the fault detector.

Stage 1)

- ***a)*** Once the fault is detected DFT filter starts with initial data window (*init_win*), calculates one estimate using (21)-(23).
- ***b)*** After three consecutive estimates with the same data window, (12)-(15) are utilized to estimate the accurate phasor.
- ***c)*** After passing *init_win* samples, prefault samples are completely removed from the data window

Stage 2)

- ***d)*** The phasor is now computed using a variable data window technique.
- ***e)*** After each estimation process, the filter progressively increases its data window length to estimate the phasor.
- ***f)*** The dc decaying offset is adaptively removed from the fault signal and the noise immunity is adaptively varied with the window length.

Stage 3)

- ***g)*** If the data window reaches full cycle length (*full_win),* the window length will be fixed. It will not change.
- ***h)*** Then the moving data window approach will be adapted by the filter for the phasor estimation

III. APPLICATION OF PROPOSED SCHEME TO DISTANCE PROTECTION

The distance relay gives the trip decision based on the fault impedance estimation. If the estimated impedance is with in the relay zone steady state characteristic then the relay gives the trip decision. Based on the estimated impedance, the distance relay can distinguish between the external and internal faults according to its reach settings.

The reach setting used for simulation studies is a parallelogram characteristic with a forward fault resistance of 10 ohm. The backward reach settings used are 73° – 79°

$$R_b = \left(\tfrac{3}{5}\right) R_f \qquad and \qquad X_b = \left(\tfrac{1}{6}\right) X_{reach} \qquad (24)$$

Where R_b , X_b are backward resistance and reactance reaches and R_f, X_{reach} are their forward counterparts respectively.

The X/R ratio or the slope of a pair of parallelogram sides is found to be 5.1375, which is roughly 79° . The ratio however, is not the same throughout the length of the line. The angle varies between 73° – 79° .

To generate the fault transients for the performance evaluation of the proposed scheme a simple transmission line system is simulated using EMTP-MIPOWER software package. The single line diagram of the power system model selected for case studies is shown in Fig. 3.

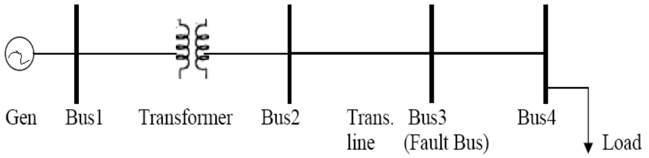

Fig. 3. Single line diagram of simulated transmission system.

The sample power system has an 11kV generator of 500MVA capacity, an 11kV/400kV, 500MVA step up transformer, 400kV, 300 km long transmission line and a load of 400MW at 0.95 p. f.

The faults are created at bus 3 (fault bus) between Bus 2 and Bus 4 as it helps in changing the length of transmission line from 10 % to 90% at which the fault occurs. The faults are created at 0.1 second after the start of simulation. To store the data, a sampling rate of 60 samples per cycle (3 kHz) is chosen, so that the waveforms can be recorded accurately.

The test data are generated for phase to ground fault only since the simulation of the proposed hybrid algorithm is developed for single phase. The faults are created at different line lengths from 10% to 90% of total length of the transmission line and at different fault inception angles like 0°,30°,60°,90° with and without fault resistance.

A total of thirty cases for phase to ground faults are generated for the performance evaluation of the proposed scheme.

IV. PERFORMANCE EVALUATION

The main idea behind simulation study of the algorithm is to evaluate its performance in terms speed and accuracy of tripping action for different fault conditions. The fault data from EMTP- MiPower tool as mentioned earlier is taken in per unit.

The simulation of proposed hybrid scheme is done using MATLAB. The input data of voltage and current signals are decomposed by wavelet transform – DWT: MRA

The coefficients of decomposition at level one are taken to the phasor estimation algorithm as explained in previous section. The on line fault detection was obtained by using D1. A1 is used for phasor estimation, so that high speed can be achieved since the phasor estimation algorithm is DFT based with decaying dc offset removal scheme which can take care of other higher harmonic frequencies [1], [2] and dc offset if present in the fault signal. Processing of the fault signals is done so that the fundamental component is passed most accurately and the rest are attenuated. Extensive simulation study is made to prove the efficacy of the proposed hybrid scheme. Impedance trajectory is obtained for different conditions of phase to ground faults. Results of sample case are presented.

Fig. 4 shows a sample fault data signals obtained for an A-G fault occurring at 30% of the transmission line length and at 0^o inception angle with respect to voltage and with zero fault resistance.

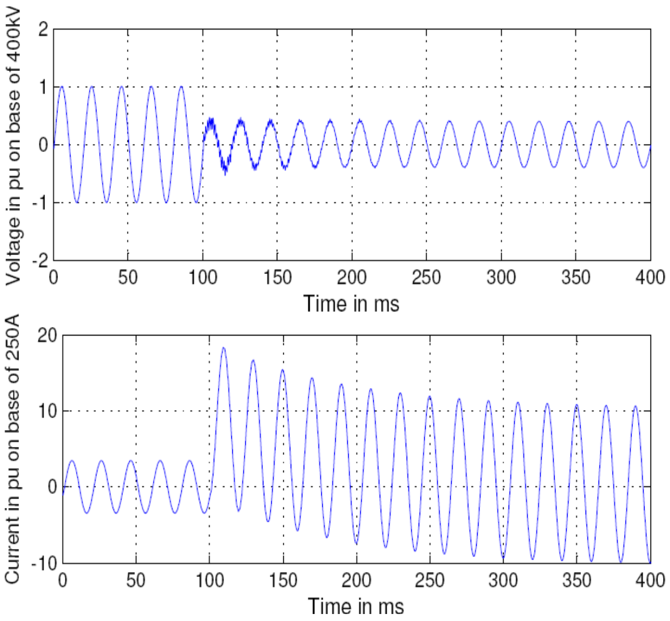

Fig. 4. Sample A. G. Fault Voltage and Current signals.

Fig. 5 is the plot of fault detection index (D) for the above sample fault signals with a threshold, Th_D, considered for fault detection.

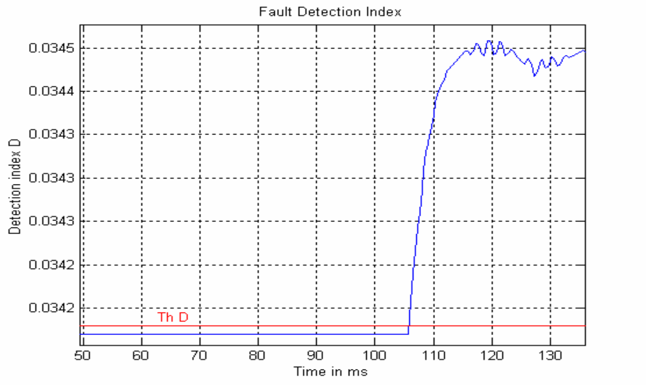

Fig. 5. Fault detection index for Sample A. G. Fault signals.

The DWT level one coefficient D1 and A1 of sample fault signals is shown in Fig. 6 and Fig. 7. The same in time domain is shown in Fig. 8.

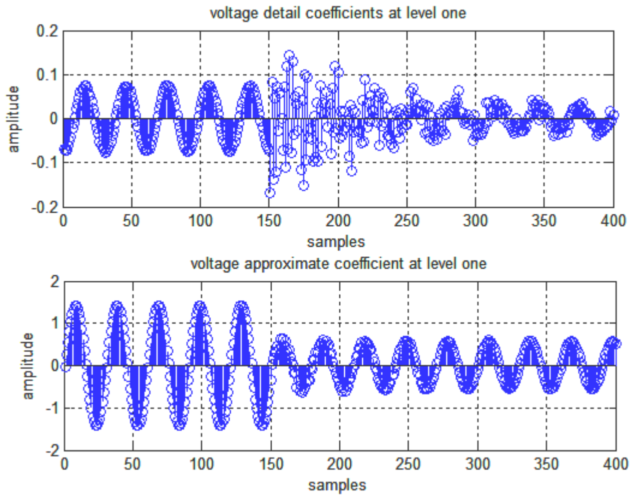

Fig. 6. DWT Coefficients at level one of fault voltage signal.

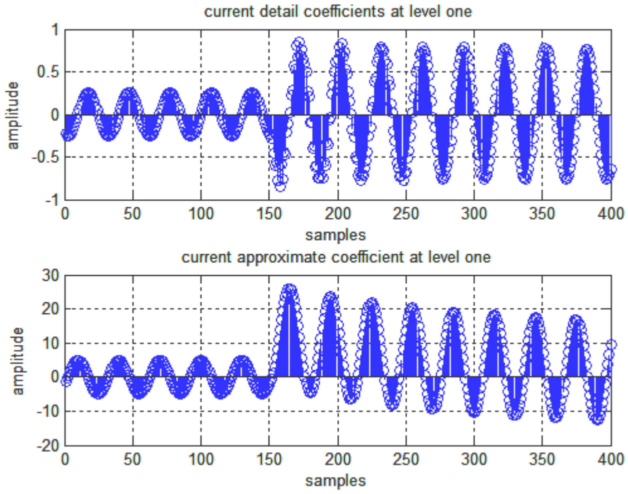

Fig. 7. DWT Coefficients at level one of fault current signal.

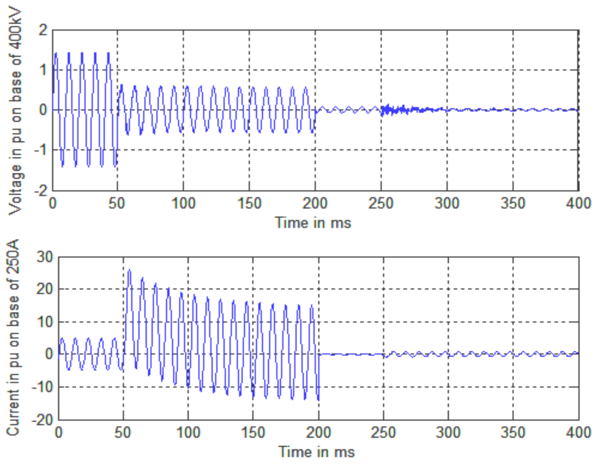

Fig.8. Fault voltage and current signals after MRA

A. Comparative studies

To prove efficacy of the of the proposed hybrid scheme, Comparative evaluation is made with that of the adaptive window DFT algorithm [1].Results are shown in the form of impudence plots .The estimated resistance and reactance plots of both algorithms are given by Fig. 9 and Fig. 10.Similarly the Impedance plots are shown in Fig. 11 and Fig. 12 respectively.

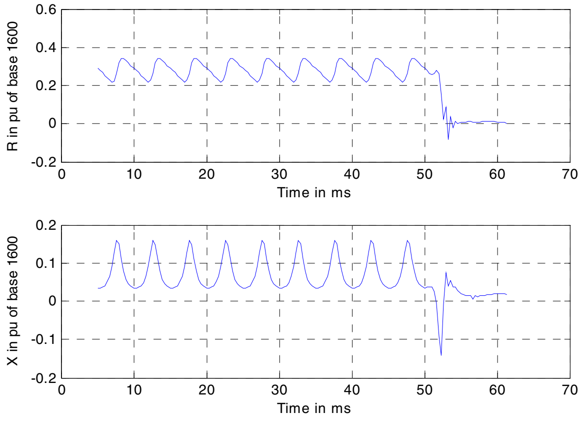

Fig. 9. Estimated Resistance and Reactance plot of proposed hybrid scheme.

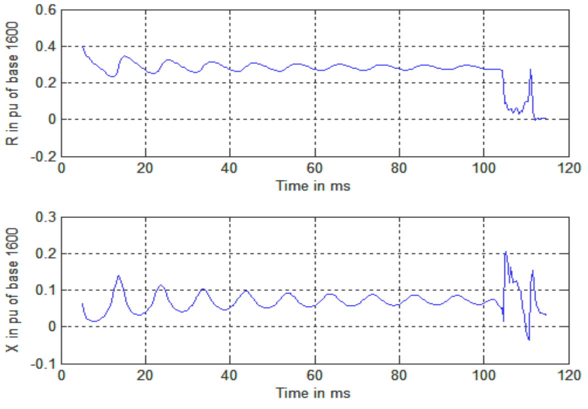

Fig. 10. Estimated Resistance and Reactance plot of adaptive window DFT algorithm.

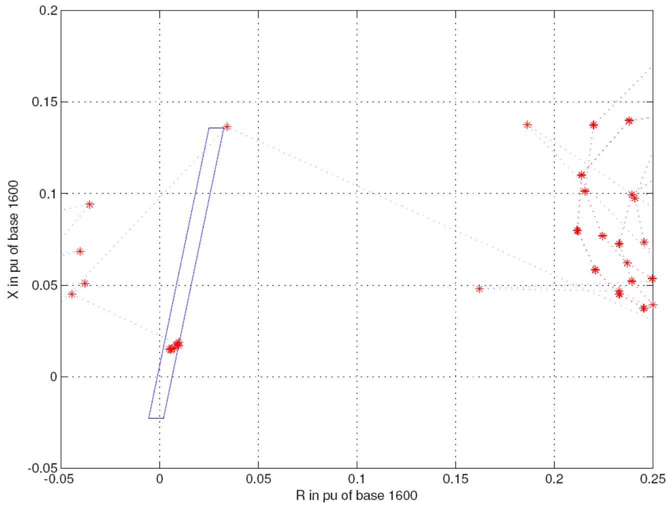

Fig. 11. Impedance plot--Proposed hybrid scheme.

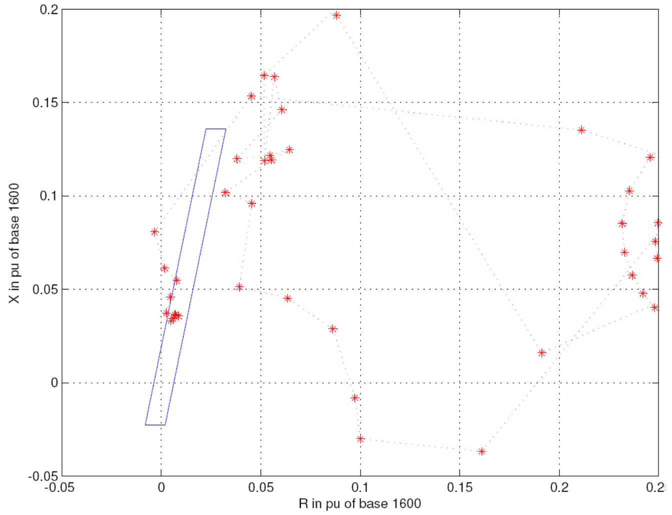

Fig.12. Impedance plot--Adaptive window DFT algorithm

The compilation of the results of the some of the sample cases of simulation studies conducted is given in following tables. The results point to the superior performance of the proposed scheme in terms of speed of tripping and accuracy. A trip signal is issued only if four consecutive impedance points fall within the reach setting. Following are variables used for the comparison as indicated in tables:

m	Fault Location (%of total length)
Φ	Fault Incidence Angle (degrees)
R_F	Fault Resistance (ohms)
$init\_win$	Initial window length (No. of samples).
T_{det}	Instant of fault detection (ms)
T_{cd}	Instant of trip Command issue (ms)
$Trip\_win$	Window length at trip instant (No. of samples).
T_{trip}	Trip time (ms)

Table I shows the comparison of instant of fault detection and trip command issue to the relay. Table II gives the comparative analysis of the relay tripping time.

TABLE I

COMPARATIVE ANALYSIS OF THE INSTANT OF FAULT DETECTION AND TRIP COMMAND ISSUE TO THE RELAY

Sl. no	M	Φ	R_F	init_win	Adaptive window DFT algorithm		Proposed hybrid scheme	
					T_{det} (ms)	T_{cd} (ms)	T_{det} (ms)	T_{cd} (ms)
1	10	0	10	15	103.00	133.33	52.00	55.33
2	20	90	0	15	105.66	116.66	53.33	62.33
3	50	45	0	15	103.66	114.00	52.33	61.33
4	60	0	0	15	104.33	122.00	52.66	94.33
5	90	90	0	15	107.00	117.00	53 .66	62.00

TABLE II

COMPARATIVE ANALYSIS OF THE RELAY TRIP TIME

Sl. No	m	Φ	R_F	init_ win	Adaptive window DFT algorithm		Proposed hybrid scheme	
					Trip_win	T_{trip} (ms)	Trip_win	T_{trip} (ms)
1	10	0	10	15	59	19.52	34	11.25
2	20	90	0	15	34	11.25	27	8.93
3	50	45	0	15	52	17.21	29	9.93
4	60	0	0	15	53	17.49	29	9.57
5	90	90	0	15	30	9.9	25	8.25

V. CONCLUSIONS

The proposed hybrid scheme with wavelet transform –MRA for signal processing and an adaptive window DFT algorithm embedded, has improved the performance of the digital distance relays in speed of operation and accuracy. The simulation studies have shown both faster time response and better steady-state accuracy of the proposed algorithm.

The advancement in modern digital technology provides a chance for the implementation of complex algorithm in distance protection to achieve optimum performance. The comparative analysis made, proves the efficacy of the proposed hybrid scheme.

With the availability of fast and low-cost signal processors, the proposed algorithm gives a great promise to fast digital distance relaying for transmission lines.

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