VOL. 4, NO. 10, DECEMBER 2009 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

A NOVEL ALGORITHM TO EXTRACT EXACT FUNDAMENTAL FREQUENCY COMPONENTS DURING FAULTS FOR DIGITAL PROTECTION OF POWER SYSTEM

P. Suresh Babu[1] and S. V. Jayaram Kumar[2]
[1]Department of Electrical and Electronics Engineering, St. Ann's College of Engineering and Technology, Chirala, India
[2]Department of Electrical and Electronics Engineering, JNTU College of Engineering, Kukatpally, Hyderabad, India
E-Mail: sureshperli@yahoo.com

ABSTRACT

Whenever fault occurs in power system, the operating quantities contain serious harmonics and decaying dc in addition to fundamental frequency component. In order to ensure better protection to the power system, protective relays must filter their inputs to reject unwanted quantities and to retain desired signal quantities. In addition, the decaying dc and higher order harmonics seriously decreases the precision and convergence speed of extraction of fundamental frequency signal. Accuracy and convergent speed of filter algorithms of protective relays had received great attention. A novel approach is proposed which combines the appropriate analog low pass filter and modified full cycle discrete fourier transform (FCDFT) algorithm to remove the decaying dc from input signals for protection. The proposed algorithm was tested for line to ground faults on 345KV, 200km overhead transmission lines. Electromagnetic transient program (EMTP) and power system computer aided design (PSCAD) were used to generate fault current signals under different fault locations and fault inception angles. The results shows that the proposed technique accurately measures the fundamental frequency component regardless of the characteristic frequency component as well as the decaying dc offset components.

Keywords: filtering algorithms, digital protection, decaying dc offset, harmonics, characteristic frequency components.

INTRODUCTION

With the ongoing growth of the electric power demand and deregulation in the electrical power industry, numerous changes have been introduced to modern electricity industry. As the characteristics of loads are changing, Transmission systems are now being pushed closer to their stability and thermal limits, and energy needs to be transported from the generation point to the end user along the most desirable path. Transmission lines are the life blood of the power delivery. Open access transmission results in increased in electricity transfer over long distances and weak topology. Power systems are more vulnerable to contingencies and probability of power failure due to faults is higher. When a fault is detected the protective relay must respond quickly to isolate the faulted line to preserve the stability of the rest of the system. However various conditions such as remote in feed currents, fault path resistance and shunt capacitance etc., degrade the performance.

Digital multifunction relays are now being used in order to reduce installation, operation and maintenance costs. Input signals of protective relays contain distortion, which must be rejected to retain signal quantities of relevant interest. In addition, filters of digital relay must decompose the fundamental frequency component quickly and accurately for enhanced protection. Decaying dc seriously influence the accuracy and convergent speed of filter algorithms. Moreover, the time constant and amplitude of decaying dc of fault lines are unknown and associated with the fault resistance, fault position and fault beginning time. Discrete Fourier Transform (DFT) is an excellent filter algorithm capable of removing integer harmonics using simple computation. However, the voltage and current signals include serious harmonics and decaying dc during the fault period. The decaying dc and higher order harmonics severely inhibit the search for an accurate fundamental frequency signal and delay the convergence time. When a fault occurs, it is desired that the relay used for protection has to respond quickly. The fundamental frequency phasor estimation of the conventional DFT algorithm is not convergent within this time limit.

The present work focuses on presenting a novel algorithm which combines the appropriate analog low pass filter and modified DFT algorithm to remove the decaying dc in operating quantities during faults. Initially, an appropriate analog low pass filter is used to remove higher order harmonics. However, the analog low pass filter simultaneously produces the new time constant of decaying dc. Fortunately, the new time constant is known and is derived according to the characteristic equation of a low pass filter. The fundamental frequency component is then estimated by applying the voltage or current signals after a low pass filter which uses DFT. Moreover, the modified DFT is used to compute and remove the decaying dc after necessary post-fault samples. The modified FCDFT algorithm requires one cycle plus three or four samples. The proposed algorithm can efficiently remove the decaying dc that can operate within the time limit of specific relay installed for protection.

DISCRETE FOURIER TRANSFORMS

For Digital protection of power systems, many popular digital filter algorithms are available in which Discrete Fourier Transforms (DFT) algorithm has received great attention among all filtering algorithms because it is an excellent technique capable of removing integer harmonics using simple calculations and less computation. DFT is used to perform two important functions.

a) Remove the dc component and harmonics.
b) Estimate the fundamental complex phasor element.

The procedure of the proposed technique to extract fundamental frequency component is shown in the following flowchart (Figure-1).

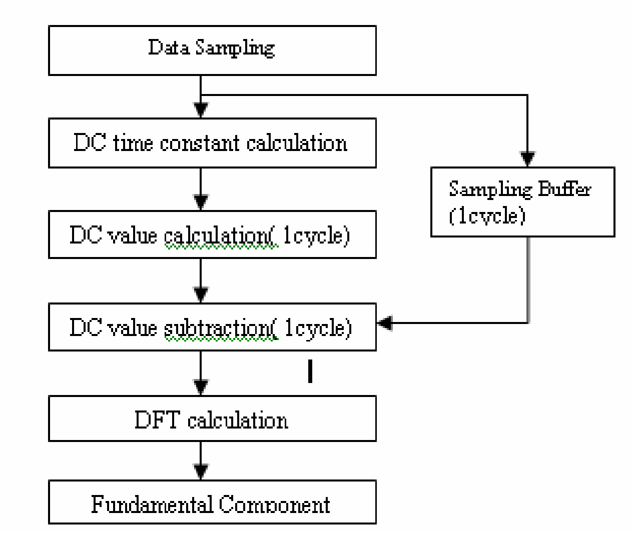

Figure-1. Procedure for fundamental component calculation.

Consider a continuous sinusoidal signal *Z (t)* which contains DC component and N-*2* order harmonics. The time period of the signal is T seconds it is expressed as

$$Z(t) = A_0 + \sum_{n=1}^{N-2} A_n Cos(n\omega t + \theta_n) \quad \ldots\ldots 1$$

Assume the sampling rate is *N* times in a fundamental frequency period. The sample period is $\Delta T = T/N$.

The k^{th} sample signal $Z(k)$ is represented as

$$Z(k) = A_0 + \sum_{n=1}^{N-2} A_n Cos(\frac{2nk\pi}{N} + \theta_n) \quad \ldots\ldots 2$$

As per Full cycle Discrete Fourier Transform, the real part of the Fundamental frequency complex phasor is expressed as

$$Z_{r(k)} = \frac{2}{N} \sum_{r=k-N+1}^{k} Z(r)\cos(2r\pi/N) \quad \ldots\ldots.3$$

Then the imaginary part is

$$Z_{i(k)} = \frac{-2}{N} \sum_{r=k-N+1}^{k} Z(r)\sin(2r\pi/N) \quad \ldots\ldots..4$$

If signal $Z(k)$ only has odd harmonics, it is represented as

$$Z(t) = \sum_{n \in odd}^{1 \le n \le N-2} A_n Cos(n\omega t + \theta_n) \quad \ldots\ldots..5$$

By considering $k \ge N$ the real and imaginary values of the k^th^ sample of the signal Z (k) are obtained as

$$Z_{r(k)} = A_1 \cos\theta_1 \quad \ldots\ldots..6$$

$$Z_{i(k)} = A_1 \sin\theta_1 \quad \ldots\ldots.7$$

The magnitude and phase angle of the k^th^ sample is

$$A_1 = \sqrt{{Z_{r(k)}}^2 + {Z_{i(k)}}^2} \quad \ldots\ldots.8$$

$$\theta_1 = \tan^{-1}(Z_{i(k)} / Z_{r(k)}) \quad \ldots\ldots.9$$

ESTIMATION OF DECAYING DC COMPONENT

Analog low pass filter can remove higher order harmonics with relative ease and, simultaneously, produces the new decaying dc time constant. Fortunately, the new time constant is known and is obtained according to the characteristic equation of a low pass filter. The Proposed method, extracting fundamental frequency component by suppressing dc offset and other characteristics frequency components, utilizes Full cycle Discrete Fourier Transform with first order low pass filter. Consider a function $f(t)$ as operating signal before low pass filter during fault period. Consider the decaying dc time constant of lines fault as τ . The time constants of low pass filter are τ_1 and τ_2 .

$$f(t) = A_0 + \sum_{n=1}^{\infty} A_n \cos(n\omega t + \theta_n) + Be^{-t/\tau} \quad \ldots\ldots..10$$

The Characteristic equation of 1^st^ order low pass filter is

$$s + 1/\tau_1 = 0,\ \tau_1 > 0$$

Which has Fundamental frequency amplitude gain: K_{A1}

Fundamental frequency phasor angle shift: $K_{\theta 1}$

The time constant and amplitude of decaying dc of fault lines are unknown and associated with the fault resistance, fault position and fault beginning time. The new time constant of the low pass filter is known then the output signal of the first order low pass filter is $z(t)$ is represented as

$$z(t) = A_0 + \sum_{n=1}^{N-2} C_n \cos(n\omega t + \varphi_n) + De^{-t/\tau} + D_1 e^{-t/\tau_1} \ldots\ldots 11$$

By applying Full Cycle Discrete Fourier Transforms, the real and imaginary components are related as follows:

$$Z_{r(N)} = \frac{2}{N}\sum_{k=1}^{N} z(k)\cos(2k\pi/N)$$

$$= C_1\cos\varphi_1 + \frac{2}{N}\sum_{k=1}^{N}[De^{-k\Delta T/\tau} + D_1 e^{-k\Delta T/\tau_1}].\cos\left(\frac{2k\pi}{N}\right) \qquad .....12$$

$$Z_{i(N)} = \frac{-2}{N}\sum_{k=1}^{N} Z(k)\sin(2k\pi/N)$$

$$= C_1\sin\varphi_1 - \frac{2}{N}\sum_{k=1}^{N}[De^{-k\Delta T/\tau} + D_1 e^{-k\Delta T/\tau_1}].\sin\left(\frac{2k\pi}{N}\right) \qquad ....13$$

To solve above relations let assign unknown parameter $e^{-\Delta T/\tau}$ as X and known parameter $e^{-\Delta T/\tau_1}$ as K_1

$$\frac{N(Z_{r(N+1)} - Z_{r(N)})}{2\cos(2\pi/N)} = DX(X^N - 1) + D_1K_1(K_1^N - 1) \qquad ....14$$

$$\frac{N(Z_{r(N+2)} - Z_{r(N+1)})}{2\cos(4\pi/N)} = DX^2(X^N - 1) + D_1K_1^2(K_1^N - 1) \qquad ....15$$

$$\frac{N(Z_{r(N+3)} - Z_{r(N+2)})}{2\cos(6\pi/N)} = DX^3(X^N - 1) + D_1K_1^3(K_1^N - 1) \qquad ....16$$

$$\{(15) - (14)\}K_1 = DX(X^N - 1)(X - K_1) \qquad ....17$$

$$\{(16) - (15)\}K_1 = DX^2(X^N - 1)(X - K_1) \qquad ....18$$

Then using the following steps, amplitude and phase angle of the signal are calculated,

a) Divide (18) with (17) obtains the value of X.
b) Using X and (17) obtain D.
c) Using X, D and (14) obtain D1.
d) Using X, D, D1 and (12) obtain $C_1\cos\varphi_1$.
e) Using X, D, D1 and (13) obtain $C_1\sin\varphi_1$.

The magnitudes and phase angles are obtained.

$\therefore A_1 = C_1/K_{A1}$ And $\theta_1 = \varphi_1 + K_{\theta 1}$

IMPLEMENTATION OF PROPOSED TECHNIQUE

The performance of the proposed technique was evaluated for Line-to-Ground fault on 345KV, 200 km overhead transmission line as shown in Figure-2.

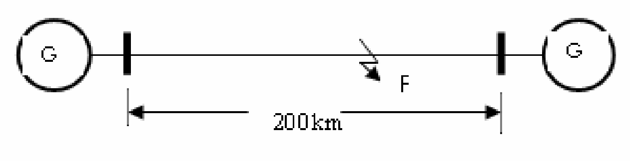

Figure-2. Single line diagram of the test system.

Test system data

Generator-1	Generator-2
15000MVA	10000MVA
X/R ratio = 20	X/R ratio = 20

Type of sequence	Name of the parameter	Value
Positive and negative sequence	R_1, R_2	0.034 Ω/km
	L_1, L_2	0.97 mH/km
	C_1,C_2	0.017 µF/km
Zero sequence	R_0	0.25 Ω/km
	L_0	2.70 mH/km
	C_0	0.005 µF/km

The EMTP and PSCAD software were used to generate fault current signals under different fault locations and fault inception angles. The sampling frequency is calculated by taking 60Hz line frequency and 128 Samples per cycle which gives sampling frequency as 7680Hz in which one sampling interval contains 0.130 milli seconds. The EMTP output was preconditioned by first order low pass filter with cutoff frequency of 600Hz in order to reject high frequency components and to prevent aliasing errors.

Proposed scheme was implemented by creating single line to ground fault at different locations and different fault inception angles θ. The L-G faults are incepted at three different angles 0^0, $45^0$and 90^0 are taken into consideration at eight different fault distances 10 km, 25 km, 50 km, 75 km, 100 km, 125 km, 150 km and 175 km from the relay point. The zero crossing of voltage of phase-A is taken as reference angle. The amplitude of the signal to be filtered is influenced by change in distance of the fault location and fault inception angle which was represented in waveforms of Figures 3a and 3b.

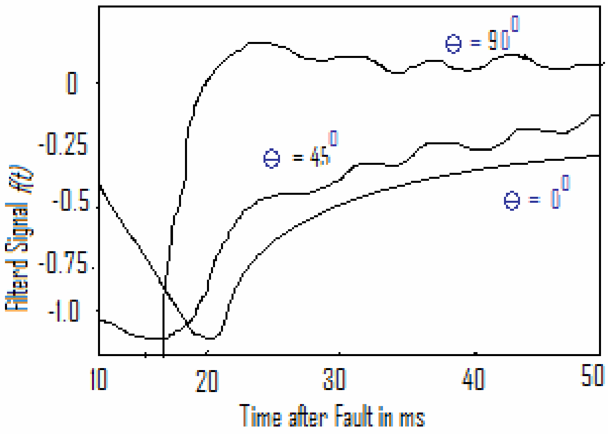

Figure-3a. Pre-filtered fault signal f (t) for L-G fault at a distance of 25 km.

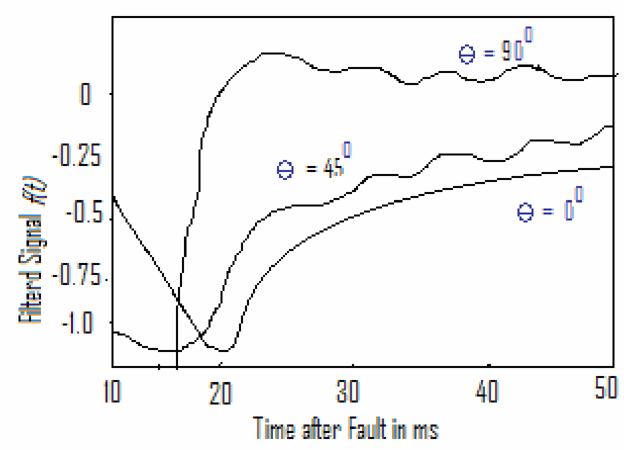

Figure-3b. Pre-filtered fault signal f (t) for L-G fault at a distance of 175 km.

CASE STUDIES

Whenever a fault occurs on a transmission line, damped resonance frequency components are generated. Present work deals with characteristic frequency components only as they are treated as damped components with lowest resonance frequency. The other resonance frequency components are not taken into consideration because they not only have much smaller magnitudes than the characteristic frequency component, but also can be almost completely eliminated by the low pass filter.

Case-I. (At the beginning of the line)

Line to ground fault at Phase-A is created at a distance of 10km from relay location. The current waveform at that fault point is as shown in Figure-4.

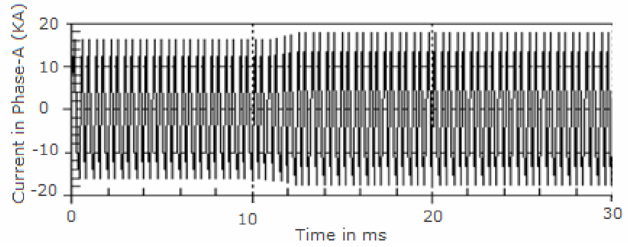

Figure-4. Fault current in phase-A at 10 km length.

The characteristic frequency component changes with the increase in the fault location from the relay point. For the present case, the characteristic frequency component contained by the signal has very small amplitude because this component was completely removed by the low pass filter. At the distance of 10 km, the amplitude of the fault current that calibrated by the proposed method is 17.537KA. The actual amplitude of the fault current is 17.539 KA.

The error in calibration is calculated as

$$\% \text{ error} = [(I_{\text{calibrated}} - I_{\text{Actual}}) / I_{\text{Actual}}] \times 100$$

For the present case the percentage error is 0.011%, which is comparatively less.

Case-II. (At the middle of the line)

Line to ground fault is created at a distance of 100 km from relay location. The current waveform at that fault point is as shown in Figure-5.

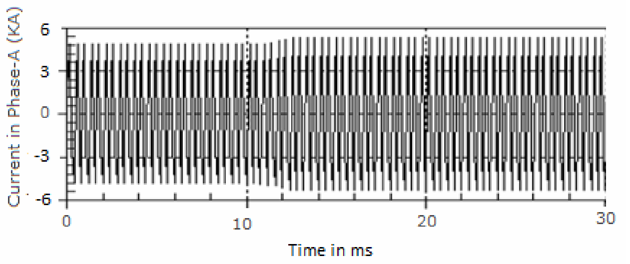

Figure-5. Fault current in phase-A at 100 km length.

The characteristic frequency component changes with the increase in the fault location from the relay point. For the present case, the characteristic frequency component contained by the signal has very small amplitude because this component was completely removed by the low pass filter. At the distance of 100 km, the amplitude of the fault current that calibrated by the proposed method is 4.8072KA the actual amplitude of the fault current is 4.8082KA.

For the present case the percentage error is 0.020%, which is also less.

Case –III. (At the far end of the line)

Line to ground fault is created at a distance of 175 km from relay location. The current waveform at that fault point is as shown in Figure-6

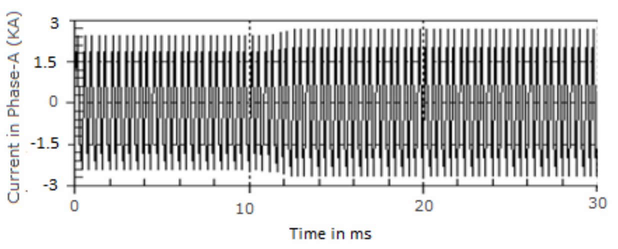

Figure-6. Fault current in phase-A at 175 km length.

For the present case, the characteristic frequency component contained by the signal has considerable amplitude when compared to Dc offset component particularly when fault inception angle is approaching towards 90^0. This is because the characteristic frequency about 690 Hz of the 175 km L-G fault on Phase-A is not so high compared to the cutoff frequency 600Hz of the low pass filter. Consequently the characteristic frequency component passes the low pass filter and causes ripples, which are negligible, on the filtered signal. Considerable measures to be taken to reduce the impact of these ripples if fault amplitudes are very high.

At the distance of 175 km, the amplitude of the fault current that calibrated by the proposed method is 2.4559KA. The actual amplitude of the fault current is 2.4563KA.

For the present case the percentage error is 0.016%

Different case studies are carried out by creating L-G fault with three different fault inception angles 0^0, $45^0$and 90^0 for eight different fault distances 10 km, 25 km, 50 km, 75 km, 100 km,125 km, 150 km and 175 km from the relay point. The test results are presented in Table-1.

Table-1.

Fault distance (km)	**Calibrated value** (KA)	**Actual value** (KA)	**%Error in calibration**
10	17.537	17.539	0.011%
25	11.939	11.948	0.075%
50	7.3384	7.3395	0.014%
75	5.3647	5.3659	0.022%
100	4.8072	4.8082	0.020%
125	3.7183	3.7195	0.032%
150	2.9317	2.9321	0.013%
175	2.4559	2.4563	0.016%

Table-1 indicates calibrated values and actual values of the power system taken for the implementation of the proposed method. It shows that the values obtained by the proposed method are almost nearer to actual values such that error is less. It shows that the proposed method can measure the accurate fundamental frequency component of the faulted signal contains decaying dc offset component and characteristic frequency component.

CONCLUSIONS

A novel technique is proposed to measure the fundamental frequency component of faulted signal distorted with dc offset, characteristic frequency components and harmonics. The proposed technique is implemented on 345KV, 200 km length overhead power transmission line by generating fault current signals under different locations and fault inception angles. The performance evolution results show that the proposed method operates reliably with satisfactory results by extracting exact fundamental frequency components of the faulted signals to be given as input parameters of relays for digital protection of power system.

REFERENCES

Yuan Liao and Mladen Kezunovic. 2009. Online optimal transmission line parameters estimation for relaying applicatons. IEEE transactions on power delivery. 24(1): 96-102.

S. Kurokawa, J. Pissolato, M.C. Tavares, C.M. Portela and A.J. Prado. 2006. A new procedure to derive transmission line parameters, applications and restrictions. IEEE transactions on power delivery. 2(1): 492-498.

L.M. Popovic. 1991. General equations of the lines represented by discrete parameters-part II: resonant phenomena. IEEE transactions on power delivery. 6: 302-308.

E.O. Schweitzer III and D. Hou. 1992. Filtering for protective relays. In: 19th annual western protective relay conference, Spokane, WA.

F.H.J. Altuve, V.I. Diaz and M.E. Vazquez. 1996. Fourier and Walsh digital filtering algorithms for distance protection. IEEE transactions on power systems.11: 457-462.

E. Rosolowski and M. Michalik. 1994. Fast identification of symmetrical components by use of state observer. Proceedings of Inst. Electrical Engineering-Generation, Transmission and Distribution. 141(6): 617-622.

Y. Tang, H. Chen, H. Wang and F. Dai. 1999. Transmission line models used in traveling wave studies. In: Proceedings transactions on Distribution conference. 2: 797-803.

M.S. Sachdev and M. Nagpal. 1991. A recursive least error squares algorithm for power system relaying and measurement application. IEEE transactions on power delivery. 6(July): 1008-1015.