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A MODIFIED FULLCYCLE DISCRETE FOURIER ALGORITHM BASED DIGITAL MULTIFUNCTION RELAY FOR TRANSMISSION LINE PROTECTION

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ABSTRACT

Since it is not possible to optimize a standard relaying system to every protection need, Digital Multifunction protection systems are proposed as they have features like cost efficiency, Functional flexibility, Adaptive relaying and Self checking capability. With the advantage of generally available hardware and software, having the speed and capability of digital relays necessary for protection application, it has now become possible for the relay engineers to develop and implement custom protection solutions for those applications where standard packages may not provide the necessary flexibility or performance. A modified Fullcycle Discrete Fourier Transform (FCDFT) Algorithm based digital multifunction relay is proposed which has capability of executing trip command by extracting exact fundamental frequency component, by eliminating harmonics and decaying DC offset component, during faults in power systems. The proposed algorithm was tested for different faults on 220KV, 100km overhead transmission line. Electromagnetic Transient Program (EMTP) and Power System Computer Aided Design (PSCAD) were used to generate waveforms under different fault locations and fault inception angles. The results show that the proposed Digital multi-function relay worked efficiently and reliably.

Keywords: digital multifunction relays, transmission line faults, full cycle fourier filtering algorithms, digital protection.

1. 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 digital multifunction relay based on an 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 to remove the decaying dc after necessary post-fault samples. The modified FCDFT algorithm requires one cycle plus three or four samples. The proposed digital multi-function relay works based on the above criterion and gives reliable and efficiently remove the decaying dc that can operate within the time limit of specific relay installed for protection.

2. FILTERING ALGORITHM

In the proposed Digital Multi-function protection scheme, Modified FullCycle Discrete Fourier Transform

(DFT) was used as it has capability not only to Remove the dc component and harmonics but also Estimate the fundamental complex phasor elements.

FullCycle DFT can easily remove DC and integer harmonics and compute the fundamental frequency phasor using one cycle samples or so; however this algorithm may not be suitable to use in UHV system applications where the decision has to be made in less than one cycle. To reduce the response time, half cycle DFT has been proposed where convergence speed to the final value is faster than the full cycle algorithm. But the half cycle DFT cannot eliminate even numbered harmonics and the decaying DC present under fault condition. As proposed method functioning is based on extraction of exact fundamental frequency component of faulted signals, a fullcycle Fourier algorithm with modifications is used to reduce response time and convergence speed.

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 an algorithm which has capability to extract exact fundamental frequency components from input signals, is presented in this work.

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

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

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

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

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

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

Then the imaginary part is

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

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

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

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

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

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

The magnitude and phase angle of the k th sample is

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

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

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 .

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

The Characteristic equation of 1st 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

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

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

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

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

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

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

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

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

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

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

Then using 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 estimated by the following expressions.

$$\therefore A_1 = C_1 / K_{A1} \text{ and } \theta_1 = \varphi_1 + K_{\theta 1} \qquad \ldots\ldots...19$$

3. RELAY LOGICS

The relay logic used in this work has two levels: Function level and Unit level. At the Function level, the logic checks for the occurrence of a fault using the predefined trip criteria that discriminate between fault and load condition. If fault is detected, the relay logic calculates the time that has to elapse before a trip command can be issued from the current instant.

At unit level, the outputs of the function level logic are correlated to generate a trip command after the lapse of the lowest of the time to trip values of the individual functions if the corresponding trip criterion still remains satisfied.

The Function Level Logic implementation is as follows:

3.1 Distance function logic

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

$$V_{L1-L2} = V_{L1} - V_{L2} \qquad \text{-----}20$$

$$i_{L1-L2} = i_{L1} - i_{L2} \qquad \text{-----}\ 21$$

$$i_R = i_{L1} + i_{L2} + i_{L3} \qquad \text{-----}\ 22$$

The ground impedance seen at the relay point is calculated as

$$Z_{Li} = \frac{V_{L1}}{I_{L1} + \frac{K-1}{3} I_R} \qquad \text{-------}\ 23$$

V_{L1}, I_{L1} *are* the RMS values of the relay voltage and current

I_R 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

$$Z_{L1-L2} = \frac{V_{L1-L2}}{I_{L1-L2}} \qquad \text{------}24$$

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. Conventionally, the instantaneous reach of the Distance function is set to 85% of the line length to allow a margin for the relay overreach due to the DC component of the fault current. The present scheme allows the extension of this setting to 95% of the line length. This is possible because the proposed method used effectively suppresses the DC offset component and harmonics in the fault signal and makes the distance function less prone to over-reaching error.

High accuracy fault locator

When the fault point is determined by measuring the impedance using local voltages and currents, the measurement error is increased as a result of the phase difference between the local and remote currents flowing into the fault point.

The fault locator, incorporated in present Digital multifunction relay, measures the distance to fault using local and remote voltages and currents. The fault point is calculated using the following Equation

$$D = \frac{V_A - V_B + ZI_B}{Z(I_A + I_B)} \qquad \text{--------}25$$

Where,

D: Distance from Relay to the fault point
VA, IA: Local terminal voltage/current
VB, IB: Remote terminal voltage/current
Z: Line impedance

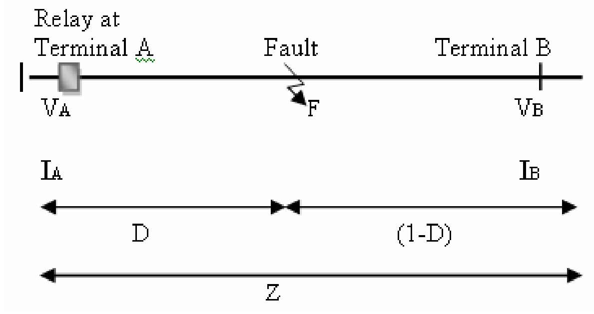


Figure-1. Fault locator.

3.2 Overcurrent function logic

The general form of analytical relationship between the operating time and input current in the form

$$t = CK/(I^n - 1) \qquad \text{--------26}$$

I is input current, K is time multiplier setting C and n are the constants determining inverseness.

The following condition thus results for the setting of the pick-up current

$$I_{F\min} > I_{Pick-up} > I_{L\max} \qquad \text{-------27}$$

IF min -- minimum fault current at the relay location for a fault at limit of the protected zone

IL max -- maximum permissible load current of the protected line

Ipick-up -- relay (set) pick-up current

In present work this setting is based on the peak values of the incoming fault current. If the relay current drops below the set value before the lapse of the time to trip, the function logic resets itself automatically and jumps to check other relay function.

4. PRECAUTIONS TAKEN TO IMPROVE STABILITY OF PROPOSED RELAY

Proposed Digital multifunction relay can increase the coverage of the instant operation zone and improve sensibility by taking proper precautions as below.

4.1 Voltage start element

In order to prevent relay operating incorrectly on open circuit, a voltage start element is used to increase reliability of the relay. The voltage start element includes a negative over voltage element and a phase to phase under voltage element.

4.1.1 Negative over voltage element

Negative over voltage element can pick up when unsymmetrical fault occurs. The criterion of negative over voltage element is

$$V_2 > V_{op,2} \qquad \text{---------28}$$

Where V_2 is the negative voltage.

$V_{op,2}$ is the operating value of the negative over voltage element:

$$V_{op,2} = K_{rel} V_{umb-2} \qquad \text{-----------29}$$

Where

V_{umb-2} is the maximal unbalanced negative voltage;

K_{rel} is the reliable coefficient.

The relay will start when the equation (29) is met and drop off when it is not.

4.1.2 Phase-phase under voltage element

Phase-phase under voltage element is used for symmetrical fault. The criterion of the phase-phase under voltage element is

$$V_{\phi\phi} < V_{op,p} \qquad \text{----------30}$$

Where $V_{\phi\phi}$ is the phase-phase voltage: V_{AB}, V_{BC}, V_{CA}

$V_{op,p}$ is the operating value of phase-phase under voltage element:

$$V_{op,p} = \frac{(0.9 \rightarrow 0.95)V_e}{K_{rel}} \qquad \text{----------31}$$

Where V_e is the normal phase-phase voltage; K_{rel} is the reliable coefficient.

To prevent Phase-phase under voltage element from start under condition of power swing, a 1 cycle pre-fault (swing) voltage is used as the normal phase-phase voltage.

The relay will start when the condition in equation (31) is met, will drop off when it is not.

4.2. Phase selector and block element

The voltage start element can prevent operation incorrectly when open circuit occurs. However when fault occurs in successive operation zone, the voltage start element will pick up. Because the remote end breaker will trip first, healthy phase relay of the healthy line may operate incorrectly.

To prevent this, a phase selection element is used to block the potential operation of the health phase.

The criteria is

$$\left|I_{1,i}\right| < K_{rel}.\max\{\left|I_{1,i}\right|\} \qquad \text{-------------32}$$

Where $I_{1,i}$ is current of any line

K_{rel} is the reliable coefficient.

Any phase current meeting equation (32) is a healthy phase and should be blocked.

5. SIMULATION AND TEST RESULTS

To demonstrate the performance of the proposed digital multi-function relay, a 100km, 220KV transmission system has been modeled using EMTP and PSCAD. The configuration of the simulated system is as shown in Figure-2. Both generators E_A and E_B are rated at 220KV. Various typical faults and evolving faults are tested for a number of fault locations.

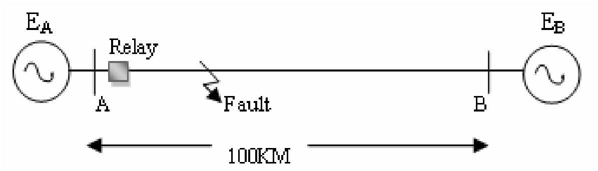


Figure-2. Single line diagram of test system.

Generator data:

Generator	Rating
Generator E_A	$220\angle 0^0$ KV
Generator E_B	$220\angle 30^0$ KV

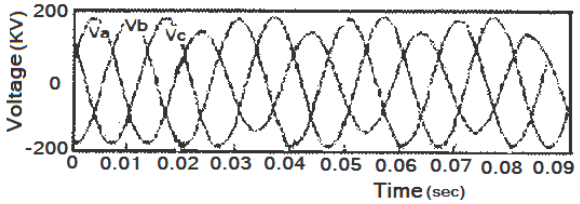
Transmission line data:

Type of impedance	Value
+ve Sequence impedance	0.03504+j0.42415 Ω/km
-ve Sequence impedance	0.00354+j1.14340 Ω/km

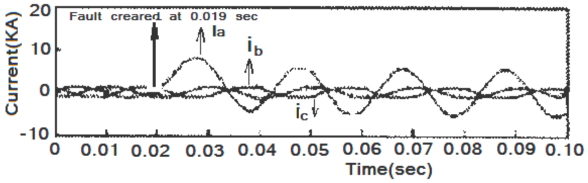
Four fault locations are set along the transmission line at 10Km, 40Km, 75km and 90Km from terminal A where the proposed digital multi-function relay was placed. The setting of zone-1 is set as 80% of the protected line impedance

Case-I: **L-G Fault**

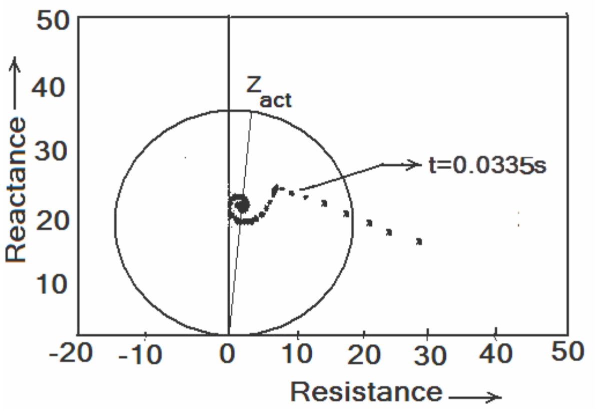
Single line to Ground fault was created on Phase A at a distance of 40Km from relay location. The fault inception angle is 0^0 with fault resistance 1Ω. The waveforms in Figure-3 are indicating voltage, current and impedance evolution for L-G fault simulated.



a) Voltage Waveform



b) Current Waveform



Impedance relay characteristics

Figure-3. Waveforms of line to ground fault.

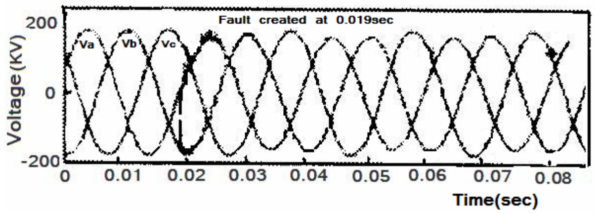
Test results

- The time instant of Phase A to Ground fault creation : 0.019 sec
- Fault inception angle: 0^0.
- Fault signals amplitude estimation and time of startup: 0.0265 sec.
- Time of faulted phase selection: 0.0283sec.
- The Time instant of trip signal generated: 0.0335 sec.
- Faulted phase displayed: "Phase-A".
- The distance of fault occurred from relay point: 39.995Km.

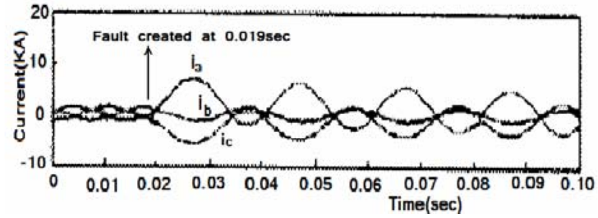
Case-II: L-L Fault

Double Line fault between phase A and Phase B was created at a distance of 90km from relay location. The fault resistance is taken as 0.001Ω and fault inception angle is 20^0.

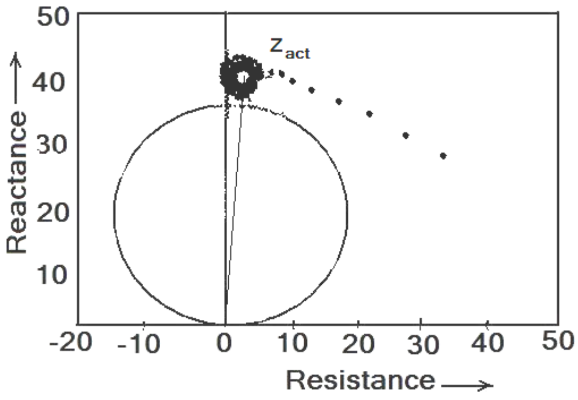
Voltage, Current and impedance evolutions are as shown in following waveforms.



a)Voltage Waveform



b) Current Waveforms



c) Impedance Relay Characteristics

Figure-4. Waveforms of line to line fault.

Test results

- The time instant of Phase A to Phase B fault creation: 0.019 sec
- Fault inception angle: 20^0.
- Fault signals amplitude estimation and time of startup: 0.0278 sec.
- Time of faulted phase selection: 0.0294sec.
- The Time instant of trip signal generated: 0.0329 sec.
- Faulted phase displayed: “Phase-A to Phase B”.
- The distance of fault occurred from relay point: 90. 024Km.

6. CONCLUSIONS

This paper presents a novel digital multifunction relay with modified discrete Fourier Transform Algorithm technique to improve performance of conventional multifunction relay. To improve the performance and to ensure reliability of trip signal generation from the proposed relay, precautions are taken in terms of voltage start and phase selection elements. Each relaying action is acting as backup for another one. Distance relay action is given with more importance than other relaying actions that voltage and current faults are also, either directly or indirectly, included in the calculation of impedance upto relaying point. Different types of faults are simulated and typical simulation results are presented in this paper. The simulation results have proved that the proposed digital multifunction relay can perform well whose tripping criterion is based on exact fundamental frequency component of fault waveforms. The sensitivity, selection of faulted phase discrimination, trip decision making are additional strengths of the proposed work.

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