

Fast and Accurate Fault Detection in Transmission Line Using Phasor Measurement

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Abstract: An accurate fault detection and classification is required to transmit power from generating station to various load centres reliably. A new approach for fault detection for interconnected system using the time synchronized phasor measurements. The scheme is depending on comparing positive sequence voltage magnitudes for specified areas and positive sequence current phase difference angles for each interconnected line between two areas on the network. The paper performance of discrete Fourier transforms method for phasor estimation. The MATLAB/SIMULINK program is extensively used to implement the idea. It is used to simulate the power system, phase measurement function, synchronization process, and fault detection.

Keywords: Fault Detection/Location Index, Discrete Fourier Transforms (DFT), Phasor Measurement and Transmission lines.

I INTRODUCTION

More recent technological advancements in microprocessor relays, combined with GPS receivers for synchronization and accurate time stamping, is providing users advanced relay systems with synchronized measurements, called synchrophasor measurements (IEEE Power System Relaying Committee, 2002; Phadke, 2002; Marek, 2002). Synchrophasor measurements together with advancements in digital communications, provides users with the power system state at a rate of twenty times per second.

A fault occurs when two or more conductors come in contact with each other or ground in three phase systems. Faults are classified as single line-to ground faults, line-to line faults, double line-to ground faults and three phase faults. Therefore, in such instances, the power system components are subjected to the greatest stresses from excessive currents. These faults give rise to serious damage on power system equipment. Fault occurs on transmission and distribution lines not only effects the equipment but also the power quality. So, it is necessary to determine the fault

type and location on the line and clear the fault as soon as possible in order not to cause such damages. Flashover, lightning strikes, birds, wind, snow and ice load lead to short circuits. Deformation of insulator materials also leads to short circuit. Most faults in an electrical system occur with a network of overhead lines are single-phase to ground faults caused due to lightning induced transient high voltage and from falling trees. In the overhead lines, tree contact caused by wind is a major cause for faults. The appropriate percentages of occurrences various faults are listed below

- Single line to ground fault – 70-80%
- Line-Line to ground fault - 10-17%
- Line-Line fault – 8-10%
- Three phase – 2-3%

When faults occur in the power system, they usually provide significant changes in the system quantities like over-current, over or under-power, power factor, impedance, frequency and power or current direction. The most common and also the one used in this thesis is the over-current and so over-current protection is widely used.

A number of phasor estimation algorithms suitable for transmission-line protection have been proposed [3]–[13]. However, the discrete Fourier transforms (DFT)-based filter is the most popular algorithm and has become standard in the industry [1] - [6]. The computational cost of recursive DFT-based filter is very low and good harmonic immunity can be achieved. However, its performance can be adversely affected by decaying dc components, leading to erroneous estimates [9]–[11]. Consequently, distance relays have a tendency to over-reach or under-reach in the presence of the decaying dc offset. For a high-performance digital relay, such a large error cannot be tolerated. This filter achieves the best performance when the time constant of the dc offset is equal to the time constant of the mimic filter. Recently, two DFT-based dc offset removal algorithms, using fixed full-cycle or half-cycle data windows, were proposed in and however, the phasor estimation cannot be very fast due to the long data window length of the filters.

The filtering capability of the DFT-based filter depends on its window length. A short data window will

give a fast response but unstable output. A long one gives stable output but the response will be delayed. The most suitable window length depends on various factors, such as fault locations, fault types, and fault resistance, etc. This means that a compromise between the filter's delay and its noise suppression capabilities is required. It is possible to select a suitable filtering algorithm and a data window at different stages of a fault to complete fast transmission-line protection [1], [2].

II DISCRETE FOURIER TRANSFORM

Discrete-time Fourier (DFT) is the most commonly and widely used technique when it comes to protection relay environment. Extraction of a particular frequency component is done using Fourier transform. However, in relay environment, sampled data at discrete time step is available for processing; therefore, the Fourier-transform calculation is also done in discrete environment and is termed as Discrete Fourier Transform or DFT. Before defining DFT, let us first understand Discrete- Time Fourier Transform (DTFT).

$$X(j\omega) = \sum_{n=-\infty}^{n=+\infty} (x[n])e^{-j\omega n} \quad (1)$$

Where ω is $2\pi f / f_s$.

Equation (1) shows the mathematical representation of Fourier transform for a sampled data signal. Therefore, a truncated version of the above is used for practical purposes. The truncated DTFT is given by (2).

$$X_N(j\omega) = \sum_{n=0}^{N-1} (x[n])e^{-j\omega n} \quad (2)$$

This truncation is equivalent to multiplying by a rectangular window of data length 'N' which results in broadening of spectral peaks and spectral leakage, i.e., presence of side lobes.

Let us now define a full-cycle (1-cycle) DFT where the window length is selected as $N = f_s/f_n$ and the frequency of interest is f_n . In power system protection, DFT is essentially the same as DTFT, evaluated at N equally spaced frequencies between 0 and 2π .

$$X = \frac{2}{N} \sum_{n=0}^{N-1} x[n]e^{-j2\pi \frac{f_n}{f_s} n} \quad (3)$$

Knowing $N = f_s/f_n$

$$X = \frac{2}{N} \sum_{n=0}^{N-1} x[n]e^{-j2\pi \frac{f_n}{N f_n} n} \quad (4)$$

$$X = \frac{2}{N} \sum_{n=0}^{N-1} x[n]e^{-j2\pi \frac{n}{N}} \quad (5)$$

For a pure sinusoidal signal such as $x(t) = A \cos(2\pi f_n t + \theta)$,

$$x[n] = x\left(\frac{n}{f_s}\right) = A \cos\left(2\pi \frac{n}{N} + \theta\right) \quad (6)$$

Equating $x[n]$ into (5) we get (7)

$$X = \frac{2}{N} \sum_{n=0}^{N-1} A \cos\left(2\pi \frac{n}{N} + \theta\right) e^{-j2\pi \frac{n}{N}} \quad (7)$$

Using Euler's identity (7) can be rewritten as (8)

Therefore,

$$X = \frac{1}{N} \sum_{n=0}^{N-1} A \left(e^{j(2\pi \frac{n}{N} + \theta)} + e^{-j(2\pi \frac{n}{N} + \theta)} \right) e^{-j2\pi \frac{n}{N}} \quad (8)$$

$$X(f_n) = A e^{j\theta} = A \angle \theta \quad (9)$$

Equation (9) represents phasor for any sinusoidal signal with the fundamental frequency of f_n . For estimating the phasor of fundamental frequency f_n , equation (7) can be written as

$$X(f_n) = \frac{2}{N} \sum_{n=0}^{N-1} A \cos\left(2\pi \frac{n}{N} + \theta\right) e^{-j2\pi \frac{n}{N}} \quad (10)$$

Using (6) and equating into (10), we get (11)

$$X(f_n) = \frac{2}{N} \sum_{n=0}^{N-1} x[n]e^{-j2\pi \frac{n}{N}} = \underbrace{\frac{2}{N} \sum_{n=0}^{N-1} x[n] \cos 2\pi \frac{n}{N}}_{X_r: \text{Real Filter}} + j \underbrace{\frac{2}{N} \sum_{n=0}^{N-1} -x[n] \sin 2\pi \frac{n}{N}}_{X_i: \text{Imaginary Filter}} \quad (11)$$

It can be observed from time response that DFT has a transient time of 1-cycle. Also, it gives a constant phasor magnitude output for a pure 50 Hz signal once the transient time is over. It can also be observed from the angle that it is constantly varying. As the window of samples is updated upon acquisition of a new sample, the inherent phase shift $2\pi/N$ occurs. Because of this phenomenon, the phasor obtained using this method is called rotatory phasor. It is possible to compensate this angle to obtain a consistent angle.

III THE PROPOSED FAULT DETECTION

The index using the synchronized voltage and current samples at both ends of a transmission line to detect the fault is presented in this section.

Consider an un-faulted single-phase (two-conductors in free space) transmission line shown in Fig.

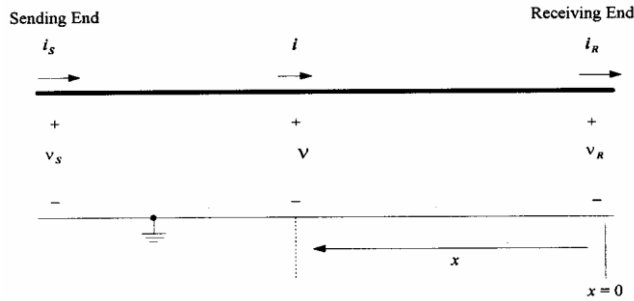


Fig.1. A single-phase transmission line.

Then both voltage and current measured at a distance x km away from receiving end obey the partial differential equations:

$$\frac{\partial v}{\partial x} = R i + L \frac{\partial i}{\partial t} \quad (1)$$

$$\frac{\partial i}{\partial x} = G v + C \frac{\partial v}{\partial t} \quad (2)$$

where R , L , G , and C are resistance, inductance, conductance and capacitance of the transmission line per unit length, respectively. Under sinusoidal steady state condition, the operator $\partial/\partial t$ in Eq.(1) can be substituted by $j\omega$, and therefore Eq.(1) can be converted into two linear, second-order, homogeneous differential equations (original lowercase variable change to upper case ones which represent the phasor quantities), whose solution are

$$V = A e^{+\gamma x} + B e^{-\gamma x} \quad (3)$$

$$I = (A e^{+\gamma x} + B e^{-\gamma x}) / Z_C \quad (4)$$

Where $Z_C = \sqrt{(R + j\omega L)/(G + j\omega C)}$, whose units are, is called the characteristic impedance (or surge impedance), and $\gamma = \sqrt{(R + j\omega L)(G + j\omega C)}$, whose units are m^{-1} , is called propagation constant of the transmission line respectively. Constants A and B can be

determined by boundary conditions at sending and receiving ends.

Suppose that a midway fault occurred at the point F which is $x = DL$ km away from receiving end R on a transmission line SR shown in Fig. 2.

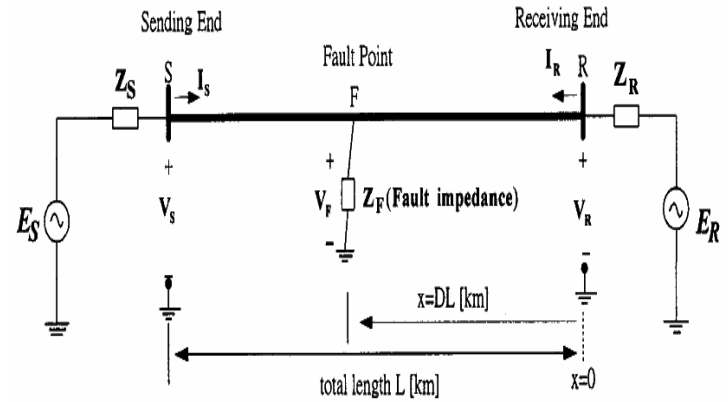


Fig. 2. A single-phase faulted transmission line.

L is the total length of the transmission line, and D is the per unit distance from receiving end to the fault and is also used as a fault detection/location index. In case of a fault occurrence at the point F , the transmission line is thus divided into two homogeneous parts. One is line section SF , the other is line section FR . These two line sections still can be regarded as perfect transmission lines. This means that the voltages at any point on the two line sections can be expressed in terms of the voltages and currents measured on both ends S and R . Moreover, at fault point F the voltages expressed in terms of these two data sets (V_s, I_s) and (V_r, I_r) are identical. We can visualize that there is a pre-fault transmission line as shown in Fig. 2. If we put the two sets of measured data (V_s, I_s) and (V_r, I_r) on the same reference position $x = 0$ and take into account the boundary condition on both ends, then the voltage on the fault position $x = DL$ km can be expressed as:

$$V_F = \frac{1}{2 \exp(\gamma L)} (V_s + Z_C I_s) \exp(DL) + \frac{1}{2 \exp(\gamma L)} (V_r - Z_C I_r) \exp(-DL) \quad (5)$$

$$V_F = \frac{1}{2} (V_r + Z_C I_r) \exp(DL) + \frac{1}{2} (V_r - Z_C I_r) \exp(-DL) \quad (6)$$

Eq. (5) and (6) represent the post-fault voltages at fault point which are expressed in terms of measured sending and receiving data (V_s, I_s) and (V_R, I_R) , respectively. Since V_F is the voltage at the same point F , equating the Eq. (5) and (6) and solving the fault detection/location index D yields:

$$D = \ln(N / M) / 2\gamma L \quad (7)$$

Where

$$N = \frac{1}{2} (V_R - Z_C I_R) - \frac{1}{2} (V_s - Z_C I_s) \exp(\gamma L) \quad (8)$$

And

$$M = \frac{1}{2} (V_s + Z_C I_s) \exp(-\gamma L) - \frac{1}{2} (V_R + Z_C I_R) \quad (9)$$

It is worthy to note that no assumptions in the procedure of derivation for the fault detection index D are made. Hence, the index D is very robust. It will be clearly shown in simulation results that the index D is hardly affected by the variations of source impedance, loading change, fault impedance, fault inception angle and fault type. The index D incorporates with the computed absolute values M and N can be utilized as fault detector. In the case of single-phase line, the computed absolute values of M and N (Eq. (8) and (9)) will all be held at zero before the occurrence of a fault. This can be proved by substituting the measured data (V_s, I_s) and (V_R, I_R) , which are used to compute M and N in Eq. (8) and (9), into the formulae of M and N . Since such measured components all satisfy the transmission line equation, i.e. Eq. (2), after algebraic manipulation, we can prove that M and N are indeed identical to zero, and hence the algorithm will give an indefinite value of fault index through Equation (7). However, as soon as the post-fault measured data been input into the algorithm through the moving data window, the computed values of M and N abruptly deviated from zero, and hence the fault index D also quickly converged to the interval of $(0, 1)$. These facts imply that M and N incorporated with index D could be employed as indicators of various fault events. Such performance will be explained in the simulation section.

Three-phase Case:

Our main concern in this subsection is to extend the techniques of the previous subsection to the three-phase line. Up to now we have proposed a fault detection approach for a single-phase two-wire transmission line. Unfortunately, the approach can't be applied straightforwardly to a three-phase transmission line due to the coupling effect of the inter-phase.

Consider an arbitrary three-phase transmission line illustrated in Fig. 3, which consists of phase a, b, c and a ground system consisting of earth and ground wires. Both

ends of transmission line of interest are labelled by S and R. The system shown in Fig. 3 is divided into two parts. The part of transmission line is plotted in three-wire form for emphasizing the transposition configuration of the line, the other parts of sources are shown in one-line diagram for simplicity. The quantities on both ends shown in Fig. 3 are all vectors of phase voltages and currents.

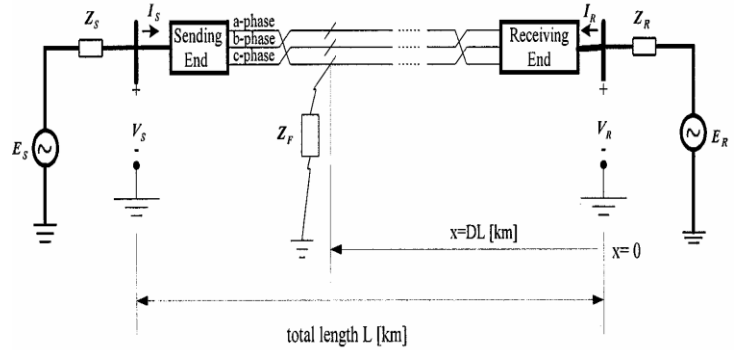


Fig.3. A three-phase transposed transmission line.

As in the case of single-phase transmission lines, the voltages and currents at a distance x km away from receiving end are related through partial differential equations:

$$\frac{\partial v}{\partial x} = R i + L \frac{\partial i}{\partial t} \quad (10)$$

$$\frac{\partial i}{\partial x} = G v + C \frac{\partial v}{\partial t} \quad (11)$$

Where both v and i are 3×1 vector, $R, L, G,$ and C are all 3×3 transposed line parameters matrices whose forms are all like as:

$$L = \begin{bmatrix} L_s & L_m & L_m \\ L_m & L_s & L_m \\ L_m & L_m & L_s \end{bmatrix} \quad (12)$$

Under sinusoidal steady-state condition, Eq. (10) and (11) can be changed into the form

$$\frac{\partial V}{\partial x} = Z I \quad (13)$$

$$\frac{\partial I}{\partial x} = Y V \quad (14)$$

In order to de-couple phase quantities, a suitable transformation, referred to as the modal (or called Clarke) transformation, is given as following:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = T \begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} \quad (15)$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = T \begin{bmatrix} I_0 \\ I_\alpha \\ I_\beta \end{bmatrix} \quad (16)$$

where 0, α and β represent the Clarke components of the voltages and currents, and Clarke transformation matrix is chosen here in as:

$$T = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 2 & 0 \\ 1 & -1/\sqrt{2} & \sqrt{3}/\sqrt{2} \\ 1 & -1/\sqrt{2} & -\sqrt{3}/\sqrt{2} \end{bmatrix} \quad (17)$$

Substitute Eq. (15), (16) and Eq. (17) into Eq. (13) and (14), after some algebraic manipulations, Eq. (14) and (13) can then be solved as:

$$\begin{aligned} V_m &= \exp(\Gamma x)A + \exp(-\Gamma x)B \\ I_m &= \exp(\Gamma x)Z_C^{-1}A - \exp(-\Gamma x)Z_C^{-1}B \end{aligned} \quad (18)$$

Where V_m and I_m are both 3×1 vector whose entries are modal components of signals, and subscript in represents 0, α and β mode of the transmission line respectively. Γ and Z_C are modal propagation constant matrix and modal surge impedance of the line respectively, whose forms are as follows:

$$\begin{aligned} \Gamma &= \sqrt{T^{-1}ZY T} \\ Z_C &= \sqrt{T^{-1}ZY^{-1}T} \end{aligned} \quad (19)$$

Note that Γ and Z_C both are 3×3 diagonal matrices. Since we have assumed that the transmission line is transposed ones, the commutative properties of matrix multiplication have been employed in the above procedure of derivation. As same treatment with single-phase case, we could still take the voltages at fault point F which locate at $x = DL$ km away from receiving and $x = 0$ as boundary condition, the fault location index are therefore solved as

$$D_i = \frac{\ln\{[A(i) - C(i)]/[E(i) - B(i)]\}}{2\Gamma(i, i)L} \quad (20)$$

where $A(i)$, $B(i)$, $C(i)$ and $E(i)$ are the entries of 3×1 vectors A, B, C , and E respectively, and $i = 1, 2, 3$ are utilized to represent 0, α and β -modal components of signals. $\Gamma(i, i)$ represents diagonal entries of the 3×3 modal propagation constant matrix. Those signals quantities utilized in the above equation can be expressed as following:

$$\begin{aligned} A(i) &= \frac{1}{2}[V_{Rm}(i) + Z_C(i)I_{Rm}(i)] \\ B(i) &= \frac{1}{2}[V_{Rm}(i) - Z_C(i)I_{Rm}(i)] \quad i \equiv 0, \alpha, \beta \\ C(i) &= \frac{1}{2}\exp[-\Gamma(i, i)L][V_{Sm}(i) + Z_C(i)I_{Sm}(i)] \\ E(i) &= \frac{1}{2}\exp[-\Gamma(i, i)L][V_{Sm}(i) - Z_C(i)I_{Sm}(i)] \end{aligned} \quad (21)$$

Where $Z_C(i, i)$ represents the diagonal entries of 3×3 modal surge impedance matrixes, and L is the total length of the transmission line. It should be noted that the quantities utilized in Eq. (21) could also be pure-fault data. Therefore, the effects of line loading on the accuracy the index can be eliminated.

IV POWER SYSTEM SIMULATION MODEL

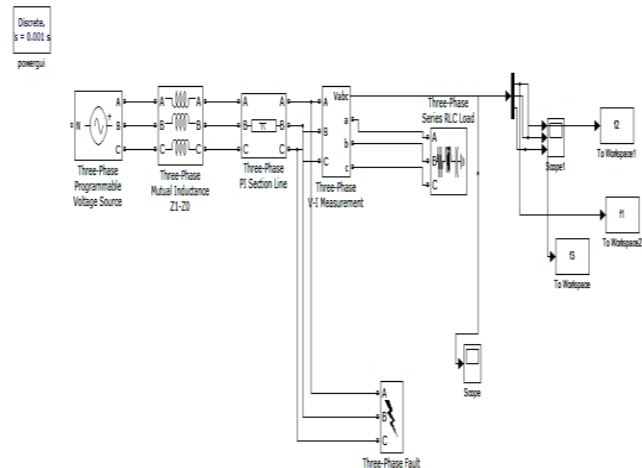


Fig.4. Typical transmission line model in MATLAB

V SIMULATION RESULTS & DISCUSSION OF FAULT CASE

Three phase fault:

Three phase voltage signals with three phase fault were shown in figure 5, 6 and 7 shown that at fault inception time there were great changes to all phases and the fault occurs in The 3 to 4 time interval then this time amplitude of phase voltage will be zero.

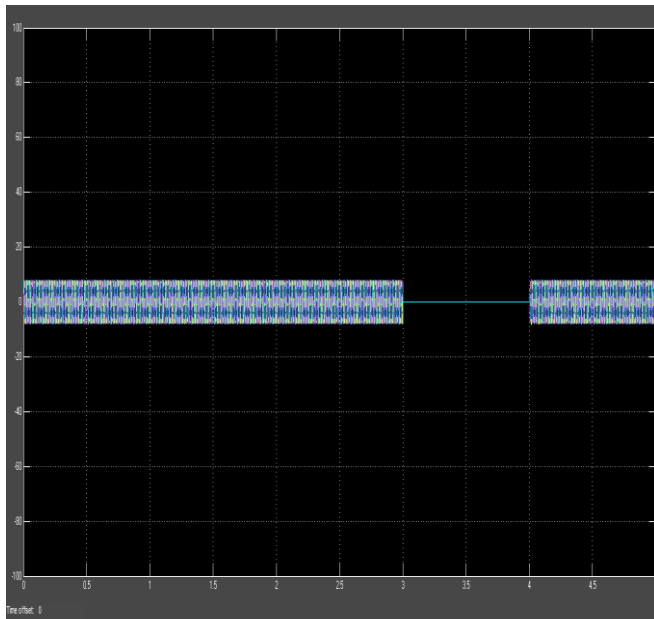


Fig.5.Three phase voltage signals at three phase fault

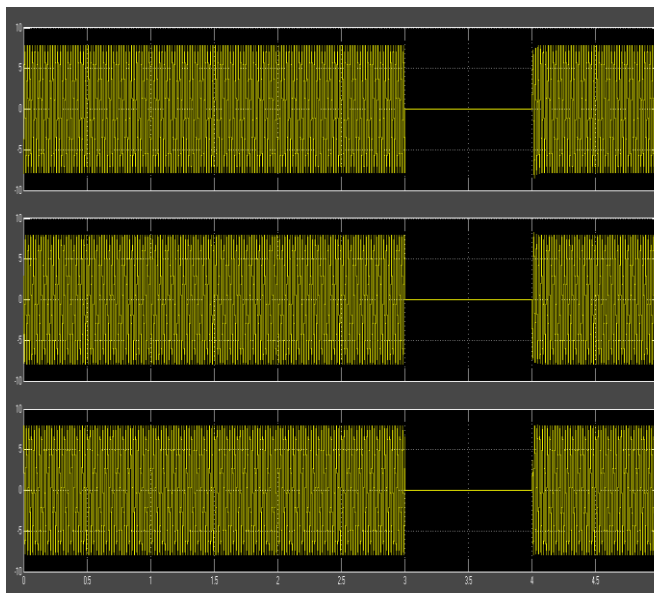


Fig .6.Separated three phase voltage signals at three phase fault

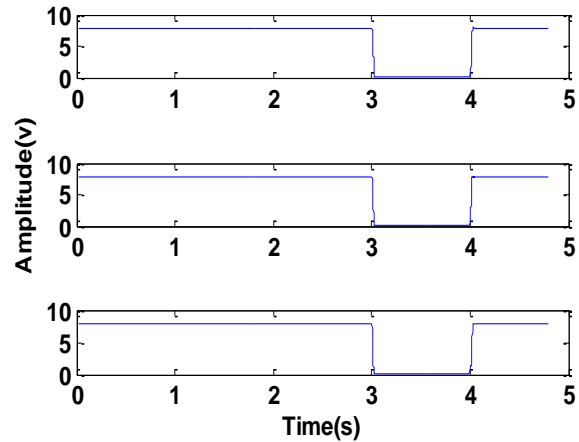


Fig.7.Output of the discrete fourier transform based algorithm for a LLL fault voltage waveform.

VI CONCLUSIONS

In this paper, we propose a fault detection technique. Specifically, a fault detection index in terms of Clarke components of synchronized phasor measurements is derived. Fault is detected by voltage waveforms transformed into the frequency domain using Fast Fourier Transform (FFT). The parameter estimation algorithm and DFT method have also been developed in this paper. With the advent of these algorithms the proposed technique can achieve an excellent performance for detecting the fault of transmission line.

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APPENDIX

The parameters of the power system model
 Line length = 300km;
 Source= 100kv;
 Frequency = 50 Hz;
 Transmission line $R_1=0.01273$, $R_0=0.3864$;
 Load=100kv.

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