Fault Location Estimation Algorithm for Digital Distance Protection Relay Based on Artificial Neural Network

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Abstract

This paper investigates study the influence of a fault resistance on the performance of a digital distance protection installed on a transmission lines, it is well known that augment of fault resistance can cause seriously overreach or underreach to distance relay depending on the different operational situations of power system, To compensate the magnitude and phase error of the apparent impedance, This algorithm uses the angle of an impedance deviation vector (α). The impedance correction algorithm for ground faults has been employed by the Fault Resistance Compensation Block (FRCB) to compensate fault resistance effect.

Artificial neural network technique using Matlab/Simulink software is trained to determine the suitable value of an impedance deviation angle for the FRCB, In order to minimize the estimated impedance error of a distance relay. The results of simulation showed that compensated scheme relay performance are acceptably improve and the impedance estimated by relay is close to the actual value via FRCB with ANN_S. So the performance of distance relay is much more reliable and accuracy.

Key Words: - Distance protection, Fault resistance, Artificial neural network.

الحساب التخميني لموقع العطل لمرحلة حماية المسافة الرقمية بالاعتماد على الشبكة العصبية الاصطناعية

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الخلاصة

يتضمن هذا البحث دراسة تأثير مقاومة العطل على أداء حماية المسافة الرقمية العاملة في خطوط النقل، إذ أن المركبة الطولية لمقاومة العطل يمكن إن تسبب قصر أو بعد في المدى الحمائي لهذه المرحلة وبشكل كبير وفق حـــالات التشغيل المختلفة لمنظومة القدرة، ولأجل تعويض قيمة وزاوية الخطأ للممانعة الظاهرية المقاسة بواسطة مرحلة المسافة بسبب تأثير مقاومة العطل تم إدخال زاوية الانحراف (α) لمتجه الممانعة الظاهرية في حسابات هـــذه المرحلـــة مـــن خلال تصميم كتلة تعويض تأثير مقاومة العطل في حال حدوث الأعطال الأرضية.

تم الاستفادة من تقنية الشبكة العصبية باستخدام برنامج **Matlab/Simulink**, من خلال تدريب هذه الشـــبكة لتحديد قيمة زاوية الانحراف (α) الملائمة وفق حالات تشغيل مختلفة عن طريق كتلة تعويض تأثير مقاومـــة العطـــل لتقليل خطأ الممانعة المخمنة لمرحلة المسافة، وقد أظهرت نتائج التمثيل من خلال مخطط التعويض تحسن أداء المرحلة بشكل مقبول جداً, وأن قيمة الممانعة المخمنة بواسطة المرحلة أصبحت قريبة جداً من القيمة الفعليـــة للمانعـــة العطـــل باستخدام (FRCB) مع تقنية (ANNs) بوجود مقاومة عطل مما انعكس على أداء مرحلة المسافة, وبالتالي باتت أكثـــر دقةً واعتمادية.

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Introduction

The digital distance relay system implementation in the microcomputer is widely used for protecting transmission systems principally because of high reliability and very little maintenance. The distance relaying scheme makes use of the transient voltage and current values passed through the current transformer (CT) and potential transformer (PT) for calculation of the impedance fault based upon fundamental frequency signals is widely used [1].

The apparent impedance estimated by a distance relay is influenced by the combined reactance effect of fault resistance as well as the power flow. The value of the fault resistance may be particularly high for ground faults, which represent the majority of the faults on overhead lines. Fault resistance causes a negative effect on the distance relays. The most serious cases are [2]:

(a)-Faults in the vicinity of a relay point in the forward direction (close-in faults).
(b)-Faults in the vicinity of a end of protected zones (remote end faults).

For close-in faults, methods based on the memory action memorizing the pre-fault voltage has been used for identifying the direction of faults, For the second case, the method changing adaptively the operating zone characteristics of the fault measuring unit was proposed [3]. More accurate results can be obtained using algorithms that use the fault data from all the terminals of the transmission line. However, remote terminal data are not widely available in practice [2,3].

This paper describes the digital distance relaying algorithm using only one-terminal data. To compensate the impedance deviation caused by the reactance effect in the fault location algorithm of a distance relay, the fault resistance compensation block (FRCB) has been designed with Artificial Neural Networks (ANN_S) in this work. The algorithm of block uses the angle of an impedance deviation vector and the apparent impedance measured. The proposed algorithm has been analyzed with single phase to ground faults. The simulation results on a (345kV),(100km) single-circuit transmission line with two equivalent network connected to the ends of the line which show that the algorithm has a highly accurate operation characteristics almost not influenced by the variations of fault resistance and fault location [3] as shown in fig. (1).

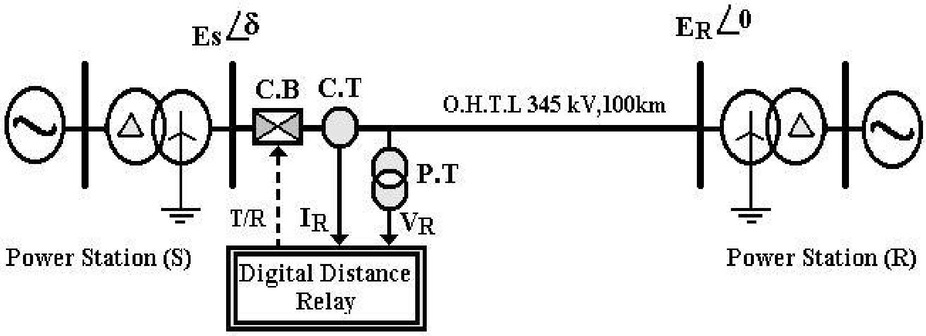


Fig. (1):- Simplified power system model with digital distance protection for single circuit-overhead transmission line, 345kV, 100 km

Artificial Neural Network Technique

Artificial Neural Network (ANN) is a comprehensive multi-paradigm prototyping and developed that can be used to solve complex problem [4]. In ANN, the unit analogue to the biological neuron is referred to as a processing element. Studies of ANN_S are growing rapidly for many reasons [5]:

- ANN_S work with pattern recognition at large.
- ANN_S have a high degree of robustness and ability to learn.
- ANN_S are prepared to work with incomplete and unforeseen input data.

This paper demonstrates that the theory of (ANN_S) can be used as an alternative computational concept to conventional approach, based on a programmed instruction sequence and designed to be incorporation with matrix based software tool Matlab version 6.5 [5]. The ANN consists basically of several layers: an input, an output, and one or more hidden layers. These layers are connected with each other by parameter cell weights, which are in structure of numerical value depending on actual problem [6]. The neuron in the input layer has a linear activation function; it is the nervous cell and is represented in the ANN universe as perceptron. The fig. (2), shows a simple model of a neuron characterized by a number of inputs [P_1, P_2, …, P_N], the weights [W_1, W_2, …, W_N] the bias adjust [b] and an output [a].

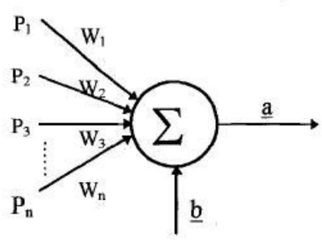


Fig. (2):- Perceptron representation

The neuron uses the input, as well as the information on its current activation state to determine the output [a], given as in the following equation [5]:

$$a = \sum_{k=1}^{n} W_k P_k + b \qquad \text{……. (1)}$$

As mentioned before, The ANN models must be trained to work properly, The desired response is a special input signal used to train neuron, A special algorithm adjusts weights so that the output response to the input pattern will be as close possible to the respective desired response.

The Back-Propagation Method

The Back Propagation (BP) algorithm is central to much current work on learning in neural networks. The Back propagation method works very well by adjusting the weights which are connected in successive layers of multi-layer perceptrons [5]. The algorithm gives a prescription for changing the weights in any feed-forward network to learn a training set input-output pairs. The BP algorithm is used in this paper. It is consists of two stages, that is forward and backward propagation. During forward propagation stage the input signals are propagated from input layer through hidden layer to output layer. The outputs of the nodes of each layer affect only the outputs of the next layer. In back propagation stage, the difference (errors) between real output values (target) and actual output values and sum of their square

are calculated and minimized by ***Least Mean Square Error*** (LMS) [4,5]. The use of the bias adjust in the ANNs is optional, but the results may be enhanced by it, A multi-layer network with one hidden layer is shown in fig. (3).

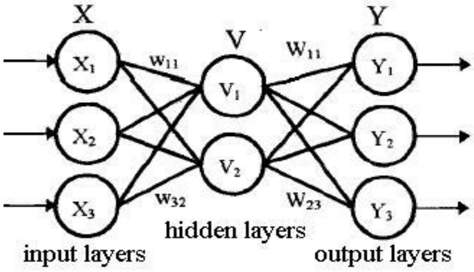


Fig. (3):- Three-layer Neural Network Architecture

This network consists of a set of N input units (X_i, i =1,…N), a set of output units (Y_i, i =1,…N), and a set of J hidden units (V_i, i =1,…J),Thus, the hidden unit Vj receives a net input and produces the output [5]:

$$Vj = F[\sum_{k=1}^{n} W_{jk} X_k] \quad \text{Where } j = 1, \dots J \qquad \dots\dots. (2)$$

The final output is then produced:

$$Yj = F[\sum_{k=1}^{n} W_{im} V_{im}] \quad \text{Where } i = 1, \dots n \qquad \dots\dots. (3)$$

F [.] is a non liner transfer function which can be of various forms. The (BP) networks often use the logistic sigmoid as the activation transfer function, The ***logistic sigmoid*** transfer function maps the neuron input from the interval (-∞**,** +∞) into the interval (0,+1), the logistic-sigmoid is applied to each element of the proposed ANN [5].

$$F[.] = \log sig(n,b) = \frac{1}{1+e^{-(n+b)}} \qquad \dots\dots. (4)$$

Where n: summation, b: bias adjusts.

The Generic Model of a Protective Digital Relay

The digital distance protection is a universal short-circuit protection, its mode of operation is based on the measurement and evaluation of the short-circuit impedance [5], when a fault occurs on transmission lines, the inception of the fault introduces abrupt changes of amplitude and phase in voltage and current, the fault signals can be contaminated with different transient components, such as exponentially decaying dc-offset components (mainly composed in current signals) and high-frequency damped oscillation (mainly composed in voltage signals) [1,5]. For reliable estimation of the fault distance, the model of a digital distance relay consists of the ***Data Acquisition Block*** (DAB) [7]. When the analogue signal of voltages and currents are taken from the transmission line to be measured, pass it through low pass filter as input real signal to filter aliasing and remove any high frequency content and then conditioned to make measurements, Then the waveforms supplied to the (DAB), which samples the analogue signal into the digital signal (for-warded as a data window of signal samples) [8]. The processing of input real signal are sampled and digitized using analogue to digital converters (ADCs). The digital values are then fed to high pass digital filter [1,7]. The fig. (4), shows the Overall blocks construction as simulation and modeling in ***Matlab/Simulink*** with ***Power System Block set***.

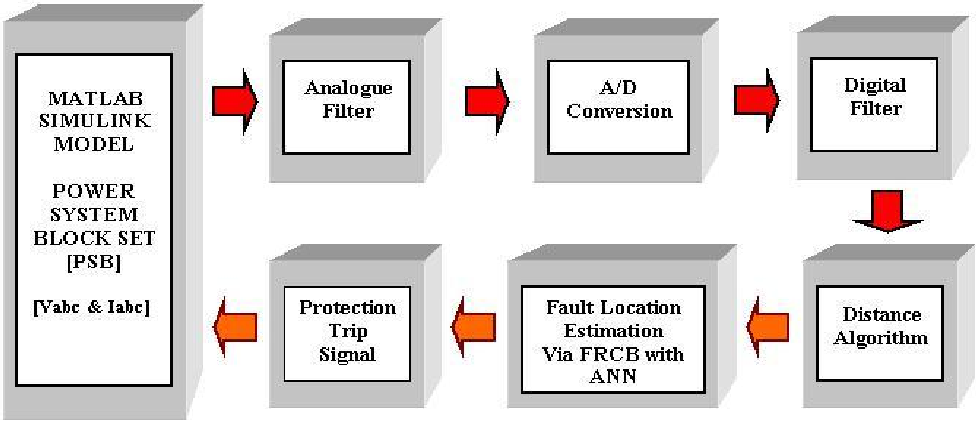


Fig. (4):- Overall Block Diagram of Simulation using *Matlab/Simulink*

The next items will describe the portion of the digital distance relay which implemented in the simulation that used in this work.

Analogue Filter (Low Pass Filter)

The sampling rate should be twice the maximum frequency in the analogue signal, In order to meet the sampling theory [9]. Sampling with a lower sampling rate results in errors due to the aliasing effects in the discrete time signals [1]. The anti-aliasing filter which in practice is an analogue filter is used to minimize such aliasing effect as well as attenuate the high frequency components. In this simulation, the anti-aliasing filter is a 2nd-order low-pass ***Butterworth*** filter (The magnitude response of a ***Butterworth*** filter is maximally flat and monotonic overall) [1,8], and the appropriate cut-off frequency of filter is 360 Hz.

Analogue to Digital Conversion (ADC)

From sampling theory, The analogue to digital conversion can be performed signal multiplication by the sequence of a ***delta impulses*** called unity amplitude impulse train, Although in practice, it is difficult to achieve enough narrow delta signals, Instead, ADCs (Analogue to Digital Converters) hold the last value until the next sample is received, This process is called ***zero-order hold*** [9]. The resulting digital signal forms an impulse train and ***zero-order hold*** as shown in fig (5). The sampling rate should be at least fourth times of fundamental frequency in the input variable which have to be accurately reproduced, Therefore; The sampling frequency (Fs =1/Ts) is 1200 kHz (20samples/cycle) [8].

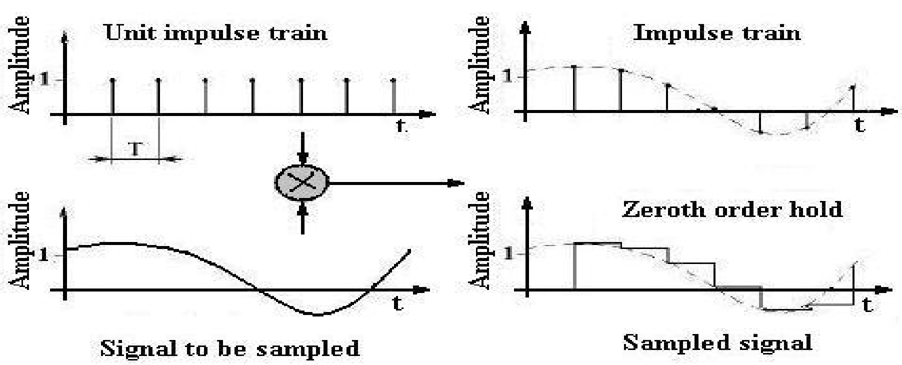


Fig. (5):- The comparison of sampling between Unit impulse train and Zero order hold

Digital Filter (Mimic Filter)

The digital filter uses generally to improve perform numerical calculations on sampled values of signal, This simulation uses specially new ***digital mimic filter*** which allows the removal of harmful oscillations that occur when DC offset is present at some filter input. If a current wave has to pass through a ***mimic filter*** circuit (analogue high-pass filter) consisting of a resistance (***R***) in series with an inductance (***L***) or impedance of the form, described as following equations [8]:

$$H(s)=\frac{v}{i}=(Ls+R)=R(1+s\frac{L}{R})=k(1+s\tau_1) \qquad \text{.......} (5)$$

Then an exponentially decaying component at the output will vanish, provided it's time constant is equal to (τ1) which is expressed in number of sample, The sum of a gain and a differentiator circuit is represented by (above equation), The differentiator circuit, represented in Laplace transform by s, can be emulated digitally by the following ***a Finite Impulse Response*** filter [1]:

$$s = 1-z^{-1} \qquad \text{.......} (6)$$

We eventually obtain (digital high-pass filter), ***FIR*** filter:

$$H(z) = K\left[(1+\tau_1)-\tau_1 z^{-1}\right] \qquad \text{.......} (7)$$

Here the gain K has to be set is such a way that, at rated frequency, the filter gain will be unity, At 60 Hz, the gain is given by the following expression [8]:

$$\left|K(1+\tau_1)-K\tau_1\cos(\omega Ts)+jK\tau_1\sin(\omega Ts)\right|=1 \qquad \text{.......} (8)$$

Where Ts is a sampling time.

Mathematical Verification of a Distance Relay at Earth Faults

When the A-phase-to-ground fault with fault resistance occurs (R_F), the phase voltage at the relaying point can be calculated as follows [10]:

$$V_R = mZ_{L1}[I_A + K_E I_E] + R_F I_F \qquad \text{.......} (9)$$

Assuming that ***residual current compensation method*** is applied. The current supplied to the earth fault relay associated with the faulty phase of line (A) may be written:

$$I_R = I_A + K_E I_E \qquad \text{.......} (10)$$

Where (I_A) is a phase fault current associated with a faulted phase voltage, (I_E) is an earth current, m is per unit distance to fault location, and (K_E) is a ***residual compensation factor***.

From (9) and (10), the equation for apparent impedance measured by the distance relay can be expressed as [2]:

$$Z_R = \frac{V_R}{I_R} = m Z_{L1} + \left| \frac{R_F I_F}{I_A + K_E I_E} \right| e^{j\alpha} \quad \text{.......} (11)$$

The apparent impedance (Z_R) is composed of the actual line impedance -positive sequence impedance - (Z_{L1}) to a fault point and fault resistance (R_F) with unknown variables. The impedance deviation vector is the difference between the apparent and the actual impedance to a fault. Therefore; a distance relay cannot operate accurately because of the impedance deviation angle (α).

Distance Relaying Algorithm using (DFT)

The main concept of the ***Discrete Fourier algorithm*** is that any signal can be regarded as a combination of periodic components, characterized by having finite discontinuous points, limited extremes and limited integration value within any period. When the distance relays receive discrete voltage and current signal, it has to convert them to phasor. ***The Discrete Fourier Transform (DFT)*** is used to estimate fundamental phasors for digital relaying [1,8]. The incoming data samples for one-cycle window DFT are correlated with reference fundamental sine and cosine waves to extract the complex value of the fundamental component. The general expressions for the sine and cosine components of the voltage at a sample point k are [9]:

$$V_S = \frac{2}{N}\left[\sum_{k=0}^{N-1} V_k \sin\frac{2\pi}{N}\right] \quad \text{.......} (12)$$

$$V_C = \frac{2}{N}\left[\sum_{k=0}^{N-1} V_k \cos\frac{2\pi}{N}\right] \quad \text{.......} (13)$$

Where V_k is the sample discrete data of the signal, and N is the number of samples per cycle. Similar expressions are evaluated for current components ***I_s*** and ***I_c***, the magnitude and phase of the fundamental component of apparent impedance for digital distance relay are calculated as a following equations [9]:

$$Z_R = \left| \frac{V_s^2 - V_c^2}{I_s^2 - I_c^2} \right|^{1/2} \quad \text{.......} (14)$$

$$\theta_R = \arctan\frac{I_s}{I_c} - \arctan\frac{V_s}{V_c} \quad \text{.......} (15)$$

The outputs of the Fourier technique responds slowly but accurately to badly distorted post-fault wave. In normal case, a full cycle-DFT (***FC-DFT***) sampling window is adopted in this paper.

Compensation of Fault Resistance Influence

The impedance relay is designed to estimate the positive sequence impedance (**Z_{1L}**) resulting from the voltages and the currents measured by the relay based upon the method of a zero sequence current compensation [10]. If fault including resistance occur in the over head transmission line, the reactance effect appeared as the impedance deviation can cause ***mal-operation*** of a distance relay. When the line is unloaded, then the fault resistance simple adds the resistance of the line impedance, but if the line is significantly loaded. The fault resistance vector gets rotated. The amount and direction of the rotation depend on the power flow direction. This causes the fault to appear close than it is actually located (***Over reaching***) or further than it is actually located (***Under reaching***). fig (6) shows the apparent impedance deviation caused by the reactance effect the deviation angle (α) varies with the locatio

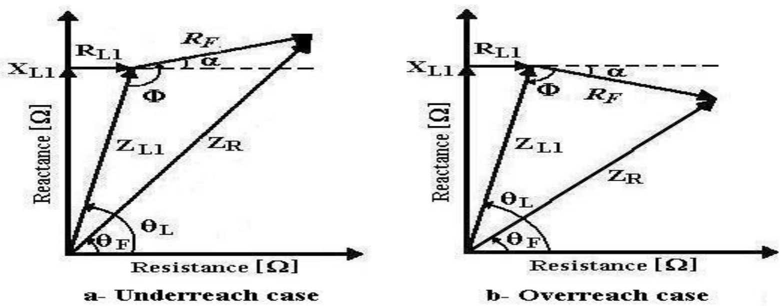


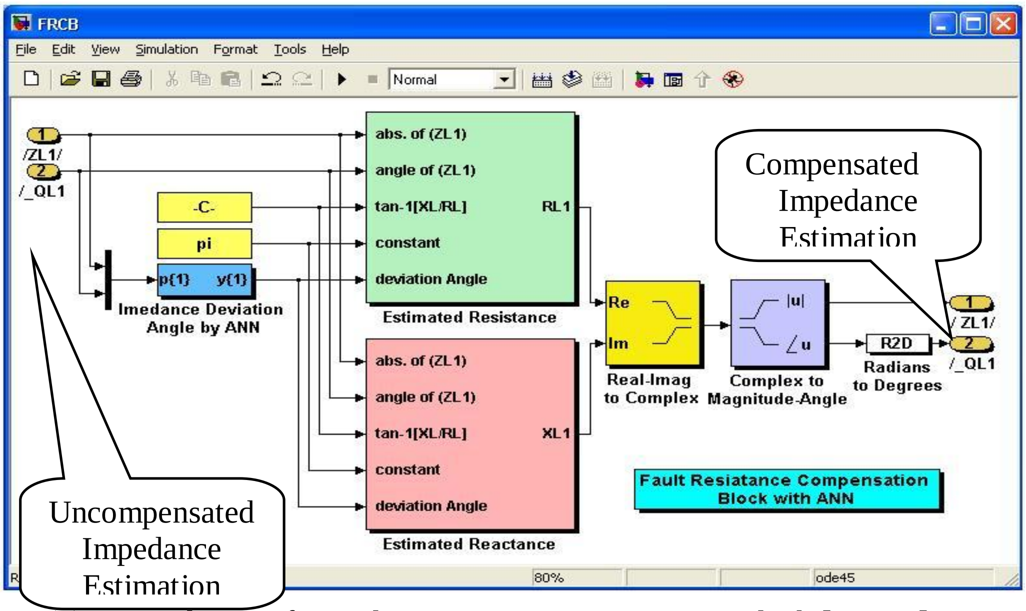
Fig (6):- Apparent impdance deviation with significant fault resistance

The contracture of a ***Fault Resistance Compensation Block*** (**FRCB**) had been designed and modeled using ***Matlab/Simulink***; it is implemented to compensate the magnitude and phase error of the apparent impedance due to fault resistance, This algorithm uses the angle of an impedance deviation vector (α) in calculation as the following equations [10]:

$$X_{L1} = |Z_R| * \frac{\sin(\theta_F \pm \alpha)}{\sin(\pi - \theta_L \pm \alpha)} * \sin(\theta_L) \qquad \text{.......} \ (16)$$

$$R_{L1} = |Z_R| * \frac{\sin(\theta_F \pm \alpha)}{\sin(\pi - \theta_L \pm \alpha)} * \cos(\theta_L) \qquad \text{.......} \ (17)$$

The aim of using the **ANN** with a **FRCB**, shown in fig (7), is to minimize impedance estimation error of the fault locator. So the accuracy of estimated fault location for digital distance relay will improve carefully. The proposed **ANN** had been trained by various fault location and different fault resistance (10-15-20) **Ω**. The **ANN** has two inputs that are the magnitude and phase of the apparent impedance. It has one output that is the suitable value of the angle of a deviation vector (α). The number of neurons in the hidden layer is specified as (30) neurons. The connective weights of back propagation **ANN** are trained (***off-line***) and according to large data with small error.



The I Fig (7): - Simulation of a Fault Resistance Compensation Block [**FRCB**] with **ANN** using ***Matlab/Simulink*** of the **PSB**

Three phase overhead transmission line, Analogue filter, A/D conversion, Digital filter, Fault resistance compensation block, Artificial neural network are simulated using ***Matlab/Simulink*** software program.

Fig. (8) shows the voltage waveform with and without the anti-aliasing low pass filter (***Analogue filter***) for single phase to ground fault. The output of the filter can be eliminated high frequency components form the fault waveform. Fig. (9) illustrates the current waveform distorted by the dc- component and the output of dc-offset removal high pass mimic filter (***Digital filter***).

Table (1) shows the results obtained without fault resistance compensation of the measured impedance, estimated fault location, and percentage error for reaches of the digital distance relay, when fault resistance (R_F =10 Ω) for various fault location. Table (2) shows the estimated impedance, fault location, and percentage error for reaches of the distance relay according to same condition in above when compensation of the fault resistance by (**FRCB**) and the effect of the angle of an impedance deviation vector is ignored ($\alpha = 0^o$). Table (3) shows the results the measured impedance, fault location, and percentage error, when the effect of the angle of an impedance deviation vector is compensated by (**ANN**) for different fault location. The percentage error in an impedance measurement of the distance relay reach is calculated as follows:

$$Error(\%) = \frac{EstimatedValue - ActualValue}{ActualValue} * 100 \quad .... (18)$$

Table (4,5,6) repeat to procedure in same situation as a mentioned in above for fault resistance (R_F =20 Ω) and with various fault location. Fig. (10, 11, 12) illustrate the relationship of convergence characteristics of impedance estimated without and with fault resistance compensation (without and with ANN), by digital distance relay using (***FC-DFT***) for different fault resistance (10 Ω- 15 Ω- 20 Ω) respectively. The ANNs will determine the suitable value of an impedance deviation angle (α) of fault resistance for the **FRCB**, So the measurement error of distance relay will minimize gradually and fault location will quite close to actual value.

Conclusions

In this paper, a three phase overhead transmission line is modeled and measured impedance by the digital distance relay in various fault location and fault resistance is presented. And a fault resistance compensation block by using ANNs is proposed to minimize error in impedance measurement of a distance relay due to angle of an impedance deviation vector (α). According to this simulation and analysis it is conclude that:

The influence of the fault resistance may cause the distance relay to underreaching (it may prevent a relay from tripping for internal faults of protective zone) and overreaching operation (it may trips for external faults of rotective zone). The impedance deviation and values of short circuit capacities of network have a major effect in this problem. The conventional distance relay cannot overcome influence of the fault resistance which is one of intrinsic problem of a distance protection, when fault location occur at (80%) of the length line with (R_F =10 Ω), the measured impedance by conventional relay is ($13.2\angle 34.5$ Ω) and estimated fault location is (145.7%) the error in impedance measurement (+ 82.24% Under reach). While the actual impedance (Target) is ($7.24\angle 79.8$ Ω), but the estimated impedance by distance relay via FRCB (α is ignored), and (α) compensated by ANN are ($7.59\angle 79.7$ Ω) and ($7.30\angle 79.7$ Ω) respectively, as consequence the measurement error will decrease gradually (4.75% $\rightarrow$0.56%).The digital distance relay with fault resistance compensation based on ANNs has improved the performance whereas more stable, reliable and precise if comparing with conventional distance relay, and estimated impedance and fault location is quite close to the actual relationship for operating characteristic.

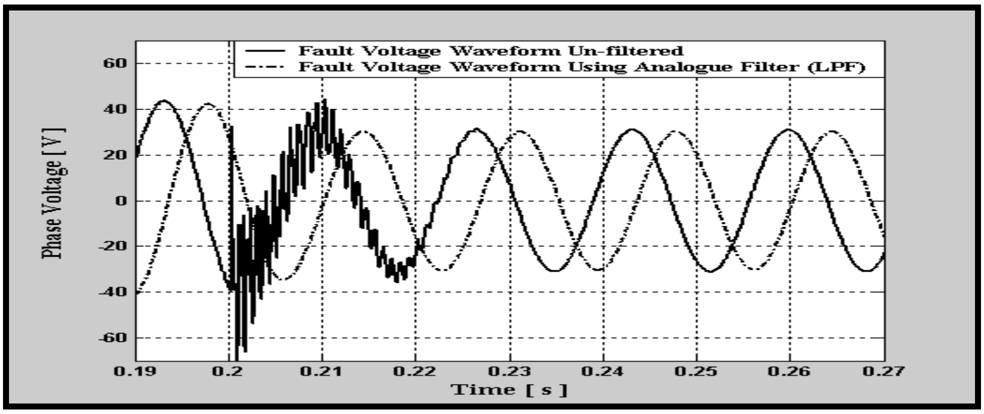


Fig. (8):- Voltage waveforms of fault using anti - aliasing filter at fault inception = -90 ^{o} and fault location = 50 %

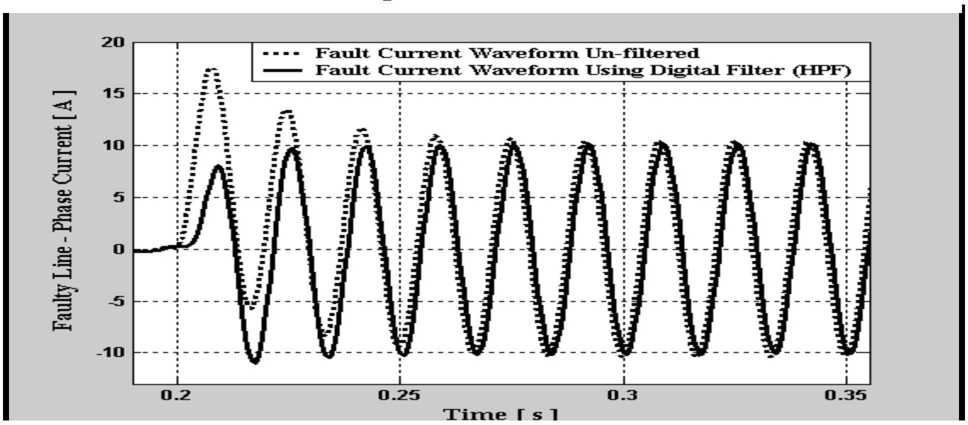


Fig. (9):- Current waveforms of fault using dc - offset removal filter at fault inception = 0 ^{o} and fault location = 50 %

Table (1):- Estimated impedance and fault location of a distance relay measured without compensation for fault resistance at R_F =10 Ω

Fault Location (F) [km]	Relay Impedance [Ω∠deg.]		Fault Distance [km]		
	Estimated	Actual	Estimated	Error (%)	Reach
F = 20	4.84∠32.9	1.81∠79.8	53.55	167.5	*Under*
F = 40	6.99∠39.3	3.62∠79.8	77.22	93.13	*Under*
F = 60	9.61∠40.4	5.34∠79.8	106.5	76.75	*Under*
F = 80	13.2∠34.5	7.24∠79.8	145.7	82.24	*Under*
F = 100	17.8∠22.6	8.61∠79.8	210.2	110.3	*Under*
Note: CT Ratio = 2000:1 ; PT Ratio = 40,0000:100 ; Z secondary = 0.5 Z primary					

Table (2):- Estimated impedance and fault location of a distance relay measured via compensation for fault resistance and without ANN_S at R_F =10 Ω

Fault Location (F) [km]	Relay Impedance [Ω∠deg.]		Fault Distance [km]		
	Estimated	Actual	Estimated	Error (%)	Reach
F = 20	2.67∠79.7	1.81∠79.8	29.56	47.8	*Under*
F = 40	4.52∠79.7	3.62∠79.8	49.97	24.9	*Under*
F = 60	6.27∠79.7	5.34∠79.8	69.97	15.4	*Under*
F = 80	7.59∠79.7	7.24∠79.8	83.80	4.75	*Under*
F = 100	7.30∠79.7	8.61∠79.8	81.25	18.8	*Over*
Note: CT Ratio = 2000:1 ; PT Ratio = 40,0000:100 ; Z secondary = 0.5 Z primary					

Table (3):- Estimated impedance and fault location of a distance relay measured via compensation for fault resistance and with ANN_S at R_F =10 Ω

Fault Location (F) [km]	Relay Impedance [Ω∠deg.]		Fault Distance [km]		
	Estimated	Actual	Estimated	Error (%)	Reach
F = 20	1.84∠79.7	1.81∠79.8	20.34	1.69	*Under*
F = 40	3.64∠79.7	3.62∠79.8	40.24	0.59	*Under*
F = 60	5.45∠79.7	5.34∠79.8	60.22	0.37	*Under*
F = 80	7.30∠79.7	7.24∠79.8	80.56	0.75	*Under*
F = 100	8.63∠79.7	8.61∠79.8	100.7	0.69	*Under*
Note: CT Ratio = 2000:1 ; PT Ratio = 40,0000:100 ; Z secondary = 0.5 Z primary					

Table (4):- Estimated impedance and fault location of a distance relay measured without compensation for fault resistance at R_F =20 Ω

Fault Location (F) [km]	Relay Impedance [Ω ∠ deg.]		Fault Distance [km]		
	Estimated	Actual	Estimated	Error (%)	Reach
F = 20	8.24 ∠ 23.5	1.81 ∠ 79.8	90.95	354.8	*Under*
F = 40	10.9 ∠ 27.3	3.62 ∠ 79.8	120.9	202.5	*Under*
F = 60	14.5 ∠ 26.9	5.34 ∠ 79.8	160.4	167.3	*Under*
F = 80	20.1 ∠ 21.5	7.24 ∠ 79.8	220.7	175.9	*Under*
F = 100	27.5 ∠ 79.7	8.61 ∠ 79.8	319.5	219.5	*Under*
Note: CT Ratio = 2000:1 ; PT Ratio = 40,0000:100 ; Z secondary = 0.5 Z primary					

Table (5): - Estimated impedance and fault location of a distance relay measured via compensation for fault resistance and without ANN at R_F =20 Ω

Fault Location (F) [km]	Relay Impedance [Ω ∠ deg.]		Fault Distance [km]		
	Estimated	Actual	Estimated	Error (%)	Reach
F = 20	1.84 ∠ 79.7	1.81 ∠ 79.8	36.2	84.6	*Under*
F = 40	3.65 ∠ 79.7	3.62 ∠ 79.8	56.4	41.1	*Under*
F = 60	5.52 ∠ 79.7	5.34 ∠ 79.8	73.7	22.9	*Under*
F = 80	7.22 ∠ 79.7	7.24 ∠ 79.8	80.3	0.37	*Under*
F = 100	5.06 ∠ 79.7	8.61 ∠ 79.8	44.2	41.3	*Over*
Note: CT Ratio = 2000:1 ; PT Ratio = 40,0000:100 ; Z secondary = 0.5 Z primary					

Table (6): - Estimated impedance and fault location of a distance relay measured via compensation for fault resistance and with ANN at R_F =20 Ω

Fault Location (F) [km]	Relay Impedance [Ω ∠ deg.]		Fault Distance [km]		
	Estimated	Actual	Estimated	Error (%)	Reach
F = 20	1.84 ∠ 79.7	1.81 ∠ 79.8	20.34	1.69	*Under*
F = 40	3.64 ∠ 79.7	3.62 ∠ 79.8	40.24	0.59	*Under*
F = 60	5.45 ∠ 79.7	5.34 ∠ 79.8	60.22	0.37	*Under*
F = 80	7.30 ∠ 79.7	7.24 ∠ 79.8	80.56	0.69	*Under*
F = 100	8.58 ∠ 79.7	8.61 ∠ 79.8	99.73	0.24	*Over*
Note: CT Ratio = 2000:1 ; PT Ratio = 40,0000:100 ; Z secondary = 0.5 Z primary					

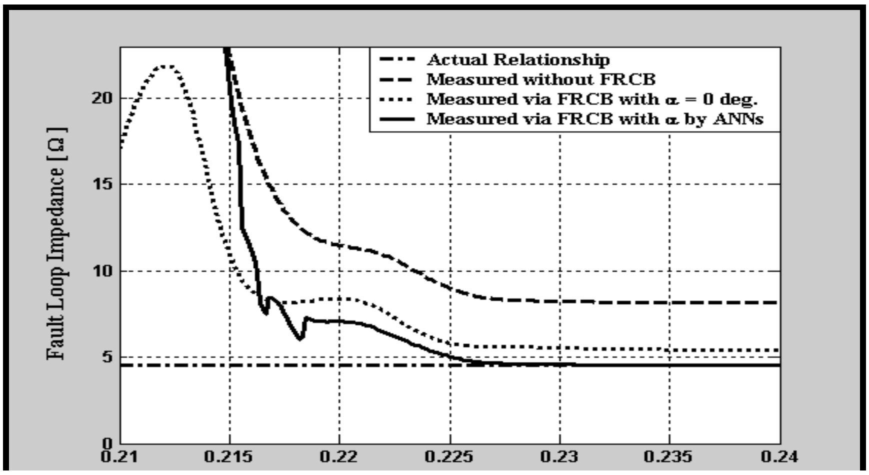


Fig. ... y

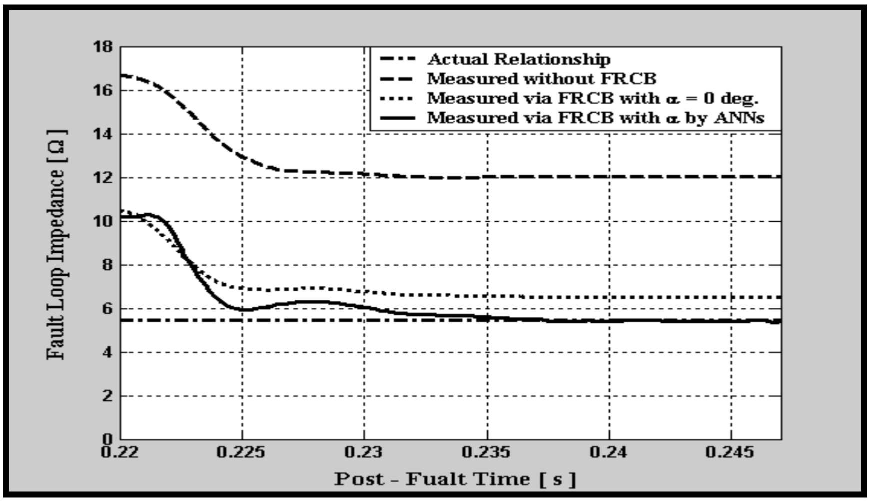


Fig. ... ay

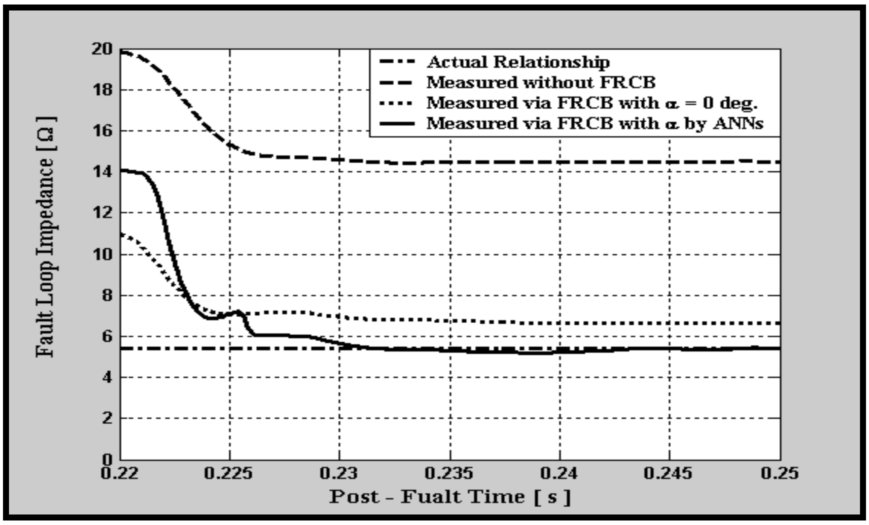


Fig. (12):- Convergence characteristics of impedance estimated by relay at fault location = 50% and R_F =20 Ω using (FC-DFT)

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Appendix (Model System Data)

Equivalent Voltage Sources: - $E_S = 345\angle 0$ kV, $E_R = 345\angle -10$ kV.
Equivalent Source Impedance: - $Z_{S1} = 0.238 + j\,5.72\ (\Omega)$, $Z_{S0} = 2.738 + j\,10.\ (\Omega)$.
$Z_{R1} = 0.238 + j\,6.19\ (\Omega)$, $Z_{R0} = 0.833 + j\,5.2\ (\Omega)$.
Length of Transmission Line & Rating Frequency:- l =100 km, fs =60 (Hz).
Line Sequence Impedance: - R_{L1}=0.0321 (Ω), R_{L0}=0.347(Ω).
L_{L1}=0.473 (mH), L_{L0}=1.370(mH).
C_{L1}=0.038 (µF), C_{L0}=0.038 (µF).
Filter: - 2 Order of ***Butterworth*** (LPF), High Cut-Off Frequency= 360 (Hz).

The work was carried out at the college of Engg. University of Mosul