1
Introduction

1.1 NEED FOR PROTECTION RELAYING

Modern Power system is a largely interconnected network containing Generators, Transmission lines, Transformers and Distribution Networks. A general overview of the power system network showing the interconnection of generation units with the distribution network through the transmission network is shown in Figure 1.1.

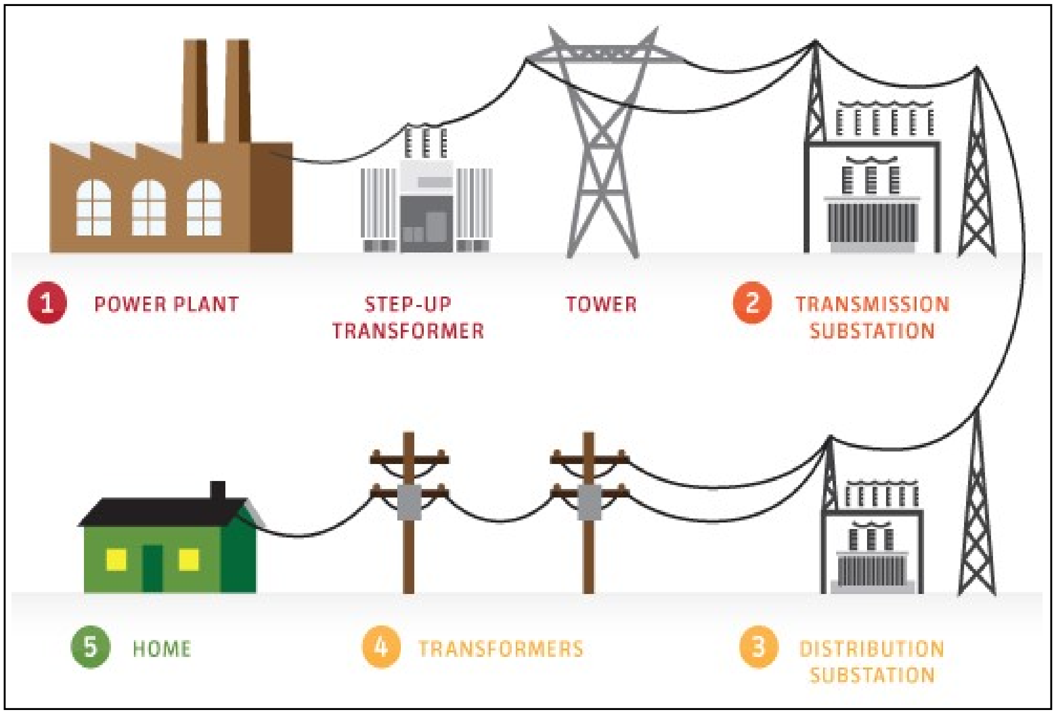

Figure 1.1: Power System Layout

Transmission lines play an important role in transferring power from remotely located generating station to the utility/ consumers. Safety and security of transmission line is essential for the reliability and quality of power supply. Since the transmission lines are exposed to atmosphere, they are subjected to faults or disturbances. These faults may be due to external reasons like lightning, storms, fog, birds etc., or internal causes like breakdown of insulation or overheating. In the event of occurrence of a fault, the voltages, currents and the frequency of the power system reach abnormal values affecting the reliability of the supply. These abnormal currents and voltages are likely to damage the components. Faults on transmission system also cause sudden changes in power flow in the network, affecting the stability of the system. A sustained severe fault may cause the system to loose its stability. Since the system is largely interconnected a fault at one location or component will lead to deviation in voltage, current and frequency (from their specified ranges) leading to poor quality of power supply at other locations. The transmission line faults can be classified as follows:

(a) Series Faults: These faults occur by breaking up of a conductor, resulting into discontinuity of the power supply. These faults are not much dangerous as they don't result in altering of current values and thus, no damage to power system components occurs.

(b) Shunt Faults: Short-circuit of one or more conductors with ground or with each other results in flowing of heavy current which is likely to damage the equipments if suitable protective relays and circuit breakers are not provided for protection of each section of the power system. These shunt faults can be further classified into:

(i) Symmetrical faults: Three-phase fault (LLL or LLLG Fault)

(ii) Unsymmetrical faults: It includes Single line to ground fault (LG fault), Line to line fault (LL fault) and Double line to ground fault (LLG fault) as shown in Figure 1.2.

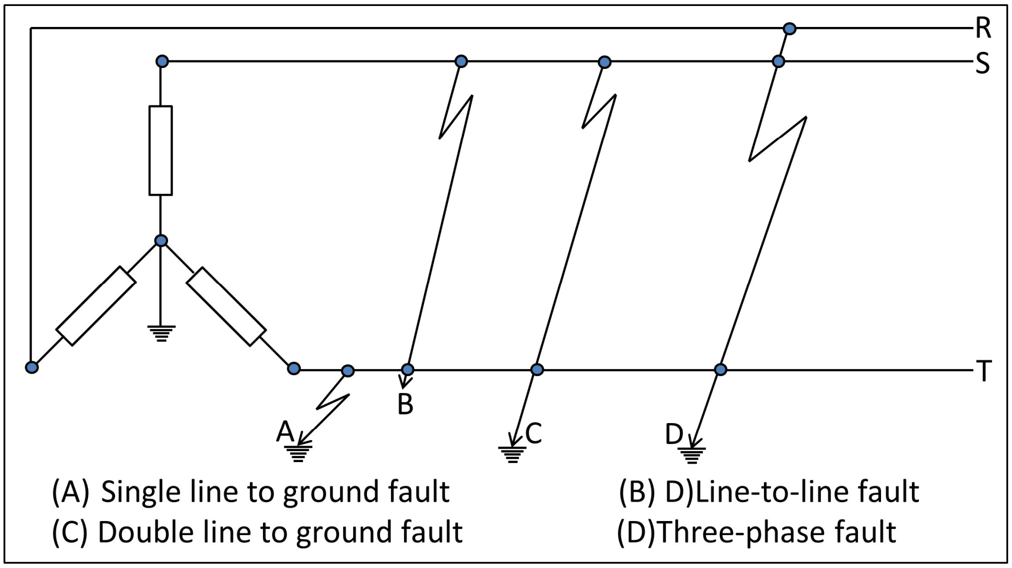

Figure 1.2: Transmission Line Shunt Faults

A protective scheme must be able to detect the abnormalities from the measured quantities (voltage, current and frequency) and issue a trip signal to circuit breakers to isolate the faulty component of the system from the rest of the network in shortest possible time such that the stability of the system, quality of the power supply and life of the equipment are not much affected. To achieve these targets the relays used in protective scheme should have the qualities like high speed to minimize the fault duration, reliability of operation, selectivity to minimize the disturbance caused due to isolation of faulty element and good sensitivity to minimize the burden on CTs and PTs.

Several schemes have been used in practice to achieve above targets in the event of faults. These are Distance Protection schemes, Schemes based on Traveling Waves, Differential Protection schemes for unit protection and Carrier based Protection schemes. These schemes were implemented using electromagnetic relays in the past and now gradually being replaced by Static relays and Digital relays.

1.2 RELAYS

Relays are the devices, which sense any abnormality in the power system. The sensing quantity could be voltage, current, phase or frequency. Various relays have been proposed for the protection of power system, based on their construction, working principle and applications. The evolution of relays has been illustrated in the following sections along with their merits and demerits.

1.2.1 Electromechanical Relays

Electromagnetic Relays work on the principle of either electromagnetic attraction or electromagnetic induction. Attracted armature type electromagnetic relays were first introduced in the protection schemes. They however suffered from contact pitting due to continuous vibrations produced. Electromagnetic Induction types of relays were later introduced. In the early 1920s Induction disc type inverse time-current over current relays were used to meet the requirement of selectivity. Induction cup type of relays was used in distance protection schemes and where ever a directional feature is required. These relays are more sensitive and faster than disc-type of relays. The electromagnetic relays were proved to be simple, reliable, robust cheap and selective both in over current protection schemes used for distribution systems and distance protection schemes used in transmission system. They were also effectively used in differential protection schemes.

These relays have moving parts and also contacts, because of which they have several drawbacks like high burden on CTs and PTs, high operating time due to inertia of mechanical parts, contact pitting and racing, requires frequent maintenance and are affected by vibrations and shocks caused by external sources. These drawbacks associated with the electromagnetic relays were overcome by using Static relays.

1.2.2 Static Relays

After the advent of semiconductor devices during the 1950s, static relays were developed incorporating semiconductor devices like transistors, ICs, diodes and other electronic components. They are also known as solid-state relays. There is a comparator circuit in the relay, which compares two or more currents or voltages and gives up output which is applied to either slave relay or thyristor circuit. Static relays possess the advantages of low burden on CT and PT, fast operation, absence of mechanical inertia and contact troubles, flexibility in the shape of characteristic, long life and less maintenance.

Static relays have proved to be superior to electromagnetic relays and they are being used for the protection of important lines, power stations and sub-stations. Yet they have not completely replaced the electromagnetic relays. In most of the static relays the output relay or the slave relay is a polarized electromagnetic dc relay. This can be replaced by a thyristor circuit due to low cost and ease of maintenance.

However these static relays are temperature sensitive. Their characteristics vary with the variations in temperature. Temperature compensation should be made using thermistors. They are also sensitive to voltage transients. Hence filters and shielding are to be provided for the protection from voltage transients. The growing size and the complexity of modern power system networks demand fast, accurate and reliable protective schemes and solution is found in digital relays.

1.2.3 Digital/ Numerical Relays

Numerical Relays are the latest development in the area of power system protection. These relays acquire sequential samples of the ac quantities in numeric (digital) data form through the data acquisition system, and process the data numerically using an algorithm to calculate the fault discriminants and make trip decisions. Numerical Relays have been developed because of tremendous advancement in VLSI and computer hardware technology. They are based on numerical (digital) devices, e.g. microprocessors, microcontrollers, Digital Signal Processors (DSPs), etc. At present microprocessor/ microcontroller-based numerical relays are widely used. These relays use different relaying algorithms to process the acquired information. Microprocessor based relays are called numerical relays specifically if they calculate the algorithm numerically.

The present downward trend in the cost of VLSI circuits has encouraged wide application of numerical relays for the protection of modern complex power networks. Economic, powerful and sophisticated numerical devices (e.g., microprocessors, microcontrollers, DSPs, etc.) are available because of tremendous advancement in computer hardware technology. Various efficient and fast relaying algorithms, which form a part of software, are used to process the acquired information. Numerical relaying has become a viable alternative to the traditional relaying systems employing electromechanical and static relays. The main features of numerical relays are their economy, compactness, flexibility, reliability, self-monitoring and self-checking capability, multiple functions, low burden on instrument transformers and improved performance over conventional relays of electromechanical and static relays. The schematic diagram of a typical numerical relay is shown in Figure 1.3.

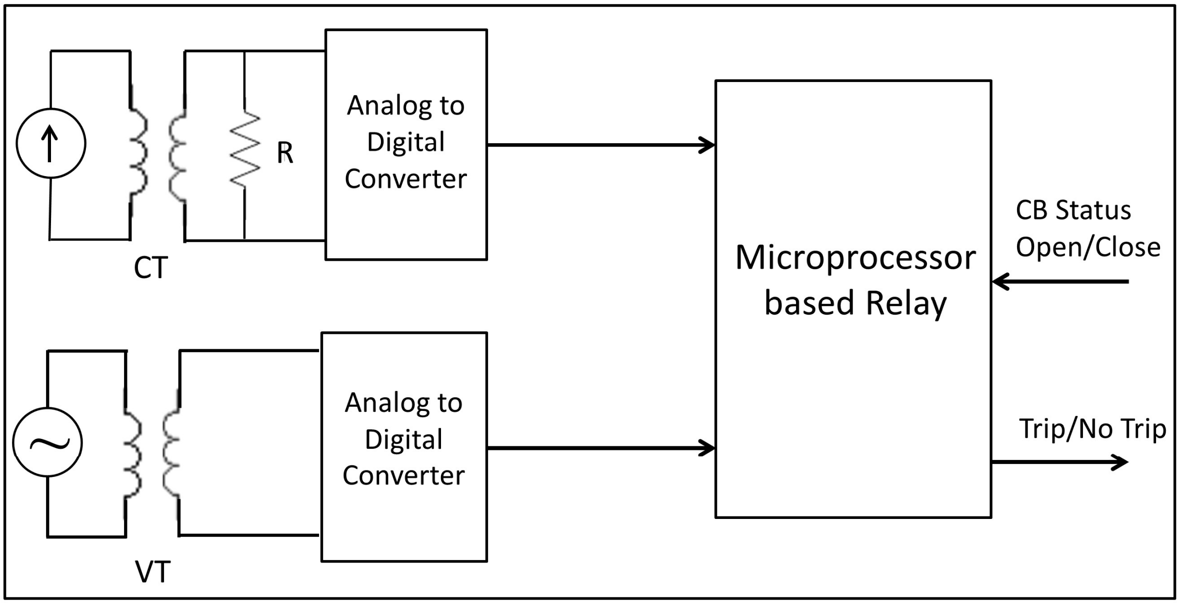

Figure 1.3: Block diagram for Numerical Relay

The levels of voltage and current signals of the power system are reduced by voltage and current transformers (VT and CT). The outputs of the CT and VT (transducers) are applied to the signal conditioner which brings real-world signals into digitizer. The signal conditioner electrically isolates the relay from the power system, reduces the level of the input voltage, converts current to equivalent voltage and removes high frequency components from the signals using analog filters. The output of signal conditioner are applied to the analog interface, which includes sample and hold (S/H) circuits, analog multiplexer and analog-to-digital (A/D) converters. These components sample the reduced level signals and convert their analog levels to equivalent numbers that are stored in memory for processing. The signal conditioner and the analog interface (i.e., S/H ckt, analog multiplexer and A/D converter) constitute the data acquisition system (DAS). The acquired signals in the form of discrete numbers are processed by a numerical relaying algorithm to calculate the fault discriminants and make trip decisions. If there is a fault within the defined protective zone, a trip signal is issued to the circuit breaker.

Various signal processing and machine learning techniques are used in designing intelligent numerical relays. Among different techniques, the Wavelet Transform, Alienation technique and Artificial Neural Network are selected as the tools for the detection, classification and location of faults. A brief overview of these techniques with their merits is provided in the following subsections.

1.3 WAVELET TRANSFORM

The Wavelet Transform is conceptually the modification of Fourier analysis (STFT) with variable window size. Since the fault transients are non-stationary in nature, therefore it is an efficient tool for their analysis in time-frequency domain. It helps in localizing the high frequency transient with respect to time. For analysis the window or vector size varies with frequency of signal, to be analyzed. At high frequencies the window size gets reduced while for lower frequencies, its width increases to collect more information.

1.3.1 Continuous Wavelet Transform

The continuous wavelet transform of a continuous function x(t) is defined as: (Grossmann and Morlet, 1984; Mallat, 1999),

$$W_{\psi}(s,\tau) = \int_{-\infty}^{\infty} x(t)\psi^{*}_{s,\tau}(t)dt \tag{1.1}$$

where, $\psi^*_{s,\tau}(t) = \frac{1}{\sqrt{s}}\psi^*(\frac{t-\tau}{s})$ (1.2)

The CWT $W_\psi(s,\tau)$ is the "correlation" coefficient between x(t) and the wavelet ψ (t) at the scale s and location τ. The wavelet necessarily satisfies an important zero-average condition (with exceptions for few wavelets)

$$\int_{-\infty}^{\infty}\psi(t)dt = 0 \quad (1.3)$$

Given, $W_\psi(s,\tau)$, f(x) can be obtained using the inverse continuous wavelet transform

$$x(t) = \frac{1}{C_\psi}\int_0^{\infty}\int_{-\infty}^{\infty} W_\psi(s,\tau)\frac{\psi_{s,\tau}(x)}{s^2}d\tau ds \quad (1.4)$$

where

$$C_\psi = \int_{-\infty}^{\infty}\frac{|\Psi(\mu)|^2}{|\mu|}d\mu \quad (1.5)$$

C_ψ is known as admissibility constant and $\Psi(\mu)$ is the Fourier transform of ψ (x).

1.3.2 Discrete Wavelet Transform

It is the CWT evaluated at a discrete set of scales and translations, $s=a_0^m$ and $\tau=nb_0 a_0^m$.

$$W(m,n) = \int_{-\infty}^{\infty} x(t)\psi^*_{m,n}(t)dt \quad (1.6)$$

where

$$\psi^*_{m,n}(t) = \frac{1}{\sqrt{a_0^m}}\psi(\frac{t-nb_0a_0^m}{a_0^m}) \qquad a_0\, b_0 \in R^+,\ m, n \in Z \quad (1.7)$$

where, a_0 and b_0 are integers and m, n controls the wavelet dilation and translation respectively. Generally, the values of a_0 and b_0 are 2 and 1 respectively, signifying dyadic grid arrangement. A scaling function is associated which at one level can be represented as a sum of scaling function of the next finer level. This is given as:

$$\varphi(t) = \sum_{n=-\infty}^{\infty} h(n)\sqrt{2}\varphi(2t-n) \quad (1.8)$$

The wavelet function is related to the scaling function as per the following equation:

$$\psi(t) = \sum_{n=-\infty}^{\infty} h_1(n)\sqrt{2}\varphi(2t-n) \quad (1.9)$$

where, h(k) and h_1(k) represent the set of coefficients called scaling and wavelet vectors respectively, and are related as

$$h_1(k) = (-1)^k h(1-k) \quad (1.10)$$

Thus, the signal function can be represented in terms of scaling and wavelet functions as:

$$y(t) = \sum_{k=-\infty}^{\infty} c_{jo}(k)2^{jo/2}\varphi(2^{jo}t-k) + \sum_{k=-\infty}^{\infty}\sum_{j=jo}^{\infty} d_j(k)2^{j/2}\psi(2^j t-k) \quad (1.11)$$

where, the first and the second term represents the approximate and detail part of the signal (x(t)), *jo* represents the coarsest scale spanned by the scaling function, c_j and d_j are the approximate and detail coefficients respectively, k is the translation parameter which determines the location of the wavelet in the time domain, and j is the dilation parameter which determines the location of frequency domain as well as the scale or extent of the time-frequency localization.

The scaling and wavelet coefficients in equation (1.12-1.13) represent the low-pass and high-pass filter coefficients. These are utilized to form set of wavelet basis functions $\varphi_{jk}(t)$ and

$\psi_{jk}(t)$ which are scaled and translated replicas of scaling and wavelet functions and are given as:

$$\varphi_{jk}(t) = 2^{-j/2}\varphi(2^{-j}t - k) \tag{1.12}$$

$$\psi_{jk}(t) = 2^{-j/2}\psi(2^{-j}t - k) \tag{1.13}$$

where, the parameters j and k are used to generate the basis functions as dilated and shifted versions of mother wave. These equations also represent low pass and high pass filters, using which the signal is decomposed into different frequency bands. Using equations 1.12-1.13, the wavelet transform decomposition for a signal x(t) for N-level decomposition can be written as:

$$x(t) = \sum_{k=0}^{2^{N-j-1}} a_{jk}\varphi_{jk}(t) + \sum_{j=1}^{J}\sum_{k=0}^{2^{N-j-1}} d_{jk}\psi_{jk}(t) \tag{1.14}$$

a_{jk} and d_{jk} are the approximate and detail coefficients which can be obtained as:

$$a_{j+1(k)} = \sum_{m=-\infty}^{\infty} a_{jm}h(m-2k) \tag{1.15}$$

$$d_{j+1(k)} = \sum_{m=-\infty}^{\infty} d_{jm}h_1(m-2k) \tag{1.16}$$

Thus, the decomposition can be schematically described as Figure 1.4.

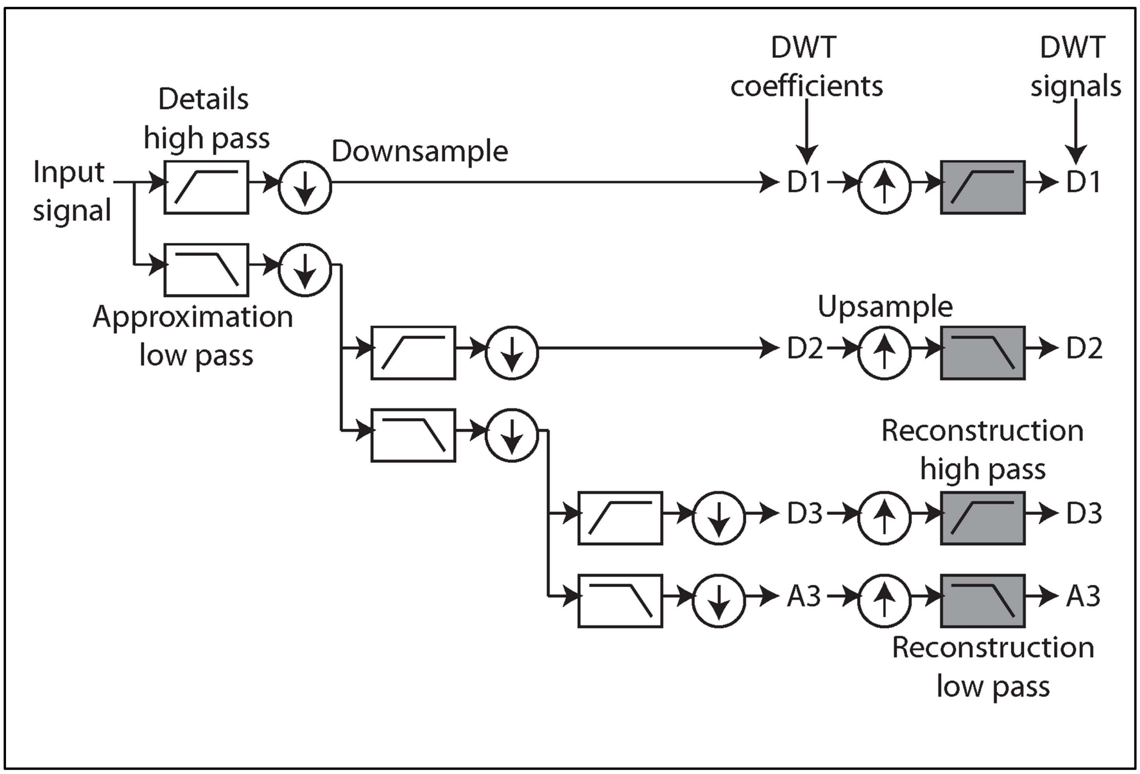

Figure 1.4 Block Diagram for Wavelet Decomposition

1.3.3 Applications of Wavelet Transform

Wavelet Transforms with their excellent feature extraction and multiresolution analysis capabilities find wide applications in the area of signal processing and data compression. Power system analysis can be broadly classified into steady state and transient analysis. An example of a steady-state analysis is a conventional power flow study (a snapshot analysis of a power system assuming 60 Hz (or 50 Hz) signals throughout) in phasor notation. In transient analysis, voltages and currents are generally not periodic functions of time. An infinitesimal resolution of frequencies is present in these transient signals. These transients of short duration and long duration can be analyzed with help of wavelets. The computational efficiency of this analysis depends on how well the mother wavelet represents both the excitation signals and the response signals (for example at Bus **N).** For the analysis of a power system transient using wavelets, it is wise to first match the excitation with a library of mother wavelets, choosing the one that creates a narrow wavelet spectrum. This results in high computational efficiency. These transient signals are analyzed both in frequency and time domain to detect and classify the nature of disturbance in the field of Power Quality. The same idea holds good in the area of Power System Protection. The voltage and current signals are sampled at suitable frequency and analyzed with an appropriate wavelet to detect faults on power system and classify and to locate them. With this motivation, an investigation has been made to protect the power system components using Wavelet multiresolution analysis, which is detailed in succeeding chapters.

Transmission lines relaying must be able to detect, locate estimate and classify disturbances on the supply lines to safeguard the power systems. Therefore, it must be supported by suitable measurement and fast acting methods. The main target of the relay is to calculate the impedance at the fundamental frequency between the relay and the fault point. According to the calculated impedance, the fault is identified as internal or external to the protection zone of the transmission line. The impedance is calculated from the measured voltage and current signals at the relay location. In addition to the fundamental frequency, the signals usually contain some system harmonics and the DC component, which has to be filtered out for the accuracy of the relay. To apply the wavelet transform for the transmission line relaying the selection of the appropriate wavelet function is very important. The wavelet with desirable frequency is first chosen as the mother wavelet and then the shifted and dilated versions are used to perform analysis. The relay identifies the type of fault that has occurred on the transmission line (i.e. L-G, L-L, L-L-G, L-L-L-G) and its location. In addition, it also identifies any other abnormal state than a faulty one, i.e. load jumps, transients, etc. The discrete wavelet analysis when applied to fault detection and classification is found to be most suitable. The algorithm based on Discrete Wavelet Transform has been developed which is independent of fault location, fault incipient angle and fault impedance, hence it is simple, robust and generalized. It can be used for the identification of high impedance faults as well as for transmission lines at any voltage level.

1.4 ALIENATION COEFFICIENTS

1.4.1 Samples based Alienation Coefficients

The Alienation coefficient (A) of the two variables x and y , is calculated as follows

$$A = 1 - r^2 \tag{1.17}$$

where, r is the correlation coefficient calculated by following equation

$$r = \frac{N_s(\sum x.y) - (\sum x).(\sum y)}{\sqrt{[N_s \sum x^2 - (\sum x)^2].[N_s \sum y^2) - (\sum y)^2]}} \tag{1.18}$$

where, N_s = number of samples in a cycle,

x = sample measured at t_0 ,

y = sample measured at (-T+ t_0), where T is the time period of the signal

1.4.2 Approximate Coefficients based Alienation Coefficients

In the proposed algorithm current signals are sampled over a quarter cycle. These samples are decomposed with wavelet to obtain approximate coefficients. The alienation coefficient (A_a) based on approximate coefficients is calculated as:

$$A_a = 1 - r_a{}^2 \tag{1.19}$$

where, r_a is the correlation coefficient, based on approximate coefficients, is calculated as

$$r_a = \frac{N_s(\sum x_a.y_a) - (\sum x_a).(\sum y_a)}{\sqrt{[N_s \sum x_a^2 - (\sum x_a)^2].[N_s \sum y_a^2) - (\sum y_a)^2]}} \quad (1.20)$$

where,

N_s = number of coefficients in a quarter cycle

x_a = approximate coeffiecients at t_0

y_a = approximate coefficients at $(-T+ t_0)$, where T is the time period of the signal.

1.5 ARTIFICIAL NEURAL NETWORK

A neural network is a parallel distributed processor that has a natural propensity for storing experiential knowledge and making it available for use. It resembles the brain in two respects:

a) Knowledge is acquired by the network through a learning process.
b) Inter-neuron connection strengths known as synaptic weights are used to store the knowledge.

These are the networks that simulate intelligence by attempting to reproduce the types of physical connections that occur in human brains. They are capable of representing highly nonlinear functions and performing multi-input, multi-output mapping.

Artificial neural networks transform a set of inputs into a set of outputs through a network of neurons, each of which generates one output as a function of its inputs. The inputs and outputs are usually normalized, and the output is a nonlinear function of the inputs that is controlled by weights on the inputs. A network learns these weights during training, which can be supervised or unsupervised. A wide variety of network connections and training techniques exist. Neural Networks can recognize, classify, convert and learn patterns. A pattern is a qualitative or quantitative description of an object or concept or event. A pattern class is a set of patterns sharing some common properties. Pattern recognition refers to the categorization of input data into identifiable classes by recognizing significant features or attributes of the data. In the neural network approach, a pattern is represented by a set of nodes along with their activation levels. A neuron is an information processing unit that is fundamental to the operation of a neural network. A simple model of artificial neural network is shown in Figure 1.5.

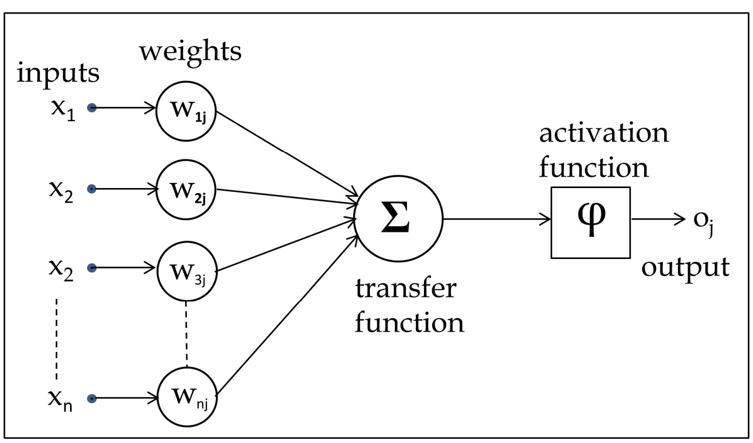

Figure 1.5: Model of Artificial Neural Network

Artificial Neural networks involve three important processes:

i). Every node is connected to other nodes via synaptic link or synapses, each of which is characterised by a weight or strength of its own. A node i connected to node j has a synaptic weight of w_{ji}, therefore, a signal x_i at node i will be multiplied to this weight to be connected to node j.

ii). A output signal at node j will be the sum of the incoming signals multiplied to their corresponding weights.

iii). The output of each node will be passed through an activation function to limit the amplitude of each output. This function can be logistic, sigmoid or a step function.

Suppose the input $x=[x_1, x_2, x_3 \ldots x_n]$ be a n-dimensional vector which is connected to the neurons through weighted synaptic links represented as $w=[w_1, w_2, w_3, \ldots w_n]$. The output of each neuron is the weighted sum of each input and is given as:

$$z = \sum_{i=1}^{n} w_i x_i + b \quad (1.21)$$

which can be written as:

$Z=W^TX$, where b is a bias term (1.22)

Thus, the synaptic operation assigns a relative significance to each incoming input signal, x_i, according to the past experience stored in w_i. This provides a linear mapping from n-dimensional neural input space, X, to the one-dimensional space, U. The output is passed through an activation function whose output is the final output of the neuron and can be written as:

$$y = \phi(Z) \quad (1.23)$$

The commonly used activation functions are linear, linear threshold, step, ramp, sigmoid and Gaussian. The sigmoid or logistic activation function is most popular binary signal function due to its computational simplicity, semilinearity, squashing property and its closeness to biological neurons.

1.5.1 Applications of ANNs in Transmission Line Protection

Power System problems regarding classification or the encoding of an unspecified non-linear function are well-suited for artificial neural networks. ANNs can be especially useful for problems that need quick results, such as those in real-time operation, because of the ability of quickly generating results receiving a set of inputs.

The ability to scale ANN applications to realistic dimensions for power system problems is a major issue. Component-related applications generally have a limited number of inputs, but realistic power systems have potentially tens of thousands of inputs at the system level. Training times are usually nonlinear with the problem size. A related concern is the size of the training set. Because of the complex, non-linear behavior of the power systems, ANNs can require large training sets to obtain sufficient accuracy. The tradeoff between training set size and solution accuracy is difficult to control analytically. It is quite possible to add cases to the training set that do not appreciably improve the accuracy of the ANN solutions.

Identification and Classification of faults on a transmission line are essential for relaying decision and re-closing requirements. The implementation of a pattern recognizer for power system diagnosis has provided great advances in the protection field. An artificial neural network can be used as a pattern classifier for the distance relay operation. The magnitude of three-phase voltage (V_a, V_b, V_c) and current (I_a, I_b, I_c) signals of the transmission line are measured using current and voltage transformers and surge filters. The waveforms are sampled and digitized using analog to digital converters. After the data acquisition, the signals are fed to a pattern recognizer. The ANN recognizer then verifies for the fault, and if it exists, then issues a trip signal. This ANN module can be either trained online or offline and the trip decision depend on how the module was trained. The advantage of ANN based relays is that it has the ability to learn aspects related to the fault condition and network configuration. Figure_ shows the block diagram of the ANN based distance relays. The ANN approach works as a pattern classifier being able to recognize the changing power system conditions and consequently improve the performance of the ordinary relays based on digital principle.

1.6 OBJECTIVE OF THESIS

The main objectives of the research work presented in this thesis, includes:

a) Detection of fault within quarter cycle time from the fault incidence.
b) Classification of all the types of faults accurately.
c) Location of fault using quarter cycle information from the fault incidence precisely.
d) Application of the proposed algorithm for different configurations of transmission systems.
e) Testing of algorithm for different case studies like variation of fault location, fault incidence angle, fault impedance, load switching, noise contamination, power flow reversal, sampling frequency, etc.

1.7 CONTRIBUTION OF THE THESIS

The contributions of the presented work in the thesis are stated as follows:

a) The quick detection of fault is important for the stability and reliability of the system. Therefore, a wavelet alienation based protection scheme has been developed to detect the fault within a quarter cycle time, i.e. 4-5ms.
b) The classification of the fault or identification of the faulty phase/s can also be done with the help of same algorithm, for various types of transmission line faults.
c) Based on the configuration and complexity of the transmission systems, the protection scheme has to be adaptive in nature in nature for different types of transmission systems. Therefore, the proposed algorithm has been tested for various transmission systems to prove the robustness of the algorithm.
d) The fault location has been achieved by ANN, making use of only quarter cycle information that can be available after the fault incidence.
e) The proposed algorithm is proved to be successful in all the possible case studies like variation of fault location, fault incidence angle, fault impedances, load switching and noise contamination.
f) The proposed protection scheme is also proved to be of less computational burden and reliable with the communication system.

1.8 THESIS OUTLINE

The thesis has been organized into six chapters, stated as follows:

Chapter 1: This chapter provides an overview of the power system protection, need of protective relays and their evolution, various mathematical tools used for the proposed algorithm like wavelet transform, alienation coefficients and artificial neural network, objective of thesis, contribution of thesis and organization of thesis.

Chapter 2: This chapter presents literature review of the research work reported in the field of transmission lines protection, with various signal processing techniques and machine learning techniques, for various types of transmission systems. Also, identified research gaps have been illustrated.

Chapter 3: In this chapter, the proposed algorithm has been applied on two-terminal transmission system, for detection, classification and location of faults. The algorithm has been tested for its robustness with various case studies like variation of fault locations, fault incidence angles, fault impedances and noise contamination.

Chapter 4: This chapter details the results for application of proposed algorithm on multi-terminal transmission system, to detect and classify the faults and also to identify the faulty section and locate the fault on line. Various case studies have also been done for testing of the algorithm. For the simulation study, three-terminal and five-terminal systems have been considered.

Chapter 5: In this chapter, fault analysis has been done for facts-compensated transmission system using the proposed algorithm. Systems with series (TCSC), shunt (STATCOM) and hybrid (UPFC) facts devices have been considered for study.
Chapter 6: Concluding remarks on the work are discussed in this chapter.

1.9 LIST OF PUBLICATIONS

International Journal Publications

1. Bhuvnesh Rathore and Abdul Gafoor Shaik. "Wavelet-alienation based transmission line protection scheme." IET-Generation, Transmission & Distribution, vol.11, no.4, pp. 995-1003, 2017.
2. Bhuvnesh Rathore and Abdul Gafoor Shaik. "Wavelet-alienation based protection scheme for multi-terminal transmission lines", Elsevier-Electric Power Systems Research. 161 (2018): 8-16.
3. Bhuvnesh Rathore and Abdul Gafoor Shaik. "Wavelet-alienation based protection scheme for STATCOM-compensated transmission lines." IET Circuits, Devices and Systems. (Under Review)
4. Bhuvnesh Rathore and Abdul Gafoor Shaik. "Fault Analysis for UPFC-Compensated Transmission Line using Wavelet Coefficients and Alienation Coefficients", Electric Power Components and Systems. (Under Review)
5. Bhuvnesh Rathore and Abdul Gafoor Shaik. "Wavelet-alienation based protection scheme for TCSC-compensated transmission lines", ISTE, Transactions of EE **(**Under Review).

International Conference Proceedings

1. Bhuvnesh Rathore and Abdul Gafoor Shaik. "Fault detection and classification on transmission line using wavelet based alienation algorithm." In Smart Grid Technologies-Asia (ISGT ASIA), 2015 IEEE Innovative, pp. 1-6. IEEE, 2015.
2. Bhuvnesh Rathore and Abdul Gafoor Shaik "Alienation based fault detection and classification in transmission lines." In 2015 Annual IEEE India Conference (INDICON), pp. 1-6. IEEE, 2015.
3. Saurabh Jangir, Ramnarayan Choudhary, Bhuvnesh Rathore and Abdul Gafoor Shaik, "Transmission Line Fault Detection and Classification Using Alienation Coefficient Technique for Current Signals", In 3rd International Conference for Convergence in Technology (I2CT), 2018.
4. Bhuvnesh Rathore and Abdul Gafoor Shaik, "Fault Analysis using Alienation Technique for Three-Terminal Transmission Line", In 2nd International Conference on Energy, Power and Environment (ICEPE),2018.