Arcing Fault Detection in Distribution Lines

Li-qun Shang

Abstract

Partial discharge of an insulator or surge arrester is a symptom of an insulation breakdown or insulation failure. It is very important to know the position of discharge source as soon as possible in order to remove this cause. In order to achieve remote monitoring of the faults due to an insulator and surge arrester on the distribution systems, the most important things need to do is to determine the type of fault. The correlation of voltage and current in an electrical arc is entirely different from that in solid conductors. In this paper, an overview of main fault location techniques and arc modeling principles were given. Preliminary laboratory tests on insulators and surge arresters and field tests on an overhead line were presented. Simulations of faults on a distribution system were carried out for the fault identification and location. These indicated that known signatures are associated with these types of failures which could be used for fault recognition. More importantly, specific configuration of the network at the point of measurement need to be known and taken into account in the analysis in order to provide accurate location of the fault.

Keywords: arc fault; fault location; distribution line; arc model; travelling wave

1. Introduction

The service continuity is one of the most important concerns to the utility company, but a fault is inevitable often resulting in power interruption. A fast fault location helps reduce the interruption time, but a conventional visual inspection not only takes a long time but also requires high manpower.

During the last decade, there has been many researches on the fault location problem that is to calculate the distance from a protective device to the fault. Most of them deal with transmission networks, which are, in general, operated in a balanced manner. Since the deregulation process has started, most of the research on power distribution systems focused on improving the performance of the electricity utilities.

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The extensive configuration distribution network with its tees and branches presents a particular challenge for a remote fault location. This is particular more difficult when the fault is due to insulator or surge arrest failures. Following such faults, it is not straightforward for the operators to pinpoint the defective devices without extensive and costly investigations. The exact location will help the electricity companies to restore continuity of supply very quickly. Therefore, it is very necessary to devise a more convenient monitoring system that allows detection and location of faulty insulators and surge arresters and avoids undesirable faults on the system.

2. Fault Identification and Location: an Overview

2.1 Characterization of Faults on Overhead Lines

There are many kinds of faults such as insulator or surge arrest failures, tree flashover, single phase grounding fault, two phase grounding fault, two phase fault, three phase fault, break of lines, etc, which can be happened on the overhead lines. Ground faults have been considered as one of the main problems in the power distribution system and account for more than 80% of all faults. There are different kinds of currents and voltages signatures and modes depending on different kinds of faults.

Ground faults can be caused by various sources. If the fault is a permanent fault, it is needed to suspect the site and recover the system. Therefore, the fault causes are essential to allow the appropriate recovering actions to be taken effectively.

In order to achieve remote monitoring of the faults due to insulator and surge arrester on the distribution systems, the most important things need to do is to determine the type of faults---an insulator (or surge arrester) discharge or a lines fault.

2.2 Measurement Techniques of Fault Transients

In order to monitor and discriminate the faults, the transient signal must be measured because the useful information is contained in transient signals.

An insulator or surge arrest failure is a symptom of an insulation breakdown or insulation failure. It is very important to know the position of discharge source as soon as possible in order to remove this cause.

To detect the discharge source, various kinds of sensors have been proposed. There are mainly two ways to determine the insulator (or surge arrester) discharge: by measuring the electric field or by measuring emitted pulse-train electromagnetic wave.

2.2.1 Measuring the Electric Field Method

Ref. [1, 2] presented a few cases of insulator having a particularly dangerous type of failure mode and found on the lines by the use of the electric field method. It is not an online detection, and needs an extra sensor. Ref. [3] adopted a method that uses the harmonic electric field to have an online detection of the faulty insulator on high voltage DC transmission lines. Ref. [4] presented an online detection by using suitable VHF sensors, and distinguishing different types of discharges. Ref. [5] used a sensitive insulator to detect the faulty porcelain suspension insulator. But as to the higher-level voltage, such 500kV, the insulator string is so long that a sensitive insulator cannot determine whether there is a faulty insulator or not. Hence this method is not very reliable.

2.2.2 Measuring Emitted Pulse-train Electromagnetic Wave Method

The basic principle of this method is that a partial discharge emits electromagnetic waves. Ref. [6] utilized a parabolic reflector to receive the ultrasonic sound generated by partial discharge. However, the direction of sensor must be correctly focused to the source that leads to the tremendous time for diagnosing point by point. Ref. [7] used multiple antennas to detect the emitted electromagnetic wave, and utilized time delay of arrival between antennas to locate partial discharge in 2 dimensions. Y. Suzuki et al[8] proposed the superimposed positioning optimization method to locate the partial discharge in 3 dimensions by moving the antennas at least two times. But it is not so convenient to move the set of antennas frequently for location. There may be other electromagnetic waves interfering noises. This will lead to determine the location wrongly.

Tungkanawanich et al [9] utilized the VHF with a band antenna array as electromagnetic sensors and calculated the time delay between them in order to locate partial discharge in 3 dimensions. The time delay estimation is statistically calculated for enhancing the reliability of the method. The smooth coherence transform is additionally conducted to improve the correlation method. New-Raphson method is applied for location of partial discharge source as point without moving the set of antennas.

The waveforms emitted from a partial discharge source are different from each other [10]. It is not easy to classify them at time-domain. In order to improve the precision of detection and classification of the partial discharge, the discrete wavelet transform to analyze the wide-band electromagnetic waves from partial discharge was proposed [11]. However, this affects the frequency spectrum of an electromagnetic wave marginally. Ref. [12] proposed applying neural networks to classify discharge sources. Ref. [13] proposed a classification method based on a fuzzy classifier for the analysis of the acquired partial discharge pulse shape signals.

2.3 Simulation Techniques for Transients

ATP EMTP is a powerful tool developed to simulate electric-magnetic transient phenomena of complex electric power systems. The latest development of the EEUG version consists of ATP-Draw, which is a powerful GUI, and EMTP, which is an analysis program developed based on the transient analysis theory. ATP is a full-featured transient analysis program, initially developed for electrical power systems. It is also capable of simulating controls, power electronics, and combined hybrid situations. The main features of ATP EMTP are:

1). System design, data entry, execution and analysis can be all done graphically.
2). Rich libraries support wide-ranging simulations.
3). Allows the user to produce his/her own models.

ATP / EMTP is probably the most widely-used power system transients simulation program in the world today. In this project, we use ATP-EMTP to simulate various scenarios of faults on the distribution network. When the fault is due to insulator or surge arrester arcing-type failures, there will be an arc at the fault point during the fault. In order to simulate the fault accurately, a model for each scenario needs to be developed.

2.4 Techniques for Transient Analysis

More than 80% of all faults on distribution systems are ground faults. Generally, useful information is contained in fault signals during the transient period. Therefore, the transient fault signal needs to be considered when identifying the fault causes and locations. The more efficient discrimination method based on fault transients requires a suitable signal-processing technique.

Experience has shown that the modes and signatures of insulator and surge arrester failures are very different from that of line ground faults. There exists a substantial literature on fault detection and location on lines, but no reports on identification of insulator and surge arrester failures were found. The accurate extraction and characterization of transient components provide the foundation for the travelling wave based protection and fault location systems. However, there are some difficulties in analyzing the transient signals, such as: a) the time domain signals often contain large amounts of high frequency noise. b) the starting point of each transient very rarely corresponds with the recorded GPS arrival time.

The identification of signal wave fronts has been one of the big difficulties in providing accurate results using the transient analysis technique. Some authors proposed the use of wavelet techniques to overcome this difficulty. The more efficient discrimination methods based on fault transients also use suitable signal processing techniques. The wavelet transform technique is one of the most efficient tools for analyzing non-stationary signals such as transients, and has been widely applied to solve problems in power systems. It can analyze transient signals in both time and frequency domains based on the mother wavelet.

Wavelet transforms map a given function from the time domain into time-scaling domain. The basic function used in the wavelet transform has band pass features and uses a mapping to the time-frequency plane. The wavelets are not only localized in frequency but also in time. This localization allows the detection of the instant when abrupt disturbances, such as fault transients, occur. The travelling waves generated by faults appear as fast transients superimposed on the power frequency signals recorded by the relays. Processing these signals using the wavelet transform can reveal their travel times between the fault and the relay locations. Magnago et al [14] proposed a fault location method based on the wavelet transform of the fault transients. For a three phase power line, the phase domain signals are first decomposed into their modal components using the modal transformation matrices. Then the aerial mode was selected for locating the fault as it is present in all fault types. Depending on the communication scheme used on the lines, the fault location problem can be solved in two different ways using the wavelet theory: (a) two ended synchronized recording and (b) single ended recording method

Insulator and surge arrester failures are similar to ground faults with higher impedance. Investigations have shown that the characteristics of zero-sequence currents and voltages are uniquely dependent on the cause of fault, and they can be used to identify the cause of the fault. Following a ground fault, there are more significant transient features appearing on the zero-sequence current than the zero-sequence voltage, and this is dependent on the fault cause. Using the wavelet theory approach, the time-frequency analysis of zero-sequence current was performed for various fault causes.

Because the distribution networks/feeders are radial or loop networks having several tees and branches, the faults at different locations may generate similar voltage and current signals at the monitoring point/substation. Based on simulation experience[15], artificial neural networks can be useful in identifying some causes of faults based on pattern recognition of dynamic spectra.

2.5 Essential Properties of Arc

2.5.1 Arc Voltage Model

The correlation of voltage and current in an electrical arc is entirely different from that in solid conductors. The voltage between the electrodes of a burning arc decreases with rising current to a limiting value, and again increases if the current diminishes. If voltage and current are measured at an arc, distorted curve shapes are found depending on the type of arc gas, the material of the electrodes, and the frequency of current. The initial breakdown of the gap between the electrodes requires a high ignition voltage at zero current. The subsequently increasing current rapidly augments the conductance of the air so that the arc voltage gradually decreases. This deviating behavior, compared with metals, is due to different types of current transport in an arc. It results in a nonlinear arc voltage-current characteristic.

From a modeling point of view, the arc voltage could be represented by

1). a nonlinear differential equation [16];
2). current- dependent models [17] or
3). piecewise arc voltage-current characteristic [18]

The arc is highly complex nonlinear, influenced by a number of factors. Due to its nonlinear nature, the modeling of an arc is a complex task. Some models are not practical enough for solving problems originating from the engineering praxis. A typical example is the modeling of a fault on an overhead transmission lines.

In paper [16], the general form of differential equation is:

$$\frac{dg}{dt} = f(g,u,i,t) \quad (1)$$

Where g, u and i are the arc conductance, voltage and current, respectively. The main problem here is model parameters selection: the unknown parameters must be estimated from test data.

In the paper [17], the authors developed a new arc-voltage model, which is described as a “current dependent voltage source with the characteristic shape of its waveform”. The model order and its complexity depend on the shape selected. The arc model represented by the following equation:

$$u_a(t) = (U_a + U_b \frac{I_0}{i_b(t)} + R_\delta \left|i_b(t)\right|)\,\mathrm{sgn}(i_a) + \xi(t) \quad (2)$$

Where $u_a(t)$ and $i_a(t)$ are the arc voltage and current. Sgn is a sign function defined as: sgn(x)=1 if $x \geq 0$ and sgn(x)=-1 if $x < 0$, and $\xi(t)$ is zero-mean Gaussian noise. The value of U_a can be obtained as the product of the arc-voltage gradient and the length of the path, i.e. the flashover length of a suspension insulator string, or the flashover length between the conductors. U_a , U_b , I_0 ($I_0 \neq 0$) and R_δ are parameters, defining the shape of the arc voltage. The expressions for i_a are as following:

$$i_a(t) = I_0,\ \text{if}\ |i_a(t)| < I_0$$
$$\text{and}\ i_a(t) = I_0,\text{if}\ |i_a(t)| \geq I_0$$

In the ref. [19, 20], the arc voltage wave shape was defined numerically on the basis of a great number of arc voltage experiment records. The arc voltage model with arc voltage amplitude V_a=1p.u. was showed in Fig.1.

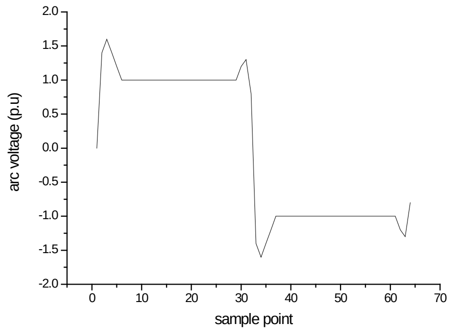

Figure 1: arc voltage wave shape

It is assumed that the sign of these values is determined by the sign of arc current. The values of $V_a$are obtained from the product of the arc voltage gradient (*E*) and the length of the path (*l*). The arc voltage gradient presented in different papers is different. In ref. [21], over the range of currents from 100A to 20kA the average arc voltage gradient lies between 12 and 15V/cm. Ref. [22] describes the arc voltage characteristics of high current arcs simulating fault arcs on 500kV class transmission lines and simulation result of the 50kA rms class fault arcs. The voltage gradient of the arc is about 9.5V/cm for arc current between 7kA and 80kA[22]. The voltage gradient of an arc in air is written as following [23, 24]

$$E=a+bI^{-n} \quad (3)$$

Where, *E*: voltage gradient (kV/m);*a*, *b*: constant; *I*: current (kA); *n*: power

The voltage gradient of an arc *E* (kV/m) in a long air gap is given by:

$$E=0.95+0.005/I \quad (4)$$

The voltage gradient of the arc jet is between 1.3 kV/m and 1.4kV/m and is 1.4 times large than that of the arc. The energy of the unit length of the arc jet is larger than that of the arc column. Various factors are thought to affect the voltage gradient of the arc jet, such as pressure, blowing speed and diameter of arc jet.

The arc model given in Tab. 1 has an important feature in the spectral domain. It can be represented by a Fourier series containing odd sine components only, as follows:

$$v_a(t) = \sum_{h=1}^{\infty} k_h V_a \sin(h\omega t) \quad (5)$$

Where *h*=1, 3, 5, … is the harmonic order, ω is the fundamental radian frequency and k_h is the coefficient of the *h*th harmonic. Using the fast Fourier transform, the coefficient K_h can be obtained. These coefficients are given in Tab. 1.

Table 1: Coefficients of the hth harmonics of the arc voltage

h	1	3	5	7	9
k_h	1.3	0.497	0.35	0.275	0.21

In comparison with other models, the advantage of the arc voltage representation through the sequence of numerical values is its flexibility. Various wave shapes can be created and the corresponding coefficients K_h can be calculated, depending on the modeling application.

The nonlinear arc is a nonlinear element and hence a source of harmonics, so these will cause the distortions in other network currents and voltages. Therefore, it is expected that the voltages and currents at the terminal of the fault line also contain harmonics. The arc-voltage total harmonics distortion (THD) factor could be calculated as follows:

$$THD = \frac{100}{X_1}\sqrt{\sum_{h=2}^{M} X_h^2}\,\% \quad (6)$$

Where X_h (h=1, 2, ….., M) is the amplitude of the *h*th harmonic.

As expected, in response to the arc-voltage odd harmonics, the line terminal voltage spectrum consists also of odd components. This important feature can be used for distinguishing arcing from metallic faults.

2.5.2Arc Voltage-current Characteristics

The voltage-current characteristics of the arc with high current show a hysteresis loop. When the current increases, the arc voltage becomes constant; whereas with decreasing current the arc voltage is approximately proportional to the current, showing characteristics of constant arc resistance. The arcs are in the first and third quadrants in the figure, indicating that these arcs mainly comprise a resistance component. Some studies show that the dynamic arc characteristics can be simulated by the following arc equation [10-12]

$$\frac{dg}{dt} = \frac{1}{\tau}(G - g) \tag{7}$$

Where, g is time varying arc conductance; G is stationary; τ is time constant.

The stationary arc conductance can be physically interpreted as the arc conductance value when the arc current is maintained for a sufficiently long time under constant external conditions. The stationary arc conductance G is given by

$$G(i) = \frac{i_{arc}}{U_{st} l} \tag{8}$$

Where i_{arc} is arc current; U_{st} is stationery arc voltage; l is arc length.

A series of laboratory tests are provided in ref. [25]. Voltage $u(t)$, current $i(t)$ and arc voltage $u_a(t)$ are recorded and digitized. The time-varying arc conductance is calculated as follows:

$$g_a(t) = \frac{i_a(t)}{u_a(t)} \tag{9}$$

Where $i_a(t)$ is arc current. By an inverse of this variable, the time-varying arc resistance can be obtained.

The instantaneous electrical power of the arc can be obtained as follows:

$$P_a(t) = i_a(t) u_a(t) \tag{10}$$

2.6 Arc Fault Detection

The ref. [26] proposed a digital signal-processing algorithm for arcing fault detection. This algorithm can be applied only for three-phase symmetrical and double-phase faults. The ref. [17] provided an extension to the research presented in ref [26]. A new approach to model arc voltage and a new solution for asymmetries and symmetrical arcing fault detections is presented.

In the case of arcing faults, voltage and current at the line terminals contain harmonics as well. The distortion of these waves depends on the fault distance and the arc voltage amplitude. Through spectral analysis it can be concluded that the line terminal voltage and currents contain harmonics induced by the arc voltage, particularly the odd components. The line equivalent circuit is shown in Fig. 2.

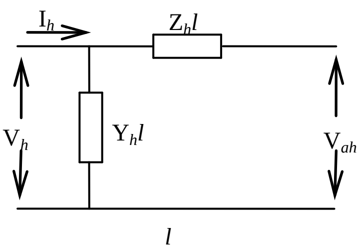

Figure 2: line equivalent circuit

Where, V_n and I_n are hth harmonic components of voltage and current at one terminal of the line, respectively. Z_h and Y_h are the frequency-dependent unit length line impedance and admittance, respectively:

$$Z_h(\Omega / km) = R(h\omega) + jh\omega L(h\omega)$$

$$Y_h(S / km) = jh\omega C(h\omega)$$

l (km) is the fault distance from the observed line terminal.

The amplitude of the hth harmonic of the arc voltage can be expressed through the relation:

$$V_{ah} = k_h V_a \tag{11}$$

Where V_{ah} is the amplitude of the hth harmonic of the arc voltage. The arc voltage amplitude can be calculated from the terminal voltage and current signals.

By using the FFT, the corresponding harmonic components V_n and I_n can be calculated. Then the hth arc voltage harmonic can be expressed as follows:

$$V_{ah} = V_h(1 + Y_h Z_h l^2) - Z_h l I_h \tag{12}$$

The single phase to ground arcing fault model given in time domain and spectral domain is shown in Fig. 3 and Fig. 4, respectively.

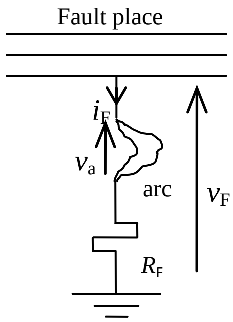

Figure 3: Fault model given in time domain

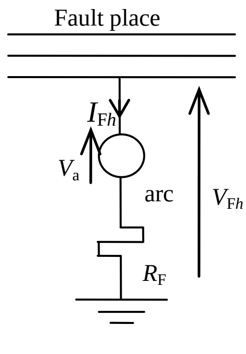

Figure 4: Fault model given in spectral domain

Fault phase voltage v_f can be given in time domain by the relation in the following:

$$v_F(t) = v_a(t) + R_F i_F(t) \tag{13}$$

In the spectral domain, the fault voltage can be expressed by the next relation:

$$V_{Fh} = V_{ah} + R_F I_{Fh} \quad (14)$$

For the single phase to ground arcing fault occurring on a three phase overhead line, shown in Fig.5, the three phase circuit can be presented by three single phase equivalent circuits: positive-(p), negative-(n), and zero-sequence (0) equivalent circuits. Positive- and negative-sequence circuits aresimilar as shown in Fig.6. Z_h is positive or negative line impedance. The zero-sequence equivalent line circuit is shown in Fig.7. In Fig.7, all variables and parameters are zero-sequence variables and parameters.

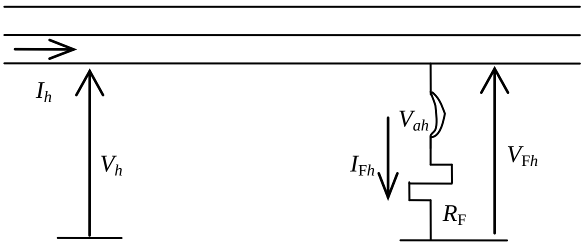

Figure 5: Single-phase-to-ground arcing fault

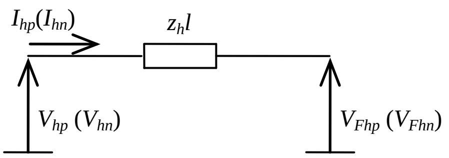

Figure 6:positive- and negative-sequence equivalent circuits

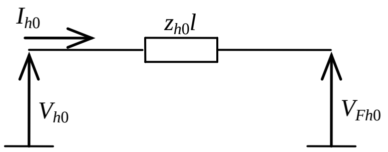

Figure 7: zero-sequence equivalent circuit

From the equivalent circuits in the Fig.6 and Fig.7, the following equations can be written:

$$V_{hp} = Z_h l I_{hp} + V_{Fhp} \quad (15)$$

$$V_{hn} = Z_h l I_{hn} + V_{Fhn} \quad (16)$$

$$V_{h0} = Z_h l I_{h0} + V_{Fh0} \quad (17)$$

Because of

$$V_h = V_{hp} + V_{hn} + V_{h0}, V_{Fh} = V_{Fhp} + V_{Fhn} + V_{Fh0}$$

The following relation can be obtained:

$$V_h = Z_h (I_h + K_{zh} I_{h0}) l + V_{Fh} \quad (18)$$

Where, $K_{zh} = (Z_{0h} - Z_h) / Z_h$ is the zero-sequence compensation factor.

Because of

$$V_{Fh} = V_{ah} + R_F I_{Fh}$$

$$V_{a1} = K_1 V_a$$

$$V_{a3} = K_3 V_a$$

The following relation can be obtained:

$$V_1 = z_1 (I_1 + k_{z1} I_{10}) l + K_1 V_a + R_F I_{F1} \quad (19)$$

$$V_3 = z_3 (I_3 + k_{z3} I_{30}) l + K_3 V_a + R_F I_{F3} \quad (20)$$

$$I_{F1} = 3 I_{F10} = 3 c_{F1} I_{10} \quad (21)$$

$$I_{F3} = 3 I_{F30} = 3 c_{F3} I_{30} \quad (22)$$

Where, c_{F1} and c_{F3} are real proportional coefficients. So,

$$V_1 = z_1 (I_1 + k_{z1} I_{10}) l + K_1 V_a + 3 R_{Fe1} I_{10} \quad (23)$$

$$V_3 = z_3 (I_3 + k_{z3} I_{30}) l + K_3 V_a + 3 R_{Fe3} I_{30} \quad (24)$$

Where, $R_{Fe1} = c_{F1} R_F$, $R_{Fe3} = c_{F3} R_F$

Using the formula above, the arc voltage amplitude and fault distance can be calculated. If the calculated value of the arc voltage amplitude is greater than the product of arc gradient and the length of the arc path, it can be concluded that the fault is an arcing fault.

2.7 Remote Fault Location

In recent years, the digital protective devices are replacing the old type devices like the electromechanical or static devices. Those digital devices are generally equipped with a fault recording function, which enables an automatic fault location.

Besides, the advances and widespread use of intelligent electronic devices have promoted progress in measurement, monitoring, protection, and control techniques applied to distribution networks. Despite of this technological progress and the need for performance improvements, the fault location progress employed nowadays is still based on trouble calls from the affected customers. When a permanent fault occurs, the operation centers identify the faulted feeder and the possible area of occurrence. Then a maintenance crew is sent to patrol that area in order to identify and isolate the fault. When a transient fault occurs, the operation center will not receive any phone calls from customers, and no information about its occurrence and location will be available. However, it may be important to investigate these faults with the purpose of preventing them from becoming permanent ones.

There are a lots of fault location algorithms developed for power transmission systems. But few methods were proposed for distribution networks due to the following reasons [27]:

Variety of conductors and structures

Along a typical distribution feeder there are different cables and configurations; therefore, there is no linear relation between the line impedance and the distance between the fault location and the substation.

Lateral branches

Unlike transmission lines, typical distribution feeders have several lateral branches. Therefore, short circuits in different geographical locations can produce the same currents and voltages measured at the substation. Consequently, the fault location procedure may result in several different points as possible locations.

Load distribution along the feeder

The current measured at the substation during a fault includes a contribution given by the sum of the load currents at each node, and, in contrast to transmission system, it is impossible to estimate these currents accurately.

Modifications in the feeder configuration

Distribution networks are subject to constant modifications in their topology. As a result, any fault location algorithm must have access to a database, periodically updated, in order to give a better estimate of the fault point.

Generally, the methods of fault location can be classified into three groups: the first one is to use apparent impedance based on fundamental components of voltage and current; the second one is to use artificial intelligent; and the last one is to use travelling waves.

2.7.1Impedance Method

Basically, there are two different approaches for locating faults in distribution networks. One is based on fault detectors installed along the feeders, whereas the other is based on algorithms that use measurements of voltages and currents signals provided by IEDs (intelligent electric devices) located only at the substation level.

The last method can be further divided into two subgroups: to use one-end information or to use information from both ends of the faulted line. Among them, the latter method gives higher accuracy; however, it needs additional devices for communication and data transmission. Therefore, the former one is more widely used with some accuracy- improving technique adopted. There has been considerable research efforts to the development of impedance-base methods for fault locations. However, like any other power frequency-based measurement methods, they suffer from limitations due to fault path resistance, line loading and source parameters etc.; as a result, the accuracy attained in fault location is limited to about 2-3% of the total line length, and it is unlikely that any further significant improvement will be achieved in the near future.

Ref. [28] suggested a fault location algorithm based on the direct circuit analysis. The fault location equation has been derived by applying matrix inverse lemma and applied for any system regardless of a phase balance condition. But this algorithm for the phase-to-phase fault in an unbalanced system needs to be investigated to enhance the practical power. Ref. [29] presents a approach in single-ended fault location for overhead distribution systems based on the concept of superimposed voltages and currents.

2.7.2Intelligent Method

Applications of artificial intelligent have been presented in an electrical system. Many researchers have applied the artificial neural network (ANN) to fault section estimation, fault diagnosis, and alarm processing [30~33]. ANN is a very useful owing to its parallel distributed process, training capability, and implicit knowledge representation. Many papers have presented the use of ANN for power system applications such as the use of multilayer back-propagation network (BPN). But training BPN is time consuming and very slow without guaranteed global minimum. The global optimization methods were also proposed to solve the fault section estimation such as the Boltzman machine; however, the training process is still very time-consuming. Another problem of multilayer network is that it is difficult to decide the number of layers and the number of hidden units in each layer. When a network topology changes, the network has to retrain, and the time-consuming process becomes a bottleneck in environment adaptation.

There has been an upsurge in research into the application of artificial intelligence techniques in fault detection and location. In particular, neural network-based fault location schemes have been developed. Feature extraction is the crucial stage in any neural network-based scheme, and studies have found that using the post-fault power frequency signal, together with the associated lower frequency signal, is far more accurate than using the travelling wave frequency signals. Therefore, any high-frequency components such as travelling waves are filtered out, and thus the neural network-based fault location schemes are very similar to impedance-based methods.

Ref. [34] discussed the application of field data to a new supervised-clustering-based arcing-distribution fault-diagnosis method. The fault-diagnosis method can perform three functions that provide preliminary fault location information for grounded and ungrounded power-distribution systems: fault detection, fault type classification and fault phase identification. It contains two main modules: a pre-processor and a pattern classifier which was implemented as a supervisedclusteringbased neural net. Field studies were conducted in which the fault-diagnosis method was trained and tested with normal and faulted phase currents generated from data recorded by events staged in the field for two four-wire systems.

2.7.3Travelling Wave Method

Theoretically, the pattern of the fault-generated travelling wave contains information about the fault location that can be used to accurately locate the fault. However, present travelling wave-based fault location methods exhibit shortcomings; a fault will not generate many travelling wave components when it occurs at a voltage inception angle close to zero degree; for a close up fault, the time difference between the arrival of an incident wave and the arrival of its reflection from the busbar will be so short that the waves are unlikely to be detected separately. This could make the interpretation of the information available in the first few milliseconds after the arrival of the first wave front virtually impossible. When the measurements involve voltage signals, the bandwidth limitation of the CVT can be a serious impediment.

Ref. [35] described aspecially designed fault locator unit that was used to extract the fault-generated high-frequency voltage transient signals from the distribution line/cable system. Three-phase voltages are monitored with a high-voltage capacitor. The signals from the capacitor are then digitized for processing. Modal mixing transforms are applied to extract the aerial-mode component and the ground-mode component. This process provides inherent filtering. Digital band-pass filters will then extract the high-frequency components for a fault location. The travelling time of the high-frequency signal was used to determine the fault position. The scheme was insensitive to fault type, fault resistance, fault inception angle and system source configuration. In the scheme, the accuracy of fault locations is proportional to the digital sampling rate.

A sudden change in system voltage on a power line or cable will generate a wideband signal which covers the entire frequency range. The initial values of these waves are dependent, among other factors, on the fault position on the line, the fault path resistance and, the most important of all, the instance of fault occurrence. These different frequency components propagate away from the fault point in both directions. In time, these signals reach other discontinuities on the line/cable and are reflected back towards the fault point. In the frequency domain, the magnitude of the individual signal components decreases, as the frequency rises and the travelling speed increases.

The theoretical aspects of the characteristics of the fault-generated travelling waves on line/cable have been well documented. The technique can be explained graphically by a lattice diagram, as shown in Fig. 18, and considers the high-frequency signals such as used by the system. Assuming a fault occurs at a point distance x from busbarR**,** travelling waves would be initiated towards both busbars. The principle of the fault location method is based on the successive identification arrival of the travelling high-frequency voltage signals at the busbar where the locator is installed. In particular, the timing of the first received and subsequent signals referenced to that first signal is used to identify the fault position. In the technique presented in the paper, the locator was designed to capture the high-frequency voltage signals in the frequency range of 1 to 10MHz. Around this frequency range, the busbar impedance is dominated by the busbar capacitance, which will reflect a voltage of the opposite sign to the step changes in the incident wave. Apure resistive earth fault in this frequency range will also reflect a voltage wave of the opposite polarity. As can be seen from Fig. 8, with respect to the busbar*S* or *R*,the reflected wave from the remote busbar will have the opposite polarity to that from the point of the fault; therefore, the two waves can be discriminated.

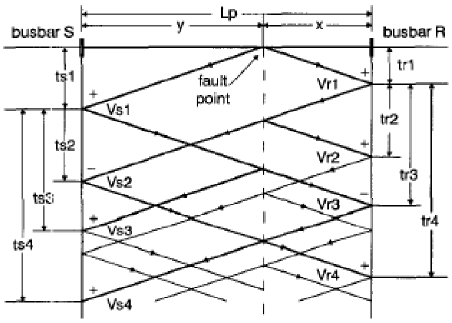

Figure 8: Lattice diagram for single-phase loss-free overhead line

Fig. 9 shows a block diagram of the fault locator unit; the three phase voltages are monitored using high-voltage coupling capacitors. The signals from these are then digitized for processing. Modal mixing transforms are used to extract the aerial mode and ground mode signals. This process provides inherent filtering. Digital band pass filters then extract the high frequency components used for the fault location.

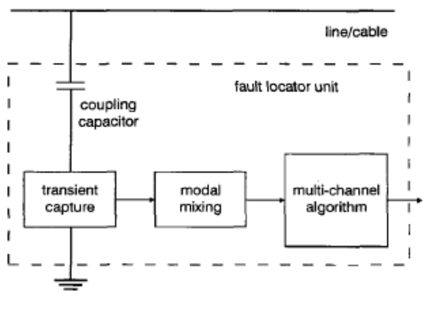

Figure 9: Block diagram of fault locator unit

Ref. [36] proposed a travelling wave fault location system in a cost-effective way for power networks especially for a distribution system. Two travelling wave sensors are developed to capture the current travelling wave flowing from the capacitive equipment to earth and the voltage travelling waves in all three phases. The outputs of the sensors are then applied to the trigger and time tagging by using Global Position System receiver. The fault position is calculated by the travelling wave arrival times in every power station where only one fault locator is installed.

The precision of fault location is determined by accurate time-tagging for the travelling wave's arrival at both ends of the line. By calculating the time difference T and the total propagation time for the travelling wave travelling from one end to another end of the line T_p, the distance L_1between the fault and the nearest terminal is shown as follows:

$$L_1 = \frac{1}{2}(L - \Delta T v) = \frac{(T_p - \Delta T)L}{2T_p}$$

But there are some limitations of the travelling wave methods:

1). require a high sampling rate;
2). choice of sampling window;
3). distinguish between travelling waves reflected from the fault point and from remote end of the line.

In recent years, the potential benefits of applying wavelet transforms for analysis of transient signals in power system have been recognized [38-40]. The applications of wavelet transform analysis and mathematical morphology have initiated considerable research activity concerned with improving the performance of fault location techniques. Wavelet transform possesses some unique features that make it very suitable for this particular application.

3. Tests in Trial Line

There are two lines in the test field. One line was used as the trial line in this project. The test line is no energy. The length of the line is about 3.7 km. Five different tests were carried out using a number of power sources which include:

1). Low voltage square pulse injection test(up to 10 V),
2). Double exponential impulse voltage test (up to few hundred volts),
3). Low voltage, high frequency ac test (up to 500Hz, and capable of 80V),
4). High voltage injection tests with simulated faults at receiving end (up to 6kV).

For the high voltage test, a partial fault and a short circuit arrangement were used at the receiving end of line to carry out two fault-scenario simulations. Measurements were taken at both sending end and receiving end measurement points. Capacitive voltage probes were used to measure voltages at both line ends with ratios 1000:1 at the sending end and 1200:1 at the receiving end. The currents were measured by means of current transformers with 0.1V/A sensitivity and Tektronix current probes. The triggering of the oscilloscopes was set up at a given level of impulse to allow synchronization of measurements at both ends. Data acquisition and storage was made using a Labview-based program.

4. Simulation of A Distribution Network

Because of the limit of the test field, the experiments were only done on the one simple line. In practice, the distribution network composed many tees and branches. It is a very complex network. Hence a distribution network model was set up by using EMTP in the laboratory. Extensive simulations of faults on a distribution system were carried out using EMTP to simulate a generic circuit. Fig. 10 is the diagram of simulation distribution network. The simulation works were carried out on this model in order to accord with the practice. The single phase grounding fault was set at point NOD 1 to NOD 8 respectively. The fault voltage and current were recorded at the substation (left side).

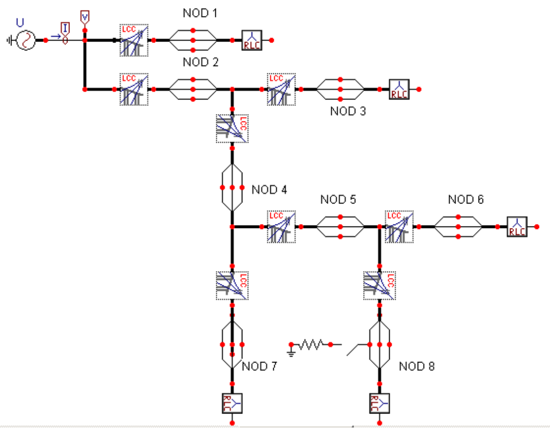

Figure 9:simulation model of distribution network

5. Conclusion

An overview of main fault location techniques and modeling principles was given. Preliminary laboratory tests were carried out on insulators and surge arresters to identify the shapes of partial failures of these devices. These indicated that known signatures are associated with these types of failures which could be used for fault recognition. Field tests on an overhead line revealed that it is possible to detect small signals even over relatively long distances. The attenuation of the signal and the multiple signal reflections need to be taken into account. Simulation of the tests gave good agreement which validated the models used. Further simulation of faults on an extensive distribution system yielded some promising results which could be useful for the fault identification/detection and location. It is, therefore, concluded that fault diagnosis and location using terminal measurements are feasible, and provide that adequate measurement and analysis systems are used. More importantly, specific configuration of the network at the point of measurement needs to be known and taken into account in the analysis in order to provide accurate location of the fault.

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