Modelling arcing high impedances faults in relation to the physical processes in the electric arc

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Abstract: - There is an increasing demand for more detailed and accurate modelling techniques for predicting transient response of power systems caused in particular by high impedance arcing faults (HIF). This is particularly so in relation to the design and development of improved equipment and new protection techniques. Accurate prediction of fault transients requires detailed and comprehensive representation of all components in a system, while the transient studies need to be conducted into the frequency range well above the normal power frequency. The HIF is a very complex phenomenon and exhibits very high nonlinear behaviour. The most distinctive characteristics are nonlinearity and asymmetry. The nonlinearity arises from the fact that the voltage-current characteristic curve of the HIF is itself nonlinear. It is observed that the fault current has different waveforms for positive and negative half cycles which is called asymmetry. The nonlinearity and asymmetry exist in every cycle after HIF. In order to obtain a model for a HIF, it is necessary to develop a model that gives the above mentioned characteristics, as well as the harmonic content of the HIF.

Key-words: - high impedance fault, electric arc modelling, transient analysis, physical processes in an arc

1 Introduction

In the case of an arcing HIF, when an energized conductor contacts the ground, the electric contact is not solid. Due to the existence of air between ground and conductor, the high potential difference in such a short distance excites the appearance of the arc.

High impedance faults (HIF) have characteristics in their transient and steady state regimes that make them identifiable. They also lead to arcing and it is the result of air gaps due to the poor contact made with the ground or grounded objects; it occurs when a conductor breaks and falls on a non-conducting surface such as asphalt road, sand, cement, grass or perhaps a tree limb, producing very little if any measurable current.

An accurate modelling method for a HIF is essential for the development of reliable detecting algorithms. The HIF model's data should contain the complex characteristics of HIF such as nonlinearity, asymmetry, the low frequency phenomena typical of an arcing fault and the angle shift of the third harmonic. Some modelling methods of HIFs have been proposed. A modelling method using a diode is presented in [1]; the HIF is modelled as a voltage source in [2, 3]; another model in [4] uses two time-varying resistances in series. Although all these methods represent well the nonlinear behaviour of HIFs, difficulty arises when the other characteristics are considered.

According to the experimental work of the Korea Electric Power Corporation (KEPCO) [4], the HIF experimental data was collected on a 22.9kV distribution system. The total number of experiments was thirty two and the sampling frequency 10 kHz. Figure 1 exemplifies the currents for the 20th and 40th cycle after the HIF has occurred; both currents exhibit some asymmetry. Figure 2 shows the voltage-current curve and demonstrates the degree of nonlinearity. We can see that the "signature" of the current curve and the current-voltage curve for HIF has a very unique shape.

In order to obtain a good model for the HIF, it is necessary to develop a model that gives the above mentioned characteristics and harmonic content of HIF.

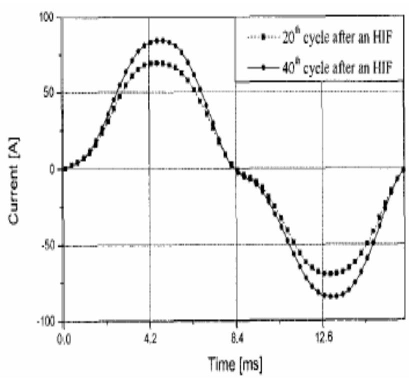


Fig.1 Current for the 20th and 40th cycle after HIF (asymmetry) [4]

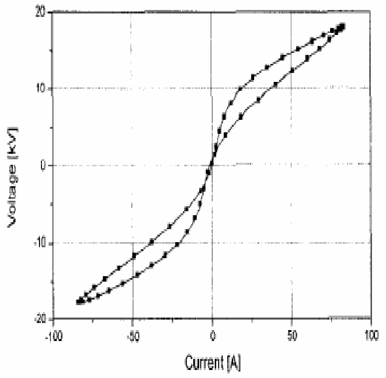


Fig.2 Voltage-current characteristic curve for one cycle in the steady state after HIF (nonlinearity) [4]

2 Physical processes in an arc

By their nature all gases are normally good electrical insulators, but it is well known that the application of a sufficiently high electric filed may cause a breakdown of the insulating properties, after which current may pass through the gas as an electric discharge. The term arc is usually applied only to stable or quasi-stable discharges, and an arc may be regarded as the ultimate form of discharge; it is defined as a luminous electrical discharge flowing through a gas between two electrodes. Electric discharges are commonly known from natural phenomena like sparks whose lengths can vary.

Discharges can occur not only in gases, but also in fluids or solids or in almost any matter that can turn from a state of low or vanishing conductivity to a state of high conductivity, when a sufficiently strong field is applied.

According to [5-10], starting with a uniform distribution of ions when the current and voltage are zero, the increase in voltage will cause space charge sheaths to form next to the electrodes and, because the mobility of the electrons is much greater than that of positive ions, most of the applied voltage will be across the space charge sheath at the anode as seen in Figure 3. The current densities in this sheath are very small and in order to 'restrike' the arc, the space charge sheath must be broken down. If there are no ionizing agents, the breakdown must be ionization by collision; it will therefore require a minimum of several hundred volts. Under the action of the electric field strength, electrons are emitted from the cathode spot. These collide with neutral molecules, thereby ionizing them electrically. The ions in the arc column fly now under the effect of the field strength towards both electrodes and heat them by impact to high temperature. The negative electrons hit the anode, and the positive ions hit the cathode. In this way new electrons are liberated within the arc column and at the electrodes, and the process starts again. According to [7] the dynamic characteristics of arcs may be represented as in Figures 4 and 5.

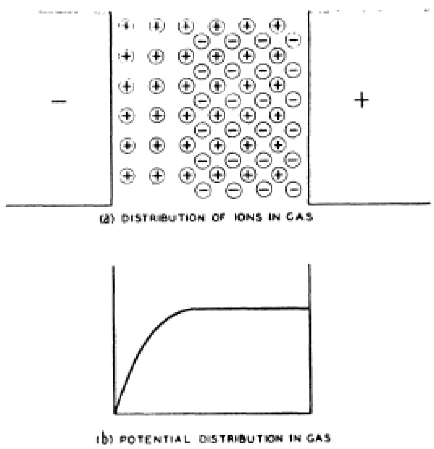


Fig. 3 Ions and potential distribution in arc discharge through Gas

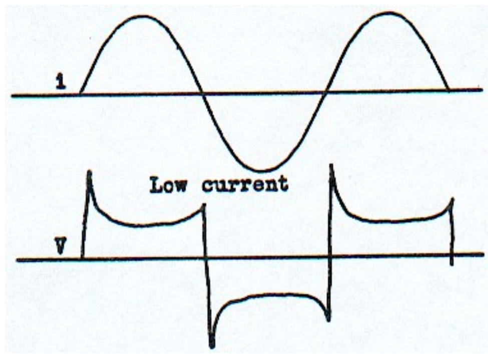


Fig. 4 Voltage and current during electric arc [7]

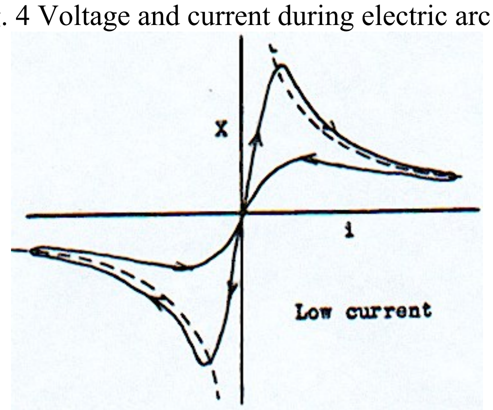


Fig. 5 *V-I* characteristics during arc [7]

3 Physical processes in the HIF arc

Arcing associated with the HIFs results in energy dissipation in the form of heat that turns the moisture in the soil into steam and burns the grass into smoke. In the arcing phenomenon associated with downed power lines, due to the existence of air between ground and conductor, the high potential difference in such a short distance excites the appearance of the arc (it resembles anode-cathode phenomenon). This normally occurs in a largely resistive circuit, and is characterized by short arc length, small current magnitude, and could persist for a long period of time [11]. The arc which penetrates the soil has typical values of temperature at the arcing spot of the order of 2000 to 3000 °C for metallic electrodes, 3000 to 4000 °C for carbon electrodes, and 5000 to 8000 °C in the gas column [12]. The arc heat is enough to fuse sand and silica in the soil into a glass-like substance, silicon carbide tubes. These glass-like tubes reach a length of 5 cm. They were found to have a linear resistance of the order of 2 to 100 kΩ/m [1]. The arcing fault's voltage-current characteristic and the fault current signal behaviour will be a result of a complex interaction of :

- nonlinearity of the arc and conductor-soil interface [11]
- Development of silicon carbide tubes,
- bounce of the conductor on the ground surface,
- Heat capacity of the conductor, earth, and arc gas,
- Moisture content in the soil,
- Generation of smoke and steam,
- Movement of the soil particles,
- Ground material itself.

As for the Fault Current Behaviour, it has been observed that the positive half-cycles of the current may be greater in magnitude than the negative half-cycles, or vice versa, and the fault current magnitude may vary greatly from one cycle to the other [1].

The asymmetry of the fault current in some cases could be a result of the rectifying action by the soil. The glass-like tubes surrounding the conductor act as hot cathodic spots that emit electrons. The voltage drop across the cathode spots is small when the conductor is positive (Figure 6). The arc voltage in the negative half-cycle is thus larger than that during the positive half-cycle. Consequently, the current conduction period, and hence its magnitude, are smaller in the negative half-cycle. The amount of moisture in the soil and the packing of its particles affect the values of the arc voltage in each half-cycle. Drier soil yields higher difference in arc voltages and, therefore, a larger degree of asymmetry than wet soil; harmonics are generated on account of this asymmetry [1, 12]. The varying current magnitude could be explained as a result of arcing at the fault, which rearranges the characteristics of the air gaps surrounding the downed conductor as well as accumulation of silicon carbide tubes around the conductor.

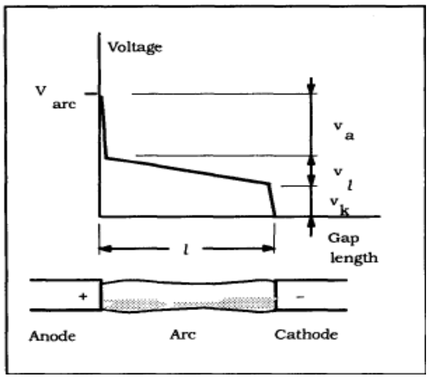
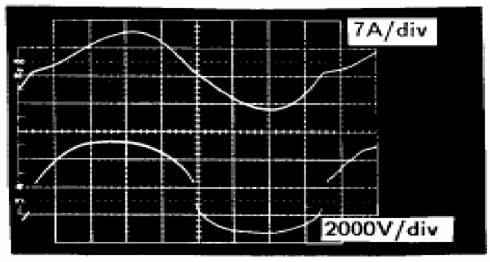
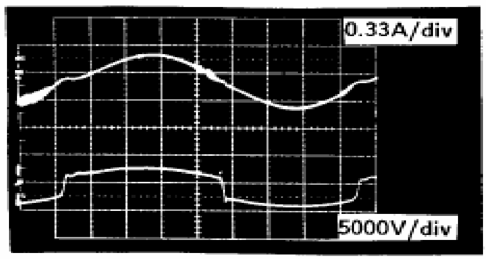


Fig.6 Voltage distributions between arc electrodes. V_a :anode drop, V_k: cathode drop, V_l: arc drop

In a field test reported in [1], measured values of current harmonics at a staged high impedance ground fault are presented, and the measured low frequency spectrum is compared with current harmonics recorded continuously for one week at the substation. It has been confirmed that faults with currents above 1A have a stable arc with nearly constant rms value for long periods of time, whereas arc currents lower than 1A are characterized by shorter periods of stable arc current and by random initiation and quenching of the arc. Based on the laboratory measurements in [1], Figure 7 shows oscillograms of currents and voltages which illustrate and validate the characteristics for large as well as for small fault currents. In Figure 8 the asymmetry is also noticeable in the *V-I* curve of the arc as well as in the arc voltage.



(a)



(b)

Fig.7 Oscillograms of laboratory arc currents; (a) large arc current (b) small arc current [1]

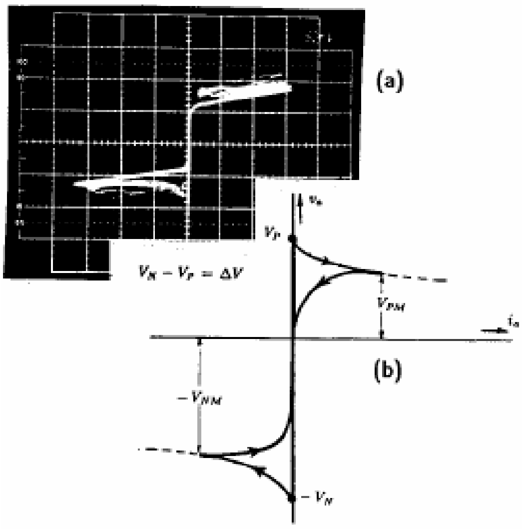


Fig.8 *V-I* characteristic of arc; (a) laboratory oscillogram; (b) theoretical description [1]

4 A new model of an arcing HIF

Many authors have worked on the theory and dynamics of voltages and currents in an electric arc based on laboratory studies. References [13, 14] propose a valid model explaining this phenomenon using a spark gap: the air gap will not conduct until the applied voltage reaches the breakdown point. Then, the current flows and reaches a maximum when the applied voltage equals the arc voltage. After that, the arc current decreases and becomes zero, i.e. the arc is extinguished. When extinction occurs, the arc requires a potential known as *restrike voltage* to re-ignite. This re-ignition will have opposite polarity. All this procedure explains the typical voltage–current waveform of an arc shown in Figure 9. Electric models have been proposed describing arc behavior, and they have been recently collected and published in [15, 16].

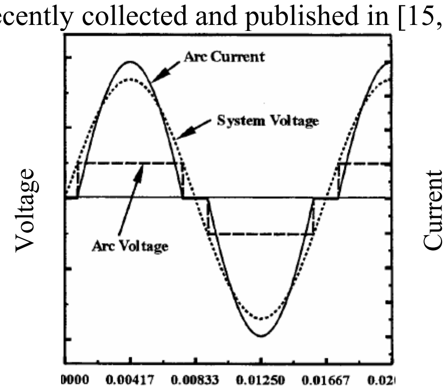


Fig.9 Electric arc voltage and current shapes

The high impedance fault model proposed by this paper includes two DC sources, V_p and V_n, which represent the *arcing voltage* of air in soil and/or between trees and the distribution line; two resistances, R_p and R_n, between diodes which represent the resistance of trees and/or the *earth resistance*; and – since most observed arcs occur in highly inductive circuits [11] – two inductances, L_p and L_n were added to the circuit. The effect of the inductances leads to the nonlinearity loop shape in the *V-I* curve and the desired asymmetrical shape for the HIF current. When the line voltage is greater than the positive DC voltage V_p, the fault current starts flowing towards the ground. The fault current reverses backward from the ground when the line voltage is less than the negative DC voltage V_n. In the case when the line voltage is in between V_p and V_n, the line voltage is counter-balanced by V_p or V_n so that no fault current flows. Typical fault current and *V-I* curves are shown in Figures 11 and 12.

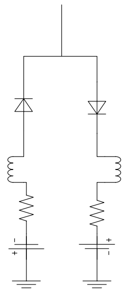


Fig.10 Two diode fault model for HIF with R_n, R_p, L_n, L_p

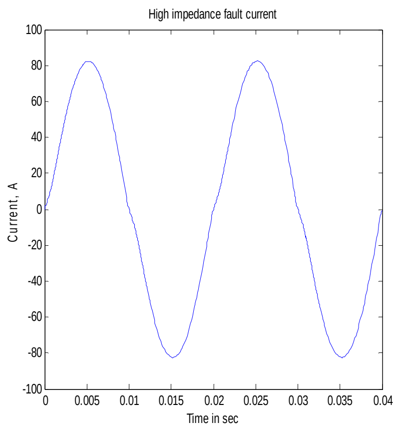


Fig.11 Current curve for HIF

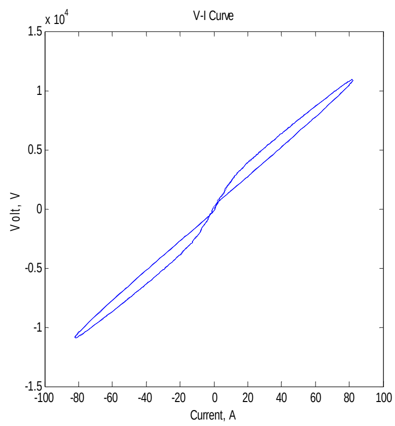


Fig.12 Voltage-current characteristic

5 The harmonic content of HIF model

This section shows the harmonic content of the HIF model and its current curve, after decomposing the line current into its spectral content and studying its harmonic content. Harmonic analysis involves the use of Matlab to identify the potential harmonic and their magnitudes with respect to the fundamental frequency. In our HIF model of particular interest are lower harmonics up to the 7^{th}. In the HIF model signal we notice the existence of the odd harmonics, and the existence of the asymmetry shape in the fundamental current. It has also been observed that a phase shift for the 3^{rd} harmonics current with respect to the fundamental has occurred.

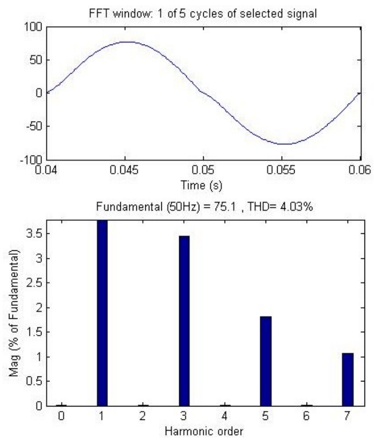


Fig.13 the HIF current and its harmonic content

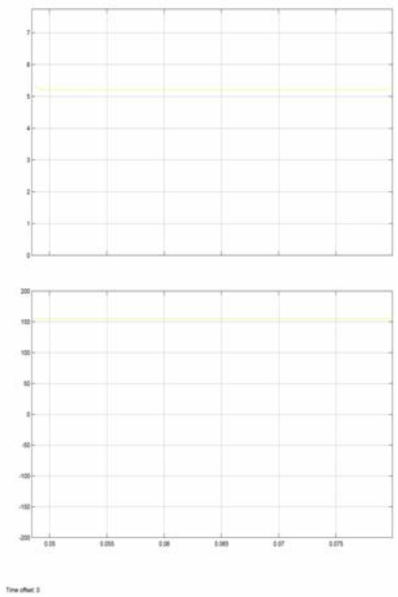


Fig. 14 magnitude of the 3^{rd} harmonics (top) and the Phase shift of the 3^{rd} harmonics (bottom) with respect to the fundamental current during HIF

6 Conclusion

The aim of this paper is to develop a model that represents and predicts all important high impedance fault characteristics, including nonlinearity, asymmetry, harmonic content and phase shift of the 3^{rd} harmonic. The physical processes occurring in an arc result in a unique characteristic signature. Accordingly, a new model for a high impedance fault has been proposed and tested, containing active as well as passive elements (voltage sources, diodes, resistances and inductances), giving a very satisfactory representation of the arc characteristics. The new model preserves the unique shape of the high impedance fault voltage and current, and it also has the harmonics content, as well as the angle shift of the 3^{rd} harmonic, consistent with experimentally observed behaviour. Thus the proposed model can be considered an appropriate and physically well justified representation of high impedance fault characteristics and can be harnessed to generate various data necessary for developing more reliable HIF detecting algorithms.

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