Digital Simulation of the Fault Transient Phenomena on EHV Transmission Lines under Non-Linear High Impedance Arcing Faults

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Abstract - **High impedance faults (HIFs) are in general difficult to detect by conventional protection such as distance or overcurrent relays; this is principally due to either relay insensitivity to the very low level fault currents and/or limitations on other relay settings imposed by HIFs. New alternative techniques for detecting such faults must be found. However, the development of any new protection technique suitable for HIF detection would inevitably require an accurate simulation of the fault transient phenomena involving such faults. The ElectroMagnetic Transients Program (EMTP) is an extensively used tool for the analysis and simulation of power system transients. However, hitherto there are no suitable, arc models used for modelling high impedance arcing faults in particular for implementing within the EMTP. This paper proposes an improved technique for modelling the high impedance arcing fault in transmission lines using the Zincoxide (ZnO) arrester which can be implemented within the EMTP. The performance of the proposed model is tested under a variety of fault conditions on a typical 345kV Korean transmission line system.**

Keywords: Transmission lines, fault transient modeling, high impedance arcing fault

List of symbols
i = current of ZnO
v = voltage of ZnO
p = constant coefficient of ZnO device
q = constant exponential coefficient of ZnO device
K = reference voltage of ZnO

I. INTRODUCTION

A HIF is a type of a fault that is extremely difficult to detect and be subsequently removed by conventional protection relays such as distance and overcurrent. This fault usually occurs when a conductor touches the branches of a tree having a high impedance or when a broken conductor touches the ground. In the case of an overcurrent relay, the low levels of currents associated with HIFs are below the sensitivity settings of the relay. In the case of a distance relay which relies on an estimation of impedance to fault based on the measured voltages and currents, the accuracy of the estimation can be significantly affected by the high impedance of the fault [1]. Thus to improve the reliability of the electric power supply, the importance of detecting HIF with arc, which can cause such hazards as electric shock, fire, etc, increases. However, there are various difficulties in simulating an actual arcing fault and in this respect, no accurate model has been established even within the EMTP which is widely used in the simulation of power systems. It is thus very important to develop an accurate arc model similar to the high impedance fault arc generated in real power systems; this can then be embedded into the EMTP model of a transmission system to generate realistic voltage and current data thereby enabling fault detection techniques of high impedance arcing faults to be developed.

Kizilcay [2,3] has suggested the possibility of using a curve of voltage-current (V-I) characteristics from the data of about 200 arc simulation experiments in actual power systems, but the studies have been confined to low impedance fault arcs. Dube [4], a developer of a sub-program MODELS within the EMTP, has proposed the usefulness of applying MODELS to arc simulation. Buchholz [5] has also suggested a method of simulating fault arcs using two diodes. The results, however, have shown similarities simply in shape to arcing faults in an actual power system, and have revealed difficulties in applying the MODELS to EMTP. Johns et al [6] have presented a technique for significantly improving the modelling of fault arcs but this is in relation to either low impedance fault arcs or the secondary arc phenomenon. Rogers [7] of Boneville Power administration, USA, has suggested to the user group of EMTP the basic concept of an arc model in free-air similar to an arcing fault in an actual power system using ZnO. However, the construction of the arc model is based on a single phase line.

The work presented in this paper extends the basic concepts of Rogers' work to three-phase systems, suggests a high impedance arc model suitable for incorporation within the EMTP and presents some simulation results under high impedance arcing faults for the Korean 345 kV transmission system.

II. ARC MODEL

A. Characteristics of HIF

A HIF is accompanied by a fault arc. The arc generated at the fault point has not only the characteristics of non-linear V-I but time-related length changes caused by power working on the arc. The curve of V-I characteristics in the case of arcing faults lie in the first and third quadrants. Also, the magnitude of fault current is extensively changed from one cycle to the next and the magnitude of a positive half cycle of current can be larger than that of a negative half cycle, or vice versa. Fig. 1 typifies the characteristics of fault path current in an actual power system in the case of a HIF [1]; these characteristics are a direct consequence of the manifestation of the highly non-linear nature of the fault arc.

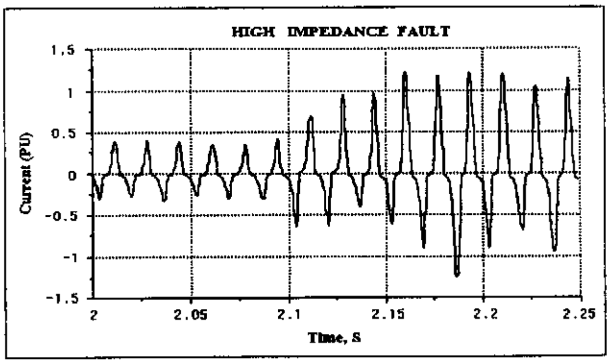

Fig. 1. Typical HIF fault-path current characteristics

B. An arc model using a ZnO arrester

An arrester is a device that controls overvoltages by allowing a large current to flow to ground, thereby establishing the operating voltage with current, controlled to its normal characteristic, after damping the overvoltage. A conventional circuit breaker consists of carbonized silicon and a series-gap, while a ZnO-type arrester, which has a highly non-linear characteristic, is in widespread usage today. The model suggested herein is a structure in which an inductor, an energy storage element, is connected to shunt ZnO elements in a series mode. Resistance is connected to ZnO elements in a parallel mode so as to attain the slope and form of the arc V-I curve. A switch is used to initiate the fault and to terminate the fault when the fault current extinguishes. The circuit for the fault arc simulation consists of ZnO, resistance R, and inductance L and is as shown in Fig. 2. The equation for representing the current i in the ZnO element and the voltage v across it is given as:

$$i = p(v/K)^q \qquad (1)$$

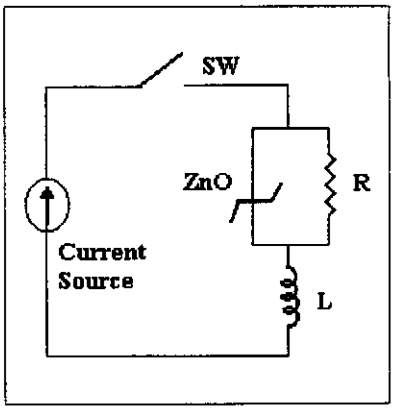

Fig. 2. Circuit model for the arc

The values assigned to the variables p,q and K in eqn (1) are such that the arc characteristic is representative of the real data recorded in an actual power system under a HIF. The established arc model is then embedded into an overall model of the Korean transmission system using the EMTP software.

It should be noted that the foregoing description of the HIF arc model is based on an empirical approach whereby the variables of interest (as shown in eqn (1) and Fig. 2) are adjusted with respect to the actual fault arc data recorded within the Korea Electric Power Research Institute (KEPRI) in order to attain a near perfect match with the latter. In essence, this is an iterative process and Fig. 3 shows a block diagram of the computational procedure adopted for achieving this mathematical model.

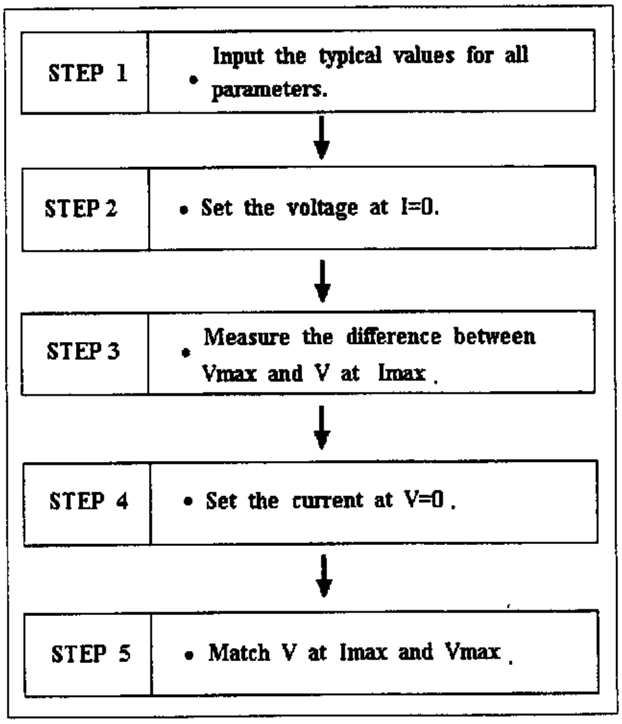

Fig. 3. A block schematic of the arc modelling procedure

III. SIMULATION STUDIES

A. The 345 kV Korean Transmission System Model Studied

Fig. 4 shows a typical 345 kV Korean Transmission System used in the simulation studies presented herein. It comprises of a 100 km line length terminated in two sources of 10 GVA and 7 GVA at ends P and Q, respectively; the nominal power frequency is 60 Hz.

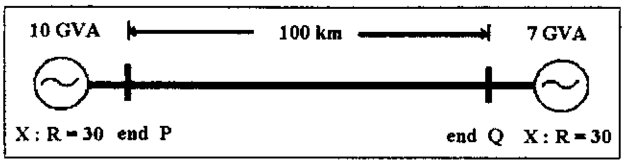

Fig. 4. The 345kV Korean transmission system studied

B. Verification of the V-I characteristics of the HIF arc model

Fig. 5 depicts the curve of voltage-current (V-I) characteristics obtained under an 'a'-phase-earth HIF occurring near voltage maximum of the 'a'-phase and at the mid- point of the line for the system shown in Fig. 4. As mentioned previously, this is obtained through an iterative adjustment of the variables representing the arc model (as shown in eqn (1) and Fig. 2), which is then embedded into the EMTP simulation of the Korean Transmission System. Essentially, the variables in question are varied in small steps until such time as the simulated voltage and current waveforms closely match the practical fault recorded data attained from the Korean System as given in references [8,9].

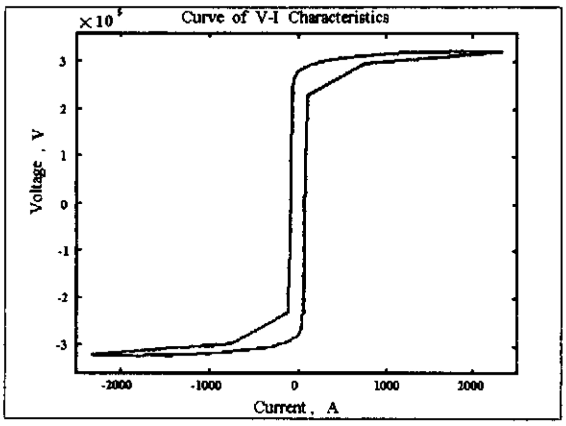

Fig. 5. Voltage-current characteristics of a high impedance arcing fault

As can be seen from Fig. 5, the relatively narrow V-I characteristics of the HIF arc model (these are markedly different from the characteristics associated with a low fault impedance arc [6]) fall within the first and third quadrants, as would be expected; this, therefore, verifies the accurate representation of the HIF arc model embedded within the EMTP simulation.

An extensive series of studies have revealed that the variables of interest constituting the HIF arc model change little at other fault positions and/or fault inception angles, once they have been deduced at the outset through the foregoing empirical approach.

It should also be noted that the V-I characteristics of the fault arc path are distinctly different from those of a solid conductor. Those for a solid conductor are linear because the voltage at both ends of the conductor is proportional to the current flowing through the conductor. The arc in the HIF is, on the other hand, characterised by a short arc length and small current magnitude, and is mainly generated in highly non-linear resistive circuits, compared with a fault within the solid conductor.

C. Typical Fault Studies

Fig. 6 typifies the fault waveforms (measured at end P of the system shown in Fig. 4) for an 'a'-earth fault near voltage maximum (2 km from end P) when a realistic HIF primary arc model of the type described previously is incorporated into the simulation. First of all considering the current waveforms at end P (Fig. 6a), it can be seen that the faulted 'a'-phase current waveform is very significantly distorted and this distortion is directly attributed to the highly non-linear nature of the fault arc. Fig. 6a also shows that the magnitudes of the healthy 'b' and 'c' phase currents are extremely small in comparison to the 'a'-phase current. When considering the measured voltage waveforms, Fig. 6b shows little high frequency travelling wave distortion (in particular on the faulted 'a' phase) at fault inception. This would be expected due to the high impedance associated with the fault arc path.

Fig. 7 shows the corresponding current and voltage waveforms for the same fault as considered in Fig. 6, but assuming the fault arc path to be represented by the conventional method of a linear resistance of about 300Ω. It should be noted that the latter can be estimated from a knowledge of the L and R parameters shown in Fig. 2. First of all comparing the current waveforms in the two cases, it is apparent from Fig. 7a that the magnitude of the faulted 'a'-phase current is lower than that shown in Fig. 6a which is for a fault with a realistic HIF arc model. More importantly, the former shows a distortion-free waveform (ie a near sine wave) and this is in sharp contrast to that attained in the case of the latter. In the case of the voltage waveforms (Fig. 7b), as expected, there is little high frequency distortion

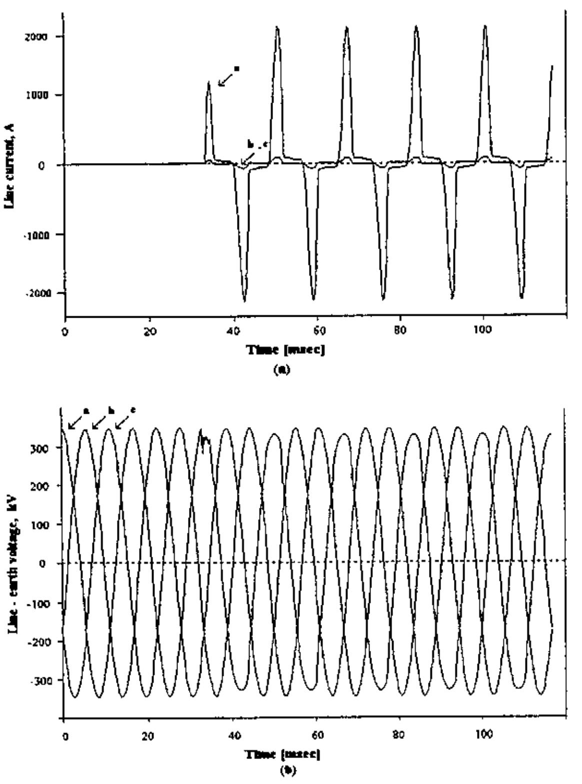

Fig. 6. Typical results for primary HIF arc study
(a) current waveforms at end P
(b) voltage waveforms at end P

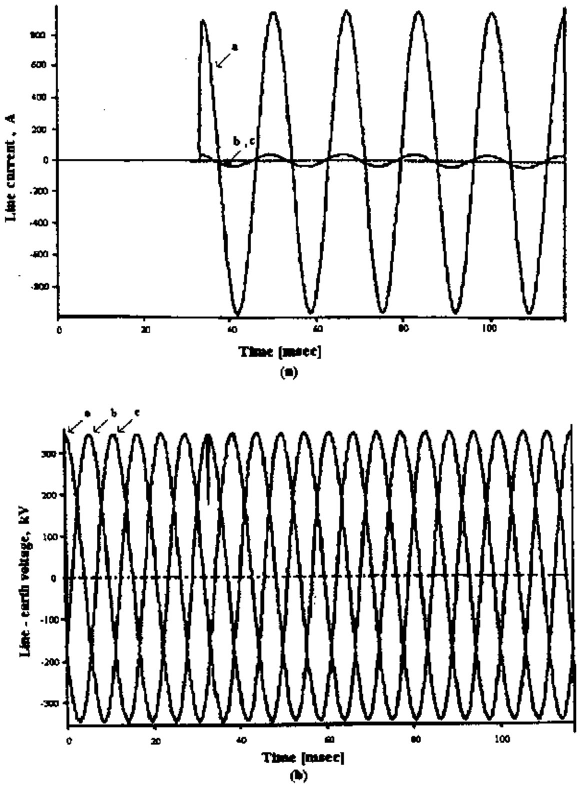

Fig. 7. Simulated waveforms assuming a linear fault path resistance
(a) current waveforms at end P
(b) voltage waveforms at end P

impressed upon the power frequency waveforms.

Fig. 8 illustrates the corresponding waveforms for the same fault as considered previously (again with an HIF arc model) but for a fault occurring near voltage zero of the 'a'-phase. In comparison with the waveforms obtained for a voltage maximum fault (Fig. 6), there is little difference between the two sets of waveforms. Also, Fig. 9 shows the randomness and asymmetrical characteristics of HIF current using improved arc model.

It should be noted that although the foregoing results have been presented for one particular fault position/faulted phase, an extensive series of studies have shown that the fault transient phenomena similar to that illustrated in the forgoing results is observed for faults on the other phases and at other fault positions; of course, as would be expected, in the case of the latter, both the magnitude of the faulted phase current and the level of the distortion are different.

It should also be mentioned that in the case of low impedance fault (LIF) arcs, although the behaviour of the fault arc path is also highly non-linear in nature, unlike the case involving a HIF, the non-linearity has very little bearing on the level of the distortion caused in the current waveforms in particular the faulted phase current; this is so by virtue of the fact in the case of a LIF, the magnitude of the power frequency component of the fault current is so large as to swamp over any distortion emanating from the non-linearity associated with the fault arc path[6].

IV. CONCLUSIONS

This paper describes a technique for significantly improving the modelling of a fault arc associated with a high impedance. The mathematical arc model suggested herein is based on the characteristics of a Zincoxide arrester whose parameters, in conjunction with suitable resistance/inductance combination, are adjusted through an empirical approach; this involves obtaining a close correlation between simulated data and practical recorded data in order to accurately represent the dynamic conducting behaviour of a HIF arc. With the incorporation of the validated and improved arc model into the EMTP, a series of simulation studies were conducted on a typical 345kV Korean Transmission System. The results obtained reveal the distinct features of the transient waveforms, in particular those associated with the faulted phase current signals.

Through a more precise definition of the HIF arc, it has thus become possible to advance the state of the

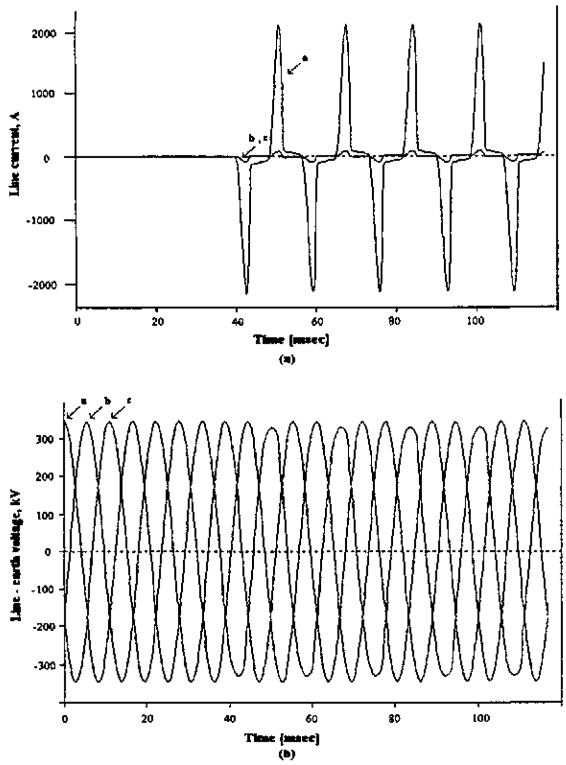

Fig. 8. Simulated waveforms under HIF arc for fault inception near voltage zero
(a) current waveforms at end P
(b) voltage waveforms at end P

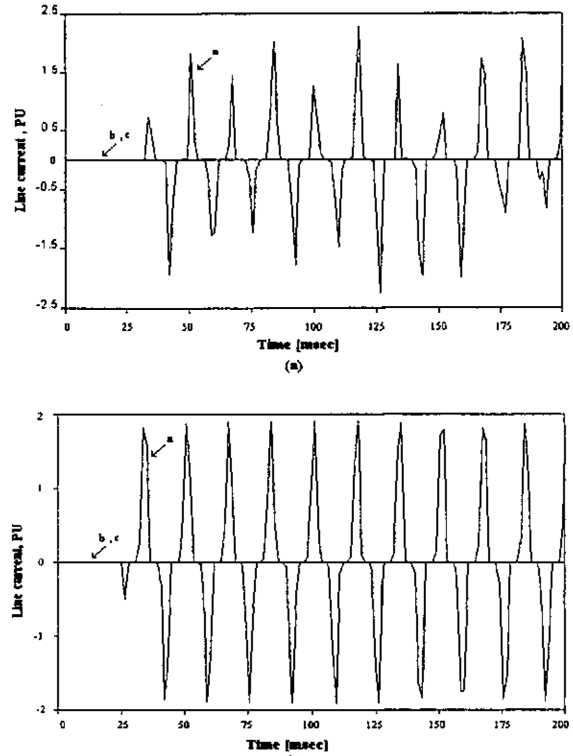

Fig. 9. Current waveforms of improved arc model
(a) fault inception angle : 45°
(b) fault inception angle : 90°

art of digital simulation of the fault transient phenomena associated with HIFs with particular relevance to the development of new improved protection techniques in the accurate detection of such faults.

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VI. ACKNOWLEDGEMENTS

The authors are grateful to the British Council and the Korea Science & Engineering Foundation for jointly funding the research collaboration between the two Universities.