

***A Strategy for
Opening Loop Disconnects***

by

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submitted to the Faculty of Graduate Studies

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A STRATEGY FOR OPENING LOOP DISCONNECTS

BY

HONG TANG

**A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University
of Manitoba in partial fulfillment of the requirements of the degree
of
MASTER OF SCIENCE**

Hong Tang

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Abstract

To open a disconnect switch in a power system, especially, in a looped circuit, the existing guidelines failed to explain some unsuccessful opening operations. In some cases, the switch current remains above a certain threshold value along the arc which in turn creates damage to the contacts and insulators.

Due to the complexity of the physics of the electric arc, it is very difficult to have an accurate arc model to describe the air-switch operation. The aim of this thesis is to develop a criteria on loop switching by integrating the mathematical arc model into the PSCAD/EMTDC™ program, in which various simulation results will be obtained to evaluate the present method and investigate the more efficient guidelines to determine whether the switch can be opened successfully or not.

The thesis also presents some improvements on the present guidelines and discuss the possibility of incorporating this model into the real-time SCADA/EMS for the loop switching operation.

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Introduction

1.1 BACKGROUND

In the AC power system, an air insulated disconnect switch can normally be used to interrupt relatively low current, such as transformer magnetizing current, charging currents of lines, (depending on length, voltage, insulation level) and small load currents, however, its current interruption capability has not been specifically designed due to lack of the accurate criteria [3]. Many studies have been carried out to examine the interrupting capacity with respect to the interruption of capacitive current and magnetizing current. To open disconnects in a looped networks, i.e., loop switching, it is more difficult to determine whether the disconnect can be successfully opened or not simply based on the definition of its interruption capacity. One principal reason is that the successful open-

ing depends on a number of factors: such as the current to be interrupted, the current already in the circuit, the impedance in series with the switch, the loop impedance, the composition of the loop impedance, and the opening time of the switch. A large number of field tests have been conducted on the interrupting ability of switches in order to get the interrupting guidelines on the switch operation in a looped network. Because of inaccuracy of the computation tools and difficulties with the arc physics, only empirical methods were employed [3].

However, it is the enduring arc between contacts when opening the disconnects that creates the damage to the contacts and endanger the operation staff on the site. Therefore, it is essential to investigate the arc behaviour of the disconnect in predicting the success of opening operation for the system control centre and determining whether the switch in a looped circuit can be opened or not. The guidelines on loop switching based on the suggested methods can be improved and upgraded.

1.2 THE DECISIVE FACTORS OF OPENING DISCONNECTS

Some of the facts that exert considerable influences upon the operation of the switch are: [5]

I) The type of disconnect switch. For example, air switches use air as an insulating medium when the contacts are open. Air switches can be further divided into three groups based upon their purpose: Disconnects , Air Break Switches and Load Interrupters.

II) The phase spacing. The greater the phase spacing and disconnect switch clearance, the higher the disconnect switch interrupting capability .

III) The Characteristic of the loop. The current flowing through the disconnect switch must be multiplied by the vectorial sum of the impedance of the loop elements to determine the voltage at the disconnect switch terminals which affect the interrupting capability.

IV) The wind. The wind has a significant influence on the interrupting capability. An interruption is not recommended at wind speeds in excess of 10 miles/hour, unless the current is very much lower (0.5 times) than the maximum which the disconnect switch is designed to interrupt.

V) The current to be interrupted and the voltage level. The current to be interrupted is the one flowing in the pre-opening disconnect switch and it can

be measured or evaluated by calculation depending on the situation. The voltage level also plays an important role in determining the switch operation.

VI) Rain, humidity and atmospheric pollution. The effects of these parameters are poorly understood. However, it is generally accepted that no interruption should be attempted in rain and severe atmospheric pollution, unless the current is also very much lower.

These internal and external factors all have influences on the opening operation of disconnects. Some of them have more decisive effects than others. For a specific air switch type, the loop impedance composition becomes the important factor under certain weather conditions.

1.3 THE DESCRIPTION OF THE SWITCH ARC

A large number of field tests have been conducted to investigate the interrupting ability of air switches on: arc behaviour in switches under various systems conditions, magnitude of currents that can be interrupted on existing switches under prevailing system condition and basic switch design factors for successful operation under specified conditions. It was found that the arc length is

proportional to the voltage and an unconfirmed arc should always extinguish itself provided clearance permits the required growth to a necessary critical length and the gap is wide enough to prevent restriking [1]. This is the preliminary concepts about the switch arc. The arc reach was presented as a criterion for comparison with switch clearances, it can be used to determine whether it is safe to open the switch. The arc reach is defined as the distance from a point midway between the arc extremities to the most remote point of the arc at the time of its maximum length [4]. The maximum arc reach must be short enough to avoid flashover to any structure, otherwise a short circuit may occur. Reach for currents below 100 amperes depends on both voltage and current. Maximum reach for practical use is 0.0165 foot per ampere per kilovolt across the open switch gap. Reach above 100 amperes is proportional to voltage but independent of current. Maximum reach for practical use is 1.65 feet per kilovolt across the open switch gap.

The arc can be generally divided into three regions: the column region, the cathode region and the anode region. The measurable variables with which each region of the arc can be characterized are electrical field and temperature distribution [1]. Fig 1.1 shows the distribution of the potential along the axis of the arc.

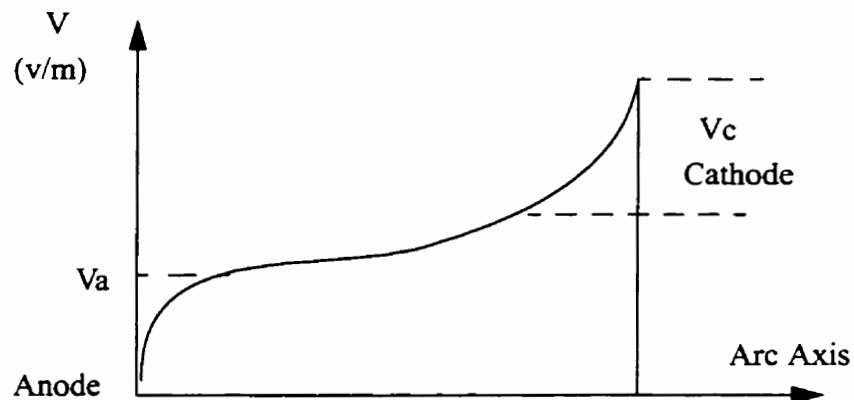


Fig. 1.1 Schematic of potential distribution in the arc

The potential gradient in the column is dependent on the arc current and the energy exchange with the surroundings, including flow velocity and solid boundaries. The potential gradient can vary by more than two orders of magnitude depending on the design of the arcing devices.

The electrode regions adjacent to the arcing contacts perform the following functions for the arc: they serve as the transition from a gaseous conductor with variable conductivity, the arc column, to a solid conductor with essentially constant conductivity. The potential drop in the cathode region V_c is primarily a

function of the cathode materials and typically is 10 to 20 V and extends to a region of 0.0001 to 0.01 mm. The potential drop in the anode region V_a is a function of geometry and shows a wide variation.

1.4 PRINCIPLES OF INTERRUPTION IN AC CIRCUITS

Alternating current can be easily interrupted than direct currents because it oscillates through zero at half-cycle intervals. It's an advantage to interrupt the ac circuit during the natural zero.

According to Slepian's theory [1], arcing can begin if a restriking voltage (the voltage across the switch when opening) causes an electrical breakdown in the region near the cathode. A positive charge is formed in front of the cathode by the rapid movements of the electrons to the anode. This leaves only the positive ions behind, which quickly accumulate to a high charge. When the AC current passes zero, the polarity is switched. The anode and cathode are reversed. If the current is interrupted for 10^{-9} to 10^{-8} second during this period, ions are prevented from moving to the new cathodes, electrons may not be free to migrate to the arc column and no new arc will be formed. It is obvious that from the above discus-

sion that the time required to extinguish the arc is a very important factor for determining the successful interruption in the AC circuits. Arc extending can be prevented if it can be extinguished during that short period of time. Another decisive factor is restriking voltage during the arcing period. Basically, the arc will be reignited provided that the rising current causes the voltage to increase to a level when the voltage across the arc reaches the value of the critical restriking voltage that allows the electrons to be released from the cathode.

The racing theory [1] can be applied to explain the arc behaviour in the interruption of AC circuits although it is not completely accurate. It assumes that the buildup of dielectric strength is independent of the rate of increase in restriking voltage, if the air around the contacts is cool enough, the dielectric strength increases faster than restriking voltage and the arc will extinguish, otherwise, if the restriking voltage increases faster than the dielectric strength, the arc may reignite.

In terms of energy balance in the arc column, if the energy input continues to increase after current zero, the arc will reignite, during the short time following current zero, the arc power loss exceeds the power of the residual arc. The input power is zero, even though the arc is still hot. If a rapidly increasing restriking

ing voltage is presented, the power inputs begins to increase. When the energy input exceeds the energy loss, the arc reignite. The rate of increase in the restriking voltage is determined by the natural frequency of the voltage, which is one of the internal factors of the ac circuit.

From the above discussion, we can draw the following conclusions with respect to the interruption of AC circuits:

I) The interruption of AC current with occurrence of an electric arc is an electromagnetic transient phenomenon;

II) The restriking reignite voltage will mainly determine the arc behaviour through the rising current passing through the arc and the temperature inside the arc column;

III) The energy balance inside the arc column will decide whether the arc will last or reignite according to the net energy content;

IV) To successfully interrupt the AC circuit, there should be no arc reignition and the interruption must be executed during a short period time to prevent the ions from moving to the new cathode.

1.5 THE THESIS OBJECTIVES

As there are some uncertainties about the guidelines for successfully opening the disconnect in a looped network. The thesis will utilize a more accurate mathematical model to describe the behaviour of the switch arc and discuss the possibility of applying this model into the real-time SCADA/EMS system. Some improvements will be proposed on the present guidelines to examine the behaviour for the specific disconnect under different operation modes. It will let the control centre get the necessary information to ensure the successful opening for loop switching. The transient simulation program called PSCAD/EMTDC™ has been used for simulating the AC network and the arc model.

The Arc Modeling for The Air Switch

2.1 INTRODUCTION

The understanding of the arc of the air switch will help us to determine when and how to open the disconnects, especially in the looped networks (i.e. loop switching). Although loop switching has been investigated before, the guidelines on the operation criterion are not accurate enough for practical application. The study on the arc modeling of the air switch will make improvements and modifications upon the existing guidelines for loop switching if arcing phenomenon can be described in a more accurate way. This chapter will discuss the mathematical model of the air switch arc based on the differential-equation. We'll first review the arc models that have been done before then present our arc model for the air switch.

2.2 ELECTRIC ARC AT LOW CURRENT

During the opening of the disconnect in a looped network, the current to be interrupted usually is relatively low because the disconnect is naturally supposed to separate the bus or contacts not for interruption of the high short current. Firstly let us look at the electric arc at the low current, then we will consider the arc at high current, the extreme case in which in theory the arc may never extinguish itself in theory.

The basic concept is the same for all circuit interruption regardless of its design and type: An electric arc is generated which burns in a gas under high pressure, and with a strong pressure gradient along the arc axis.

The model to describe the low current arc plasma which is in local thermodynamic equilibrium has been proposed by the different authors. According to Slephian [1], the failure or success of the opening switch depends on a race between the rate of recombination of the ions, which increase the sheath thickness for a given voltage and so reduces the sheath field, and the rate of rise of recovery voltage (i.e., restriking voltage), which increase both the thickness of the space-

charge sheath and the electrical field in the sheath. Many other arc models were formed from this theory.

In contrast to Slepian's race theory, Prince [1] proposed a simple wedge model: at a current zero when there is no electrical power input, the arc is cut by a wedge of cold gas entering the upstream region between the electrodes. Whether an electrical current continued after current zero was thought to depend on whether electrical breakdown occurred through this wedge of cold gas when the circuit voltage is repled after current zero.

As an alternative to the cold wedge theory, Cassie [1] postulated that the arc area was continuously reduced by the convective flow. The deformation of the column due to the gas flow something like that of a piece of elastic of circular section fixed at one end to the upstream contact while the other end is made to move at a speed equal to that of sound in the gas at arc temperature. Based on this assumption, the following model was developed, see (2.1) [2]

$$\frac{1}{G} \cdot \frac{dG}{dt} = (E/\alpha - \beta)$$

where, G is the arc conductivity. I stands for the arc current, E , α and β are the experimental constants. The above equation considers the decay of G by thermal conduction and uses an empirical constant. It suggests that the guideline on the design and operation of switches can be developed based on the differential equation of the arc and experimental results.

Unfortunately, the exact physical theory is not yet complete enough to explain this phenomenon, the transient arc in the low current can be studied by concentrating the local thermodynamic equilibrium. It is reasonable to use a mathematical model to describe its behaviour from the electrical point of view.

2.3 THE ELECTRIC ARC CHARACTERISTICS IN AIR

Because of energy storage in the arc associated with its conductance and finite rates of energy flow, the arc conductance cannot respond to current changes instantaneously but together with the arc voltage, lags behind the current changes. This is called dynamical characteristics of the electric arc as shown in the voltage-current relationship of Fig 2.1 [1].

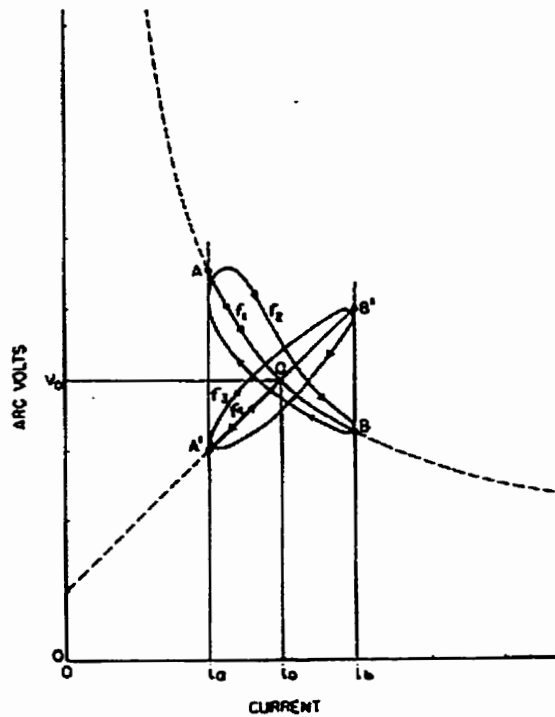


Fig 2.1 Dynamic Characteristics of An Arc

Fig 2.1 [1] illustrate successively higher AC frequencies. Frequency f_1 allows the static characteristic to be followed. Frequency f_4 is the highest and at that point, the conductance (I/V) cannot follow at all but remains approximately at the midvalue. Frequency f_2, f_3 have intermediate values between these two extremes.

It has been proved that both high current and low current AC arc have the almost same voltage-current characteristic (60 cycle AC systems) [13].

The average voltage gradients at current peak for 60 cycle arcs lie between 31 and 38 volts per inch for currents over the entire range from less than 100 to over 20,000 peak amperes. From the electrical point of view, there exists similarities among arcs for different current values. It is believed that it is due at least part to the magnetic forces acting on the arc which tend to shift the arc core into new arc paths that are less highly ionized and require high arc voltage to maintain the current.

The above experimental results can be used to modify the empirical equation to match the tests of the characteristics of arc in the air. This will allow us have a good understanding about the arc behaviour and its influence upon the current interruption operation only through electrical point of view.

2.4 THE THEORITICAL MODELS FOR THE ARC

The classical equations of Cassie and Mayr assumes that the arc is a non linear resistor depending on the other factors, such as the energy balance, temperature and the internal electrical elements. In order to simplify this theory model while providing a valuable practice guide, further efforts have been done. One of the difficulties arises from the complex nature of the equations describing the arc: we must solve the continuity, energy momentum equations of gas dynamics along with Ohm's law and the equation of state. A second difficulty arises from the non linear characteristic of the thermodynamic and transport properties of interrupting gases. A third difficulty arises from the complex flow fields generated with supersonic flow and shock waves. A fourth difficult arises from stability problems encountered in numerical methods. Another difficult is the uncertainties in modeling arc turbulence and radiation. It is obviously that the simplification process need be taken. Therefore, the Electrical Characteristic becomes our major concern in the modeling of the arc.

The Arc Integral Equations include: [2]

Continuity (2.2)

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial z}(\rho V_z) + \frac{1}{r} \cdot \frac{\partial}{\partial r}(r \rho V_r) = 0$$

Axial Momentum (2.3)

$$\rho \cdot \frac{\partial V_z}{\partial t} + \rho V_z \frac{\partial V_z}{\partial z} + \rho V_r \frac{\partial V_z}{\partial r} = \left(-\frac{\partial P}{\partial z} + \frac{1}{r} \frac{\partial}{\partial r} [\eta + \eta_r] r \frac{\partial V_z}{\partial r} \right)$$

Energy (2.4)

$$\sigma E^2 - U + \frac{1}{r} \cdot \frac{\partial}{\partial r} \left[(k + k_r) \cdot r \frac{\partial T}{\partial r} \right] = \left(\rho \frac{\partial h^0}{\partial t} + \rho V_z \cdot \frac{\partial h^0}{\partial z} + \rho V_r \cdot \frac{\partial h^0}{\partial r} \right)$$

Ohm's Law (2.5)

$$I = E \int_0^r 2\pi \sigma dr$$

Where ρ is the air density, V_z is the axial velocity and V_r is the radial velocity. In equation (2.3), P is the air pressure, η is the molecular viscosity and η_r

is the turbulent viscosity. In (2.4) σ is the electrical conductivity, κ_t is the turbulent thermal conductivity. h^0 is the total enthalpy.

To relate with Cassie-Mayr theory, assume that a typical arc can exist after current zero because the arc temperature exceeds a certain value. Equation (2.4) can be integrated from $r=0$ to the arc radius and yields another equation, which is accurate enough for the realistic application purpose so it is not necessary to include the other equations any more. This equation (2.6) can be used in the

$$\frac{I^2}{\left(4\pi R^2 \cdot \int_0^1 \sigma \eta d\eta\right)} = \left(\frac{\partial}{\partial t} \int_0^{R(z,t)} [F - F_e] r dr + \frac{\partial}{\partial z} \int_0^{R(z,t)} \rho V (h - h_e) r dr + N(z, t, R) \cdot R^2 \right)$$

more general cases with respect to the circuit breaker and can be modified to match the test data for different cases. Where F is the energy density.

In addition, modeling the accurate arc is further complicated because of lack of the knowledge of its exact physical parameters. However, to derive an engineering mathematical model, it is possible to focus on the electrical aspects of the arc nature such as the Cassie-Mayr model. Equation (2.6) has a wide application on the modeling of arc, it can be applied by matching it with existing data to get the useful mathematical model and implementing it with relevant algorithm.

2.5 THE PRACTICAL ARC MODEL FOR THE AIR SWITCH

A. T. Johns [15] presented both a primary and secondary arc model for modeling fault arcs on faulted EHV transmission lines. The arc behaviour in the air switch is somewhat similar to the secondary fault arc, because they both have the following common features:

- I) The current to be interrupted is relatively small, usually less than 100 A
- II) There is occurrence of periodical extinction and restrikes of the arc
- III) The insulation medium is air

John's secondary model has been used as our arc model to provide us a detailed and comprehensive representation of the arcing phenomenon. Similarly, the primary arc model can be used as the model to interrupt high current for the air switch.

The hysteresis characteristic of the volt-ampere cycloramas for low current arcs has been experimentally obtained as shown in Fig 2.2 [15]

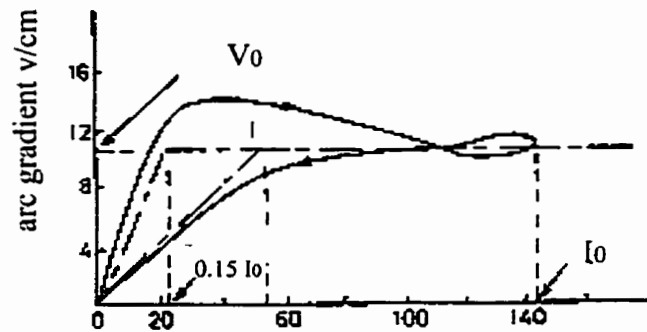


Fig 2.2 The Hysteresis Characteristics

The voltage-current relationship of the arc is shown in Fig 2.3 [15]

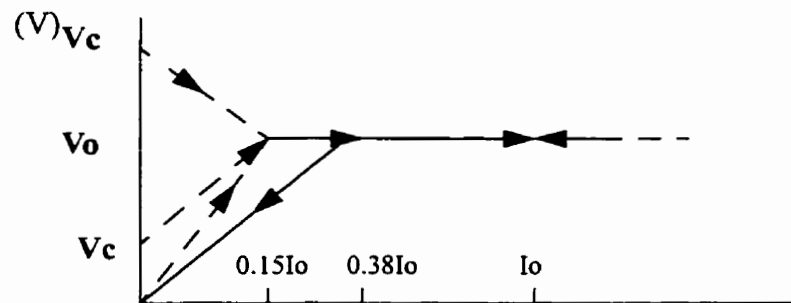


Fig 2.3 The Voltage-Current Characteristics of Arc

Based on this experimental result done by A. P. Strom [13] , which is shown in both Fig 2.2 and Fig 2.3, the following equations are proposed:

$$\frac{dG}{dt} = \frac{1}{T}(G_0 - G) \quad (2.7)$$

where,
$$G_0 = \frac{|i|}{V_0 L(t)} \quad (2.8)$$

$$V_0 = 75I_0^{0.4} \text{ V/cm} \quad (2.9)$$

G_0 ----- Conductance parameter value at a certain time t

G ----- The arc conductance

i ----- The current passing through the arc

T ----- Time constant, it is determined by (2.10), as shown later

L ----- The arc length, a function of time t , as shown in (2.11) later

V_0 ----- The constant voltage parameter (gradient parameter)

I_0 ----- The peak current passing through the switch before opening

$$T = \frac{\beta I_0^{1.4}}{L(t)} \quad (2.10)$$

$$L(t) = L_0 \quad \text{when } t < 0.1 \text{ s and } t = 0.1 \text{ s}$$

$L(t) = L_0 \cdot 10t$ when $t > 0.1$ s (2.11) (wind velocity is between 0 -1 m/s)

$\beta = 0.00251$ the coefficient is obtained by fitting the above equations with the test data.

t ----- Time from the beginning of the arc

Equations (2.7) ~ (2.9) reflect the results as shown in Fig 2.2, while (2.10) and (2.11) correspond to the results as shown in Fig 2.3 .

These equations establish a basic calculation model for the arc of air-switch and can be solved in terms of time step computing technology.

2.6 THE RESTRIKING VOLTAGE

As discussed before, the arc will reignite as long as the voltage across the air switch during the opening exceeds a certain value, an important empirical equation to define this critical value (volts per arc length) has been found as

(2.12)

$$V_c = \left[5 + \frac{1620T}{2.15 + I_0} \right] (t-T) u(t-T) \times 10^3 \quad \text{V/cm}$$

When the voltage across the arc of the air switch is less than this critical value, there is no current passing through the arc. The critical voltage is determined by the arc length, the peak current passing through the switch before opening, the time of initialization of the arc, and time T when the arc current reaches zero. The step response function $u(t-T)$ indicates that only when $t > T$ is there a non-zero value for this critical value.

As T and the arc length increases with time, this implies that the critical voltage keeps increasing too, when the voltage across the switch will be always less than this critical voltage, there will be no chance for the arc to reignite, i.e., the arc has been finally extinguished. The critical voltage has to be determined by repeatedly performing simulation for arc currents.

The critical voltage V_c is shown in the Fig 2.4,

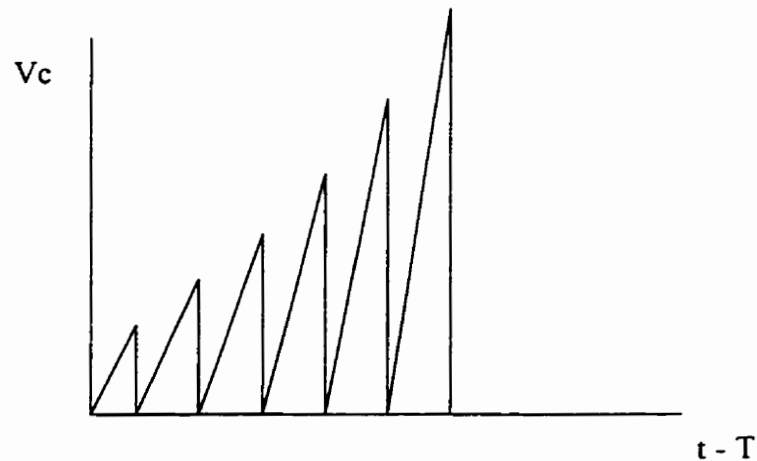


Fig 2.4 The Critical Voltage

It is important to point out that the current zero occurs at the peak of the sawtooth waveform and the check for restrike is done by comparing the arc voltage with this peak.

2.7 THE COMPUTING ALGORITHM

Combining (2.7) ~ (2.12), the following algorithm used to simulate the arc behaviour of the switch:

As the arc can be regarded as a non linear resistance, the arc current and voltage across the switch at a particular time can be calculated according to

the arc resistance value. The simulation time is therefore discretized into time step as required by the specific accuracy. During that time step, the transient state of the system can be treated as quasi-static state and the load-flow and the other electrical computation can be carried out.

The input consists of peak current and initial arc length, which will be used for the calculation of arc conductance. The arc has non linear time-varying conductance. A controlled switch can be used to set the starting for opening operation. Both the value of the non-linear resistance and the command signal are computed inside the model and incorporated into each time step of the computation as long as the arc is formed during loop switching. The instantaneous dynamic conductance is obtained according to the equation (2.7). At this point, every time the arc current magnitude is less than a minimum established, the air begins to regain its dielectric properties and the critical reignition voltage starts to increase. While the voltage impressed across the arc path is less than the critical reignition voltage, the arc current will hold at zero, once the recovery voltage exceeds this threshold value, the arc is reignited and arc current passes through the switch again.

The computing algorithm is shown in Fig 2.5

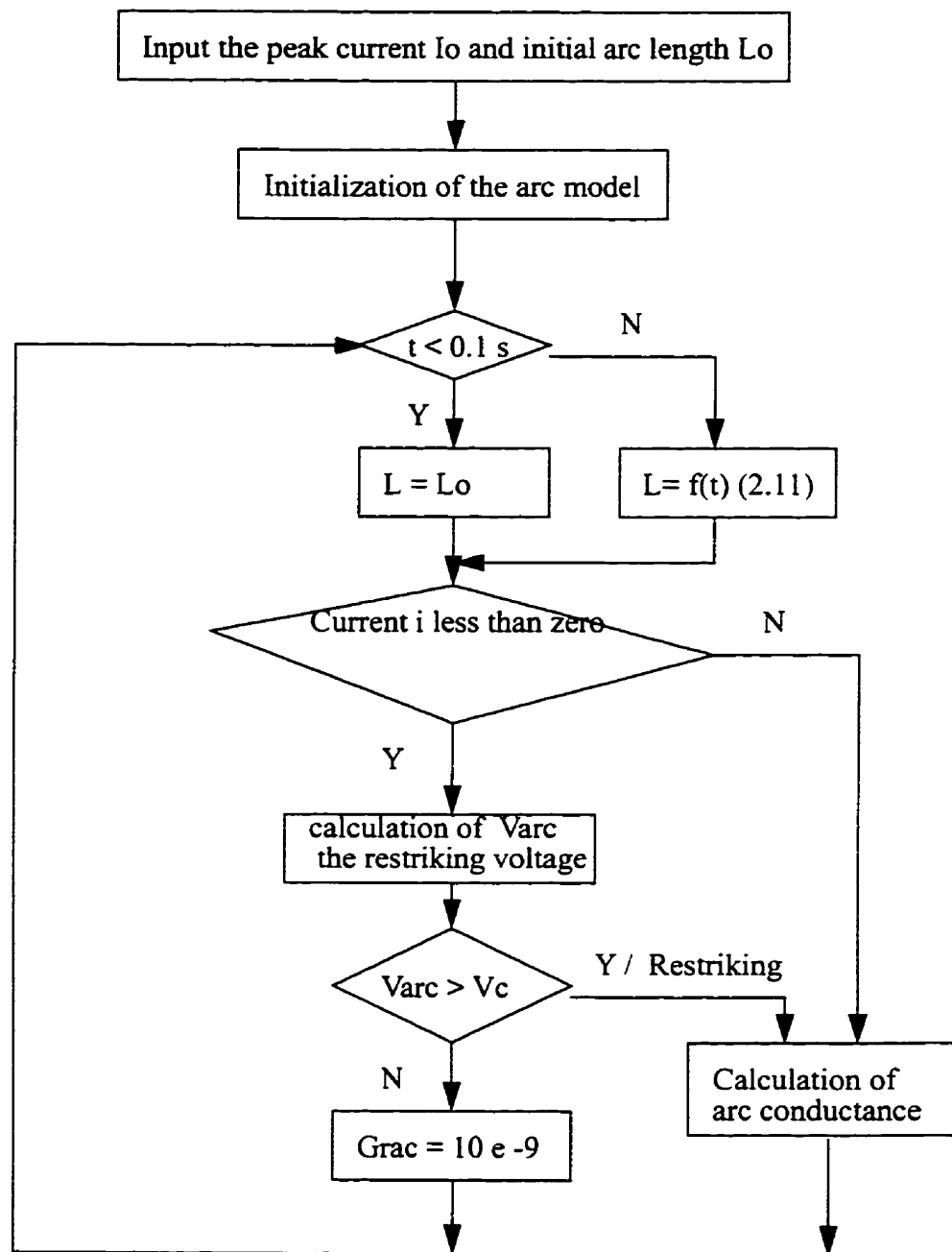


Fig 2.5 Computing Algorithm

2.8 ELECTRIC ARC AT HIGH CURRENT

Now consider the extreme case that the arc between the contacts of the air switch is difficult to extinguish, since the input of the energy is always greater than the output of the energy inside the arc column because of the high current. Under that circumstance, the air gap between the two contacts may be broken down. This model is based on Johns' primary arc model [15].

A non-linear resistance model can be used to describe this type of arc, in which the current is relatively high, there is no restriking and the voltage along the arc is decreasing and no voltage reversal occurs. This is similar to the primary arc during the fault duration in that there is no significant elongation of the arc. The following equations are used for the simulation.

The dynamic resistance is determined by (2.13)

$$\frac{dG_H}{dt} = \frac{1}{T_H} (G_{H0} - G_H)$$

The variable meanings are the same as the equation (2.7), where subscript H refers to the high current for the arc model. G_{H0} is determined by (2.14)

$$G_{H0} = \frac{|i_H|}{V_H L_H}$$

i_H ----- The arc current

V_H ----- The constant voltage parameters. usually at 15 V/cm

L_H ----- The arc length

The time constant τ_H can be decided by (2.15)

$$\tau_H = \frac{\alpha I_H}{L_H} \quad \text{this is a constant number too. Where}$$

α ----- The coefficient, set at 2.85×10^{-5}

I_H ----- The peak value of the arc current

L_H ----- The arc length

The above constant parameters were obtained by matching with the field tests. Since there is no restriking, this model can be easily solved after the calculation of (2.14) and (2.15).

The reason that we present two kind of models for the electric arc is that the arc behaviour is different with respect to the various ranges of current. In our cases, the air switches are used to interrupt relatively small current. The high current interruption model can be used as the guideline to interrupt the high current in some emergency events. It is obvious that the arcing development can be divided into specific stages because the basic physical explanation of the arcing can be significant different. As discussed before, the arc's physical nature is still under research, from the electrical point of view, it is a practical method to study the electric arc in terms of different current range.

Simulation Implementation Using PSCAD/EMTDC

3.1 INTRODUCTION

The arc model of the air switch was incorporated into the PSCAD/EMTDC transient simulation program and the arc model was validated to determine an accurate switch opening guideline. The electric arc of the air switch is a transient electrical phenomenon, PSCAD/EMTDC is the best available tool for its powerful transient analysis capability. We create an arc model for the air switch based on the mathematical models as mentioned in Chapter 2. The method of discrete time calculation will be used for the investigation of the arc behaviour and its influence upon the loop switching operation.

3.2 INCORPORATION PROCESS

PSCAD provides the interface which can connect a user developed model into the general simulation framework. The Draft module allows graphical editing of the circuit and parameters.

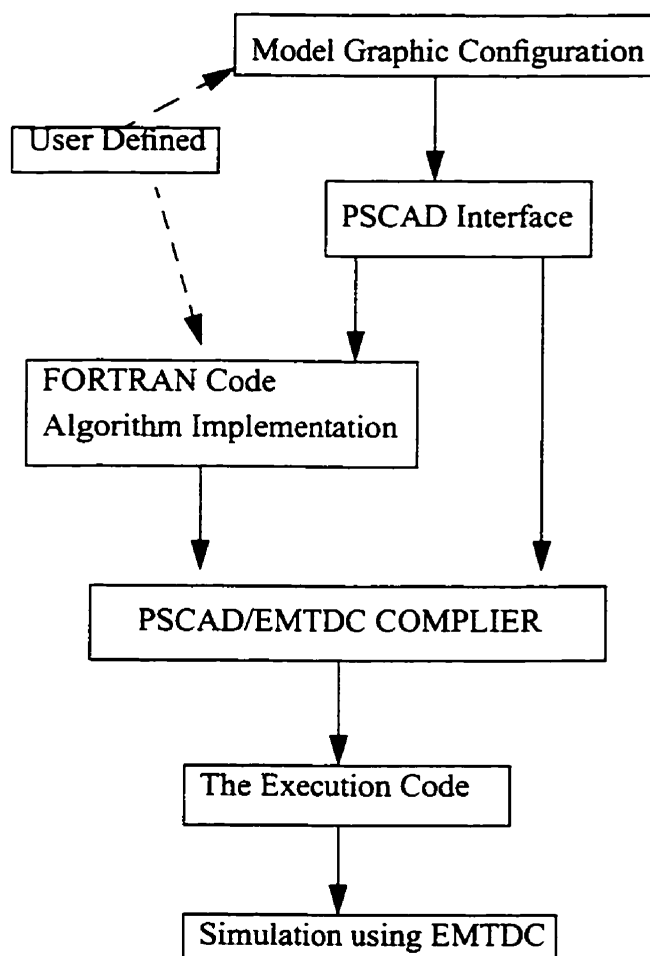


Fig 3.1 Incorporation Process

The arc model consists of Fortran code and graphic representation, which describes changes of the arc conductance via the differential equation as shown in (2.7) and is based on the secondary arc model [15], as we are only interested in the switching of relatively small current.

EMTDC is based on the studies of Node Equation for the network

$$[V] = [Y]^{-1} [I] \quad (3.1)$$

where $[V]$ is the matrix of the node potential, $[Y]$ is the admittance matrix of the network and $[I]$ is the current matrix of the network. The arc is regarded as a non linear resistor whose conductance varies with time. Every time the arc conductance changes (i.e as shown in Fig. 3.2(i)), the whole admittance matrix $[Y]$ changes and needs to be inverted. Instead of changing arc conductance in every time step, we create a combination of current source and equivalent conductance to represent the non linear conductance of the arc. As shown in Fig 3.2,

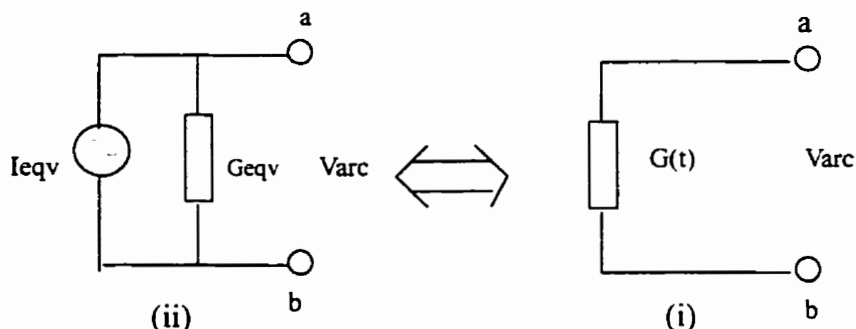


Fig 3.2 The Equivalent Model for Non linear Arc

controlling the current source I_{eqv} , we can efficiently change the value of the arc conductance. The two circuits are equivalent because the conductance seen from

the terminal a and b are the same. This reduces huge calculation to invert the [Y] matrix. The current source can be calculated by the equation show below:

$$I_{eqv}(t) = V_{arc}(t-\Delta t) [G_{eqv} - G] \quad (3.2) \quad \text{where } G \text{ is defined by (2.7)}$$

We refer to the current I_{eqv} as "correction current", G_{eqv} is initially set at 20 S, which is a suitably small impedance (this value can be set up according to the real situation); $t-\Delta t$ refers to last time step.

$$\begin{aligned} G_{eqv} &= G && \text{(if } I_{eqv} > \text{Threshold Value)} \\ G_{eqv} &= 0 && \text{otherwise} \end{aligned} \quad (3.3)$$

The correction current is set up to be less than a threshold value, which is a certain percentage of the peak current passing through the switch before its opening. If the correction current is larger than this threshold value, let G_{eqv} equal to G at that particular time, this avoids changing I_{eqv} every time and saves the computing time. The calculation is based on the previous value. Every time the current passes across zero, we assume that arc extinguishes. Starting from that time, at every time step, a value of restriking voltage is calculated and there is no calculation of arc conductance G and G_{eqv} is set to a very small number, i.e., the arc is not conducting, this situation is kept until voltage across the arc is larger

than the critical restriking voltage; if this happens, calculation of arc conductance is resumed, if not; the arc is extinguished finally.

To calculate the new value of arc conductance G based on the solution of the differential equation (2.7), we use a method based on the Trapezoidal Method of Integration.

From (2.7) $\frac{dG}{dt} = \frac{1}{T}(G_0 - G)$ we have the following two equations:

$$\frac{dG}{dt} = \frac{G(t) - G(t-\Delta t)}{\Delta t} \quad (3.4)$$

$$\frac{dG}{dt} = \frac{\left[\frac{1}{T} \cdot (G_0 - G(t)) + \frac{1}{T} \cdot (G_0 - G(t-\Delta t)) \right]}{2} \quad (3.5)$$

$$\text{From (3.4) (3.5)} \quad \frac{G(t) - G(t-\Delta t)}{\Delta t} = \frac{1}{2T} (G_0 - G(t) + G_0 - G(t-\Delta t)) \quad (3.6)$$

$$\text{Then} \quad G(t) = G(t-\Delta t) \cdot \frac{2T-\Delta t}{2T+\Delta t} + G_0 \cdot \frac{2\Delta t}{2T+\Delta t} \quad (3.7)$$

$$G_0 = \frac{|i|}{V_0 L(t)} \quad T \text{ is defined in (2.8)} \quad \Delta t \text{ is the time step}$$

3.3 THE AIR SWITCH MODEL IN PSCAD/EMTDC

The arc model of the air switch has been created in the PSCAD/EMTDC as a user-defined model and can be loaded through the library. In the Draft module as shown in Fig 3.3:

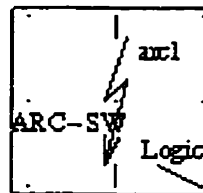


Fig 3.3 Arc Model in EMTDC

Fig 3.4 shows the parameters to be determined for the arc model such as the initial arc length and peak value of current passing through the switch before its opening.

Arcl	Initial arc Length		m
Iarc	Peak value of current		kA
Name	Arc Name	arcl	
GA	arc conductance	garc	1/ohm
PlotI	Plot Arc Current in Run Time	<input type="checkbox"/> No	<input type="checkbox"/> Yes
MonI	Measure Arc Current	<input type="checkbox"/> No	<input type="checkbox"/> Yes
?	PROCEED	CANCEL	

Fig 3.4 The Input Parameters in the Arc Model

The time fault logic module can be used to set the opening time of switch operation and the controlling signal can be transmitted through the node definition as shown in Fig 3.5:

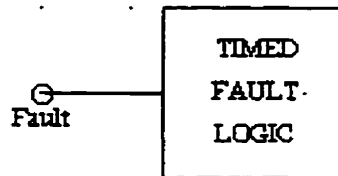


Fig 3.5 The Time Logic Control

The node is defined as Fault and can be connected with the arc model of the air switch to set up the opening time and the fault time duration. The parameters in the time logic control module are shown in Fig 3.6:

TF	Time to Apply Fault	0.2	sec
DF	Duration of Fault	10.0	sec
REP	Repeat?	<input type="checkbox"/> No	<input type="checkbox"/> Yes
?	PROCEED	CANCEL	

Fig 3.6 The Parameters of Time Logic Control

As shown above, the air switch will be opened at time 0.2 second and the calculation could last as long as 10 seconds. After completion of draft mod-

ule, the compiler will be used to combine this model with other system components and create a executable code for simulation.

3.4 THE SIMULATION FOR OPENING OF THE AIR SWITCH

To focus on the arc behaviour of the air switch during the opening operation, only the single-phase air switch is considered and the further practical studies for three-phase air switches can base on it. The basic configuration for the simulation should include the switch, the impedance in series with the switch $Z1$ and the impedance in parallel with the switch $Z2$, and the external electrical systems as shown in Fig 3.7:

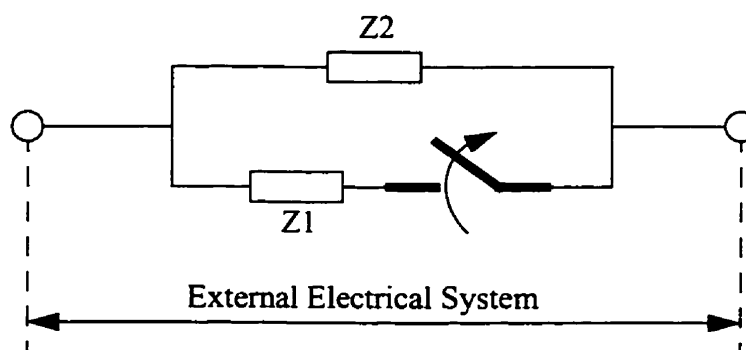


Fig 3.7 The Basic Composition

Z1 and Z2 play important roles in determining the arc behaviour as they are the internal factors that affects the opening operation. The external electrical systems affect the voltage across the switch, current passing through the switch and the phase difference between the voltage and current.

Based on the above assumption, the testing circuit was created to do the simulation as shown in Fig 3.8:

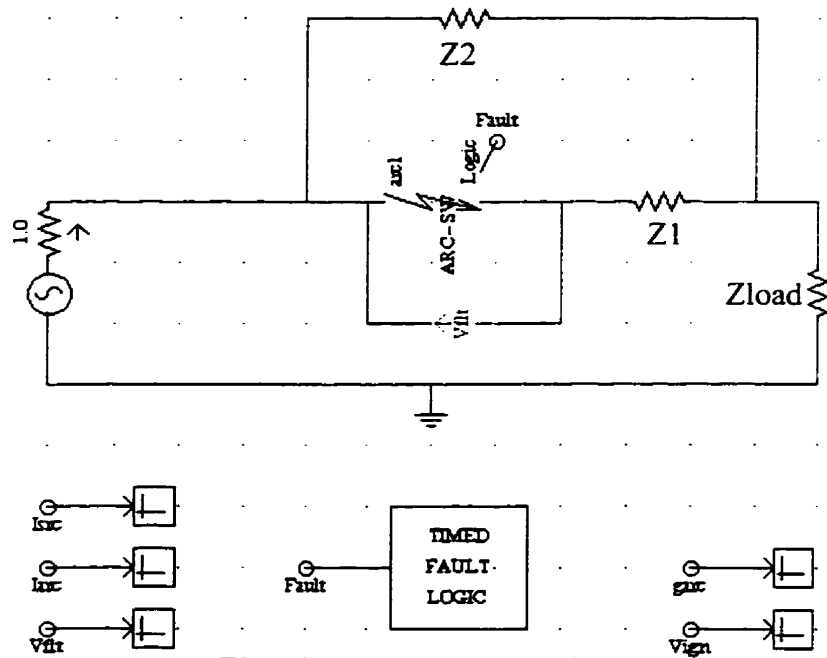


Fig 3.8 The Testing Circuit

The source and load sides can be modelled using standard component library of PSCAD/EMTDC. Quantities to be plotted can be selected using the output channel component.

In Fig 3.9, the definition of the parameters are:

I_{src} ----- the current source

V_{flt} ----- the voltage across the switch during the opening and arcing

I_{arc} ----- the current passing through the air-switch during the opening and arcing

g_{arc} ----- the conductance of the arc

V_{ign} ---- the critical ignition voltage across the switch as shown in Fig 2.4

3.5 THE CASE STUDY

Loop switching will be successful when the impedance of the arc across the opening switch contacts becomes greater than the impedance of the

loop around the switch. The success of any loop switching can be determined by knowing the current flowing through the switch to be opened and the impedance of the loop. This is called Loop Impedance guideline [11].

According to Andrew [4], there exists the so called "arc reach", which is the distance from a point midway between the arc extremities to the most remote point of the arc at the time of its maximum length. It can be calculated (approximately) as:

$$ArcReach = 0.0165 \frac{I^2 Z}{1000} \quad \text{when current is below 100 amps (3.8)}$$

$$ArcReach = 1.65 \frac{IZ}{1000} \quad \text{when current is above 100 amps (3.9)}$$

where I is the loop current passing through the switch, Z is the impedance of the loop path.

To determine the maximum current to be interrupted in a loop, the arc reach should be no more than 56.8% of the phase spacing, see equations (3.8) and (3.9). The following formula now applies for current above 100 amps [11]:

$$SwitchPhaseSpacing \times 0.568 = 1.65 \frac{IZ}{1000} \quad (3.10)$$

$$\text{SwitchPhaseSpacing} \times 0.568 = 0.0165 I^2 \frac{Z}{1000} \quad (3.11)$$

This is the basis of the loop impedance method.

A loop impedance table can be derived and used to predict the success of loop current interruption when the length of the parallel loop and the current through the switch are known.

In the sections below, we check whether this guideline yields comparable to those obtained from a detailed EMTDC simulation.

A case study (115 kV system) from Manitoba Hydro is presented as shown in Fig 3.9:

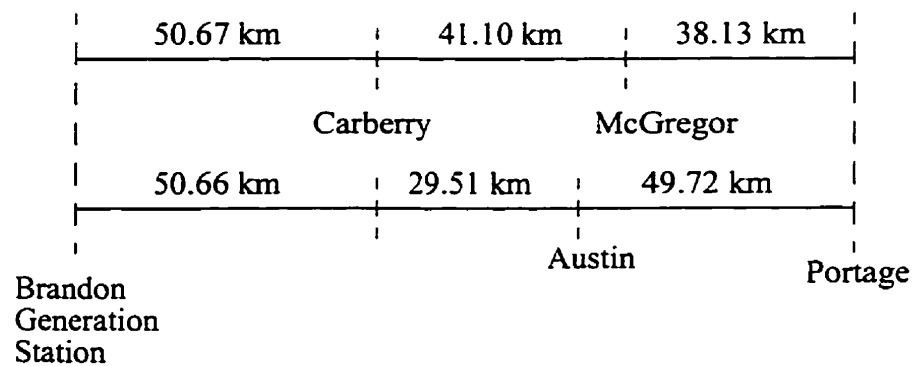


Fig 3.9 115kV system

According to the Loop Impedance method, the maximum loop current that can be interrupted (I_{sw}) is about 53 amps at the Portage station. We will use the arc model of the air switch to verify it.

First we set the current to be interrupted at 53 amps and create the equivalent circuit as shown in Fig 3.10, where

$$Z_1 = (50.76 + 41.10 + 38.13) \times 0.004 \times \frac{115^2}{S_B} \text{ ohm} \quad (3.12)$$

$$Z_2 = (50.66 + 29.51 + 49.72) \times 0.004 \times \frac{115^2}{S_B} \text{ ohm} \quad (3.13)$$

The impedance per km for 115 Kv transmission line is 0.4%, (100 MVA base MVA level). The resistance is ignored. Since the current passing through the switch is 53 amps, the load impedance can be derived (assuming that the load power factor to be 0.80). The load is composed of a resistor and an inductor at the value of 501.096 ohm and 0.997 H respectively.

The equivalent circuit is shown in Fig 3.10:

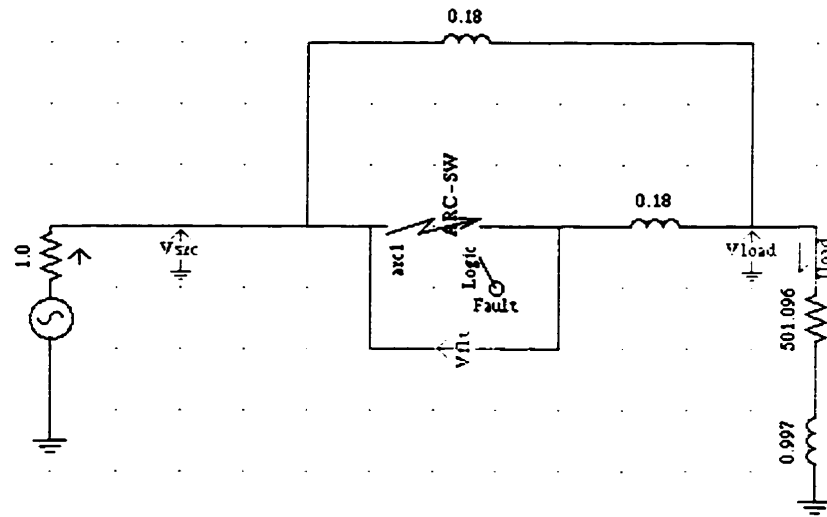


Fig 3.10 The Equivalent Circuit

The simulation results are shown in Fig 3.11

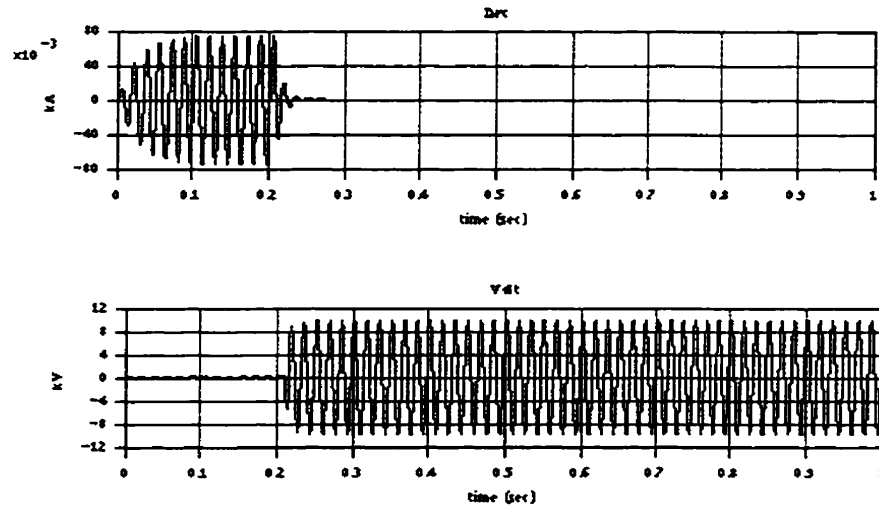


Fig 3.11 The Simulation Results ($I_{sw}=53A$)

When the switch is opened at $t = 0.2$ sec, the arc can last for less than 3 cycles, during that short time, the arc can not enlarge to create damage to the other electrical components, we can say this is a successful opening operation.

If the current to be interrupted at Portage station is 80 amps (I_{sw}), then the corresponding load is composed of resistor $R = 331.976$ ohm and inductor $L = 0.66$ H, the simulation results are shown in Fig 3.12 .

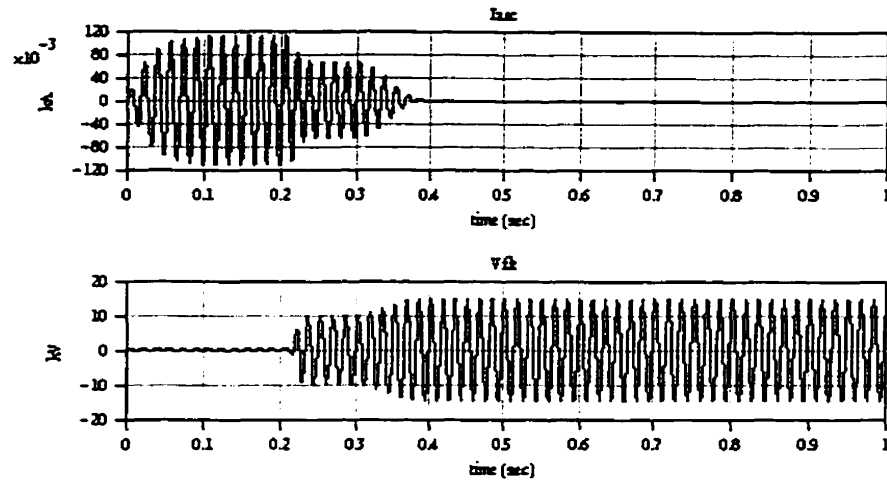


Fig 3.12 The Simulation Results ($I_{sw} = 80 \text{ A}$)

Note: This corresponds to an arc length of $1.96L_0$ from Equ. (2.11).

We can see that the arc will last about 196 ms, the arc length will increase, the enlarged arc may cause short circuits with other electrical components and even make it dangerous for the operation staff to open the disconnect manually on site.

I_{arc} is the switch current passing through switch. When the switch is closed before $t = 0.2 \text{ s}$, the current is regarded as a small resistor, (in our case

0.05 Ω). After 0.2 sec, because the arc resistance is increasing, the magnitude of switch current will decrease.

The switch voltage V_{ft} refers to the voltage across the switch. It is compared with the critical voltage to determine whether the arc will reignite or not. If V_{ft} is never greater than the critical voltage, the arc will be extinguished successfully, if the extinction time is within the reasonable range, the arc will not create the transient damages to other electric components and system operation, this opening of the switch can again be considered.

After the switch is opened, the magnitude of switch voltage will keep increasing as the arc resistance becomes greater. After the arc is finally extinguished, the switch voltage will reach a new stable state level which is determined by the steady state of the power system.

After comparing the simulation results with the oscillosgram of loop current interruption test which was done by Andrew [4], we found that the simulation results show good agreement: the waveshape for the switch voltage and current in both Andrew's test and our simulation are similar, which indicates the following:

During the opening operation, the arc current is keep decreasing while the arc voltage increasing, the arc model does reflect the electrical behaviour of the arc on the air switch. Therefore, the electric arc can be regarded as a dynamic electrical component to be incorporated into the EMTDC simulation program.

Now let us see the arc conductance shown on the following diagram

Fig 3.13 . (In the case of interrupting the 80 amps current)

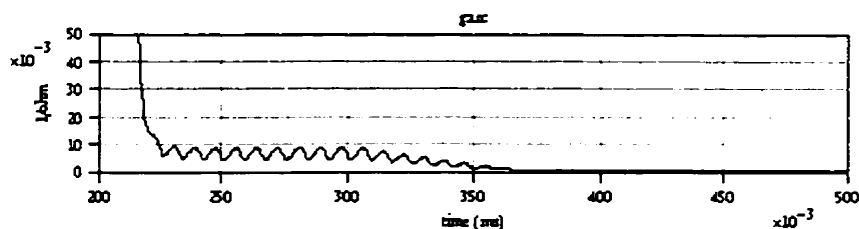


Fig. 3.13 Arc Conductance

The switch is opened at the time of 200 ms, we assume that the air switch resistance is 0.05 ohm in normal condition when it is closed.

In Fig 3.13, the arc conductance g_{arc} is varying with the time, before the opening operation, it is treated as a little resistor (0.05 ohm); from $t=230$ ms to $t=300$ ms, the arc conductance shows a periodical steady state behaviour since the

arc length doesn't change; after $t=300$ ms, it decreases with a periodical ripple; when the arc conductance reaches zero, the current passing through the switch will be zero, the arc is finally extinguished.

3.6 THE EFFECTS OF LOAD POWER FACTOR AND LOAD COMPOSITION UPON THE ARC

From the electrical aspects, the magnitude of voltage and current and the phase angle difference between them are the other factors affecting the behaviour of the electric arc. The loop impedances both in series and parallel with the switch and the load ought to influence the electric arc behaviour in terms of the voltage and current amplitude and their phase differences. We'll use the same case from Manitoba Hydro to verify this point.

The peak current passing through the switch before opening is the input parameter of the arc model. It is defined that the loads are equivalent provided that the peak currents passing through the switch before its opening are the same.

3.6.1 The Load Composition

Assume that we need to interrupt the 85 amps current.

The equivalent load and initial voltage source magnitude are:

When load is purely resistive, the result is shown in Fig 3.14

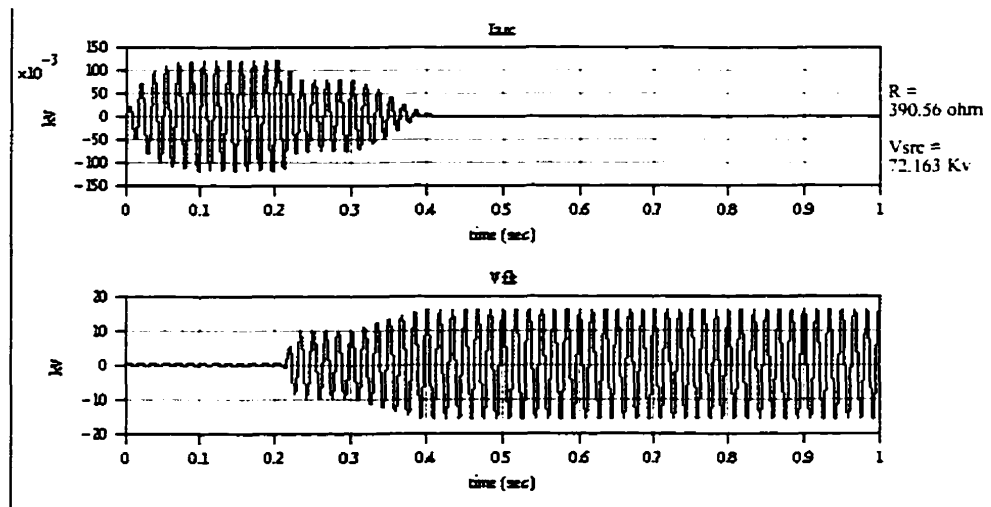


Fig 3.14 The Simulation Results (Pure Resistive)

When the load is purely inductive, the result is shown in Fig 3.15

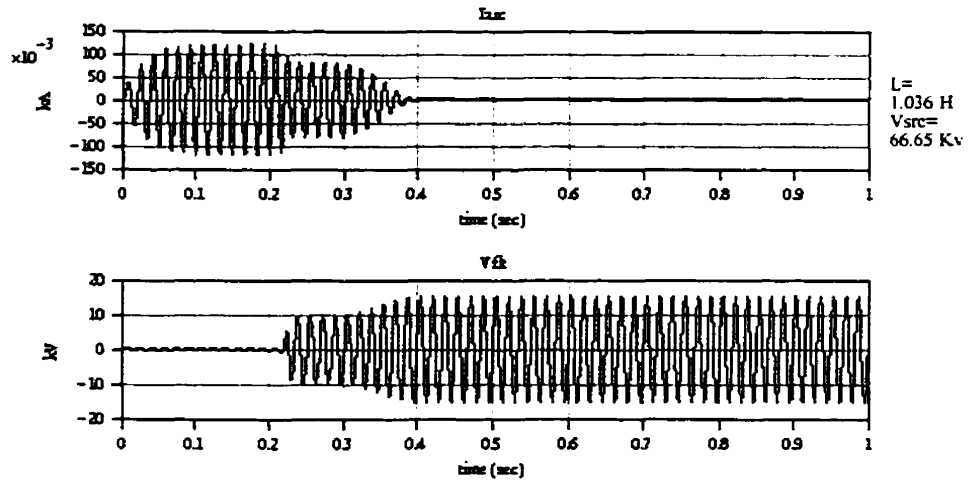


Fig 3.15 The Simulation Results (Pure Inductive)

when load is purely capacitive, the result is shown in Fig 3.16

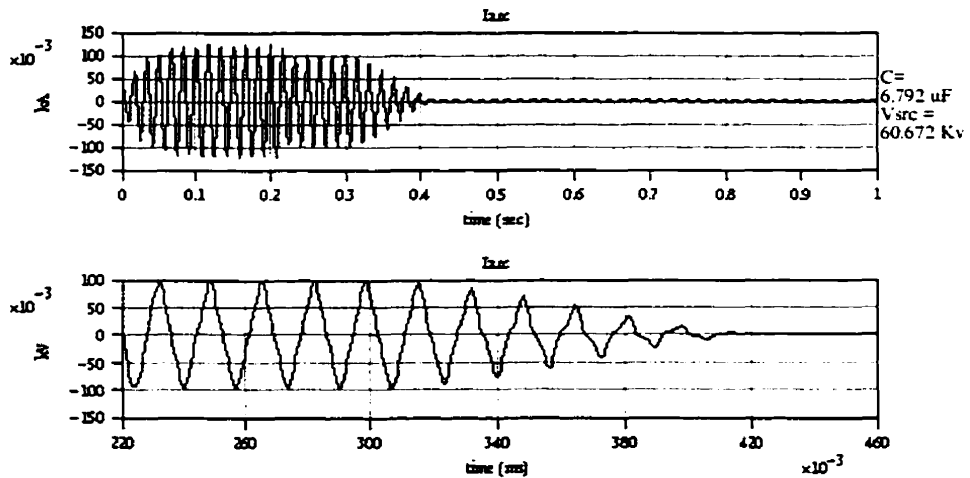


Fig 3.16 The Simulation Results (Pure Capacitive)

The results show that there is little difference in terms of arc extinction time for the resistive, inductive and capacitive load, in all cases, the extinction time is about 200 ms. Specifically, the arcing extinction time for capacitive load is marginally longer, i.e., 210 ms.

The above results are in consistency with that test conclusions drawn by F. E. Andrew [4], which further proves the validity of the arc model.

3.6.2. *The Load Power Factor*

Let us set the power factor at 0.6, 0.7 and 0.8 to see its affects upon the arc behaviour when interrupting the larger current at 85 A. (Assume the load is composed of either resistor R and inductor L)

When power factor is 0.8, $R = 312.448 \text{ ohm}$ $L = 0.622 \text{ H}$

$V_{\text{src}} = 70.008 \text{ kV}$, the result is shown in Fig 3.17:

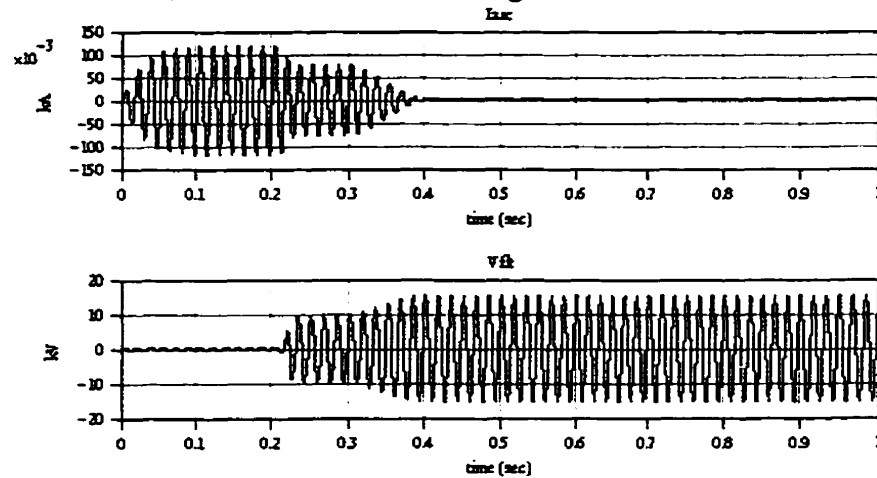


Fig 3.17 The Simulation Results (power factor at 0.8)

When the power factor equals to 0.6, $R = 234.336 \text{ ohm}$ $L = 0.829 \text{ H}$

$V_{\text{src}} = 71.094 \text{ kV}$, the result is shown in shown in Fig 3.18

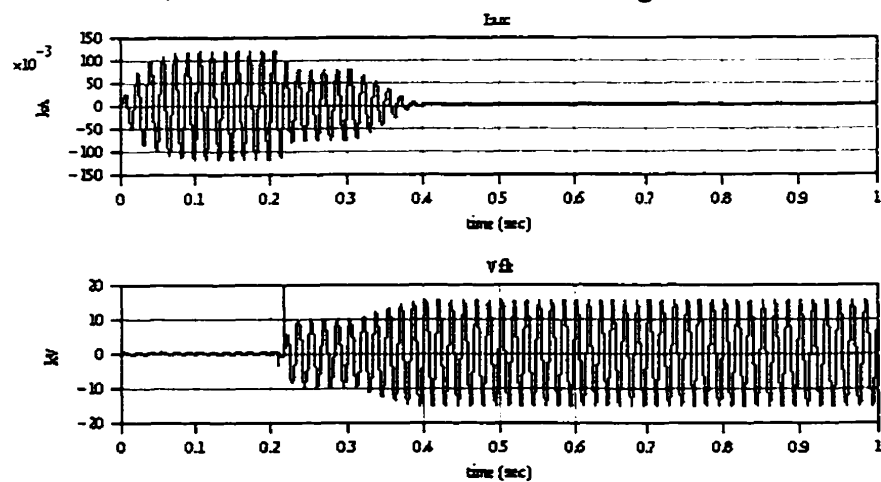


Fig 3.18 The Simulation Results (power factor at 0.6)

Now set power factor at 0.4, $R = 156.224 \text{ ohm}$ $L = 0.95 \text{ H}$

$V_{\text{src}} = 71.719 \text{ kV}$, the results are shown in Fig 3.19:

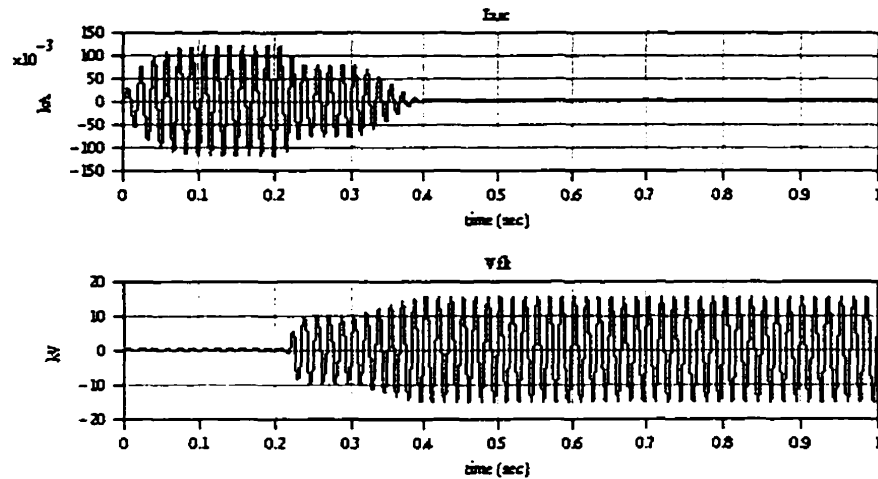


Fig 3.19 The Simulation Results (power factor at 0.4)

In the above simulation, the extinction time is near 200 ms, which indicates the power factor doesn't play a significant role in the extinction of arc.

F. E. Andrew [4] also found that there are no differences with variation of circuit power factor in the loop current interruption tests.

3.7 THE SIMULATION OF ARC UNDER HIGH CURRENT

In the case of interruption of very high current, it can be considered as an extreme case study for the arc model. In that case, there is the possibility of the air breakdown as discussed in Chapter 2. The arc is regarded as a non-linear resistance too. However the arc has no restriking. It tends to keep conducting through the arc path under this high current, which makes the arc extinction impossible.

The model [15] described in Chapter 2 has been incorporated into EMTDC. Using the case from Manitoba Hydro again, this time, set the current to be interrupted is 1kA, then load consists of $R = 26.558$ ohm and $L = 0.053$ H, and $V_{src} = 120.082$ kV. (open at time of 0.2 sec)

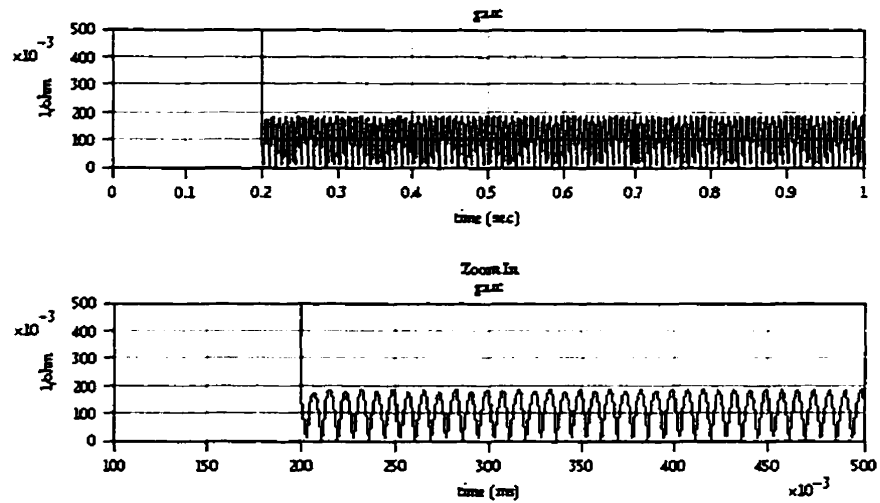


Fig 3.20 Arc Conductance Under High Current

The arc conductance oscillates periodically without decreasing as shown in Fig 3.20.

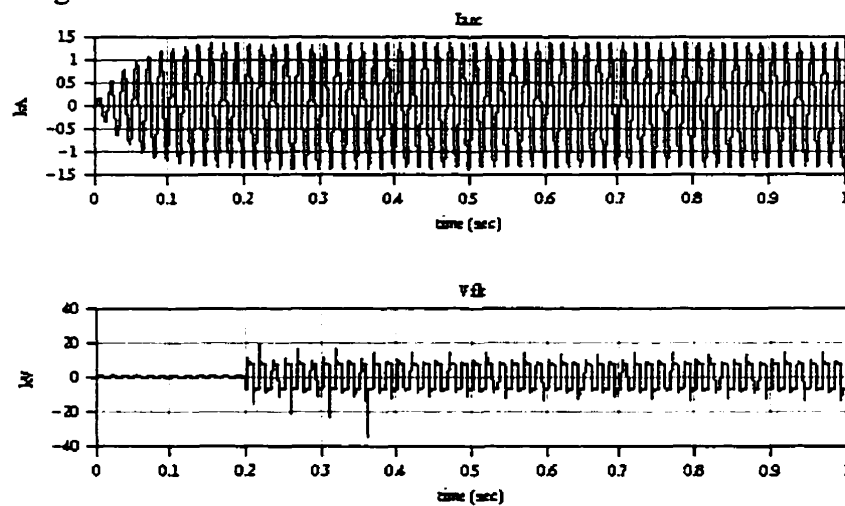


Fig 3.21 The Simulation Results Under High Current

Both switch current and switch voltage show periodical steady state as shown in Fig 3.21.

The simulation reflects that the arc under the high current tends to last for a longer time, perhaps infinitely, which is absolutely not tolerable in system operation. Although the arc length will not enlarge significantly compared with that under low current, the long lasting time of the arc may cause the other switches or breakers to be opened by the control signals coming from the relay protection system.

Note: In the above high-current arc model, the primary arc model has been used.

Guidelines for Loop Switching

4.1 INTRODUCTION

This chapter will investigate guidelines for loop switching, which can be used to determine whether the opening is going to be successful or not. There were many unsuccessful attempts of loop switching operation based on the existing guidelines. The existing guidelines are not based on accurate mathematical models to describe the arc behavior, instead, most of them are empirical methods. The arc model of the air switch developed in this thesis can take the advantage of the accuracy of the transient analysis tool PSCAD/EMTDC so as to evaluate the efficacy of present guidelines and propose some improvements on them.

4.2 EVALUATION OF THE PRESENT GUIDELINE

The same case from Manitoba Hydro will be used to evaluate the efficacy one of present guidelines for loop switching (Loop Impedance Method) , i.e., opening disconnects in a looped network.

According to Loop Impedance guideline [11], switching will be successful in switching loop currents when the impedance of the arc across the opening switch contacts becomes greater than the impedance of the loop around the switch. The success of any loop switching can be determined by knowing the current flowing through the switch to be opened and the impedance of the loop. Once the loop impedance is known and the flow through the switch is determined, loop switching will be successful providing the current through the switch equal to or less than the maximum current which can check from a table.

To determine the success of loop switching, a summation of the loop impedance, on a 100 MVA base, around the switch is calculated using the following constants:

24 kV lines ----- 8.5% per kilometre

33 kV lines ----- 5.3% per kilometre

66 kV lines ----- 1.2% per kilometre

115 kV lines ----- 0.4% per kilometre

For this case, the total impedance is 103.92%, which is corresponding to maximum current to be interrupted at the value of 53 amps.

As shown in chapter 3, the summation of the loop impedance is not the only factor to determine the success of loop switching. In this chapter, we will find that the loop impedance distribution also affects the switch opening too.

a) When $Z_1 = 0.18 \text{ H}$ $Z_2 = 0.18 \text{ H}$ $R = 501.096 \text{ ohm}$, $L = 0.997 \text{ H}$ $V_{\text{src}} = 68.614 \text{ kV}$ (Chapter 3), it takes nearly 100 ms to extinguish the arc, The arc length will not enlarge within 100 ms from the time the switch is opened [7]. In other words, the arc length will remain the same as the initial length. The opening could be regarded as a successful one if the arc can be extinguished in 100 ms from the time the switching is opened such that the arc length is not be able to be enlarged. The results are shown in Fig 4.1, it shows that the arc length remains the same length as the initial arc.

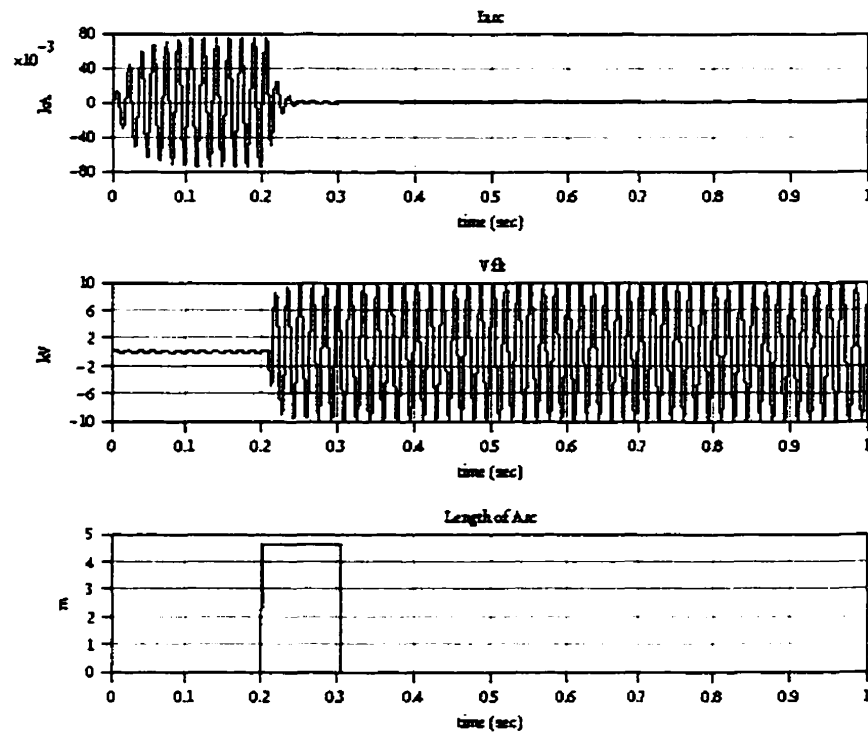
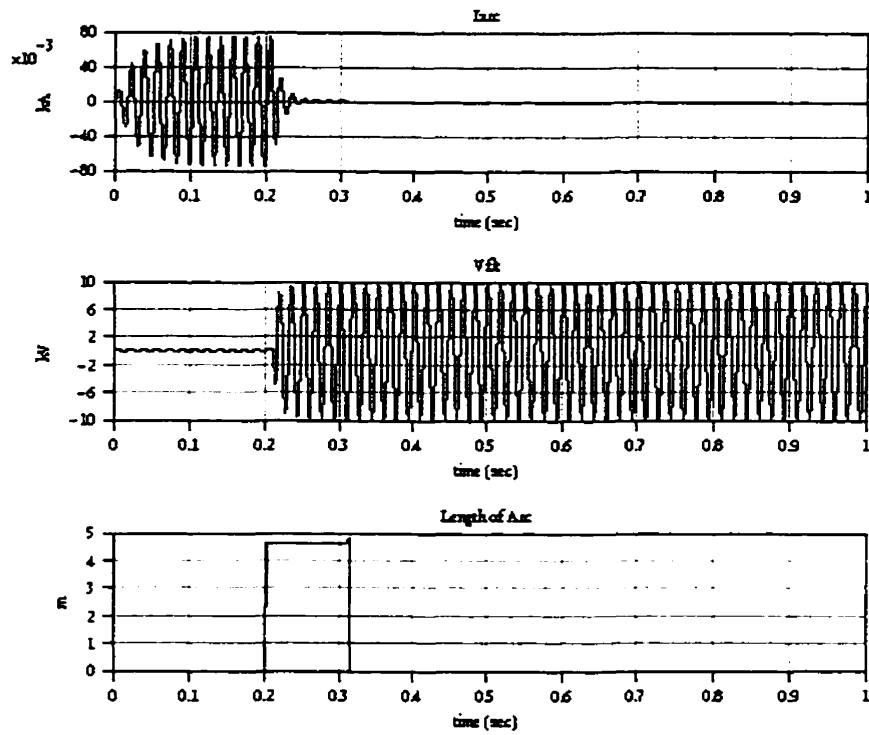


Fig 4.1 The Simulation Results ($Z_1=Z_2=0.18H$)

b) Now set $Z_1 = 0.26 H$ $Z_2 = 0.10 H$ $R = 278.387 \text{ ohm}$ $L = 0.554 H$
 $V_{src} = 669.636 \text{ kV}$, then it takes 105 ms to extinguish the arc, where the arcing time exceeds 100 ms, the arc will enlarge to nearly 5 meters from the initial arc length as the arc length will increase linearly with time. The arc reach will enlarge too. The opening may be an unsuccessful operation. The results are shown in Fig 4.2 .

Fig 4.2 The Simulation Results ($Z1 > Z2$)

c) When $Z1 = 0.10$ H $Z2 = 0.26$ H $R = 723.806$ ohm $L = 1.44$ H
 $V_{src} = 67.613$ kV, it takes 97 ms to extinguish the arc, the situation is almost same
as Case a, the arc length doesn't change either. The results are shown in Fig 4.3 .

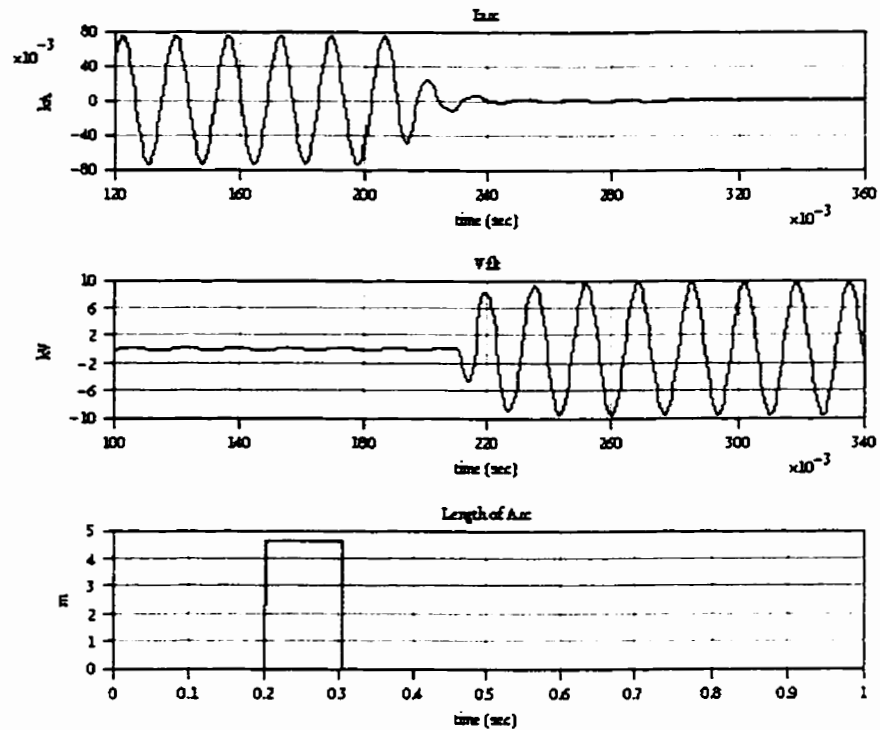


Fig 4.3 The Simulation Results ($Z_1 < Z_2$)

The above simulation indicates that the loop impedance distribution along the switch loop is another important factor which should be taken into consideration for the guideline of loop switching. Because during the 100 ms after the switch opening, the arc length will remain the same as the initial arc length [7], we define that 100 ms is the maximum arc extinction time. Case a) and Case c) will be successful openings while b) will be an unsuccessful one. Note that all the

three cases have the same loop impedance summation of 0.36 H, but the simulation results are marginally different.

The detailed simulation results show that the loop impedance criterion is generally valid. Only minor differences are observed with the more detailed simulation.

4.3 ARC LENGTH CRITERIA

Another factor is the arc length since arc enlarging may create short circuit to other electrical components, which is very dangerous to the operating staff at the site. The arc length can be set as the supplementary criteria to predict the success of loop switching.

In the paper “Self-extinction of arcs created in long air gaps” [7], Anjo measured the increase in arc lengths as a function of time, according to his work, the arc length will remain at the initial arc length during the 100 ms from the time of opening the switch, then increase linearly with time.

Comparing with the phase spacing, the arc length must be restricted below a certain value. For the case of interrupt 60 amps current, the arc length is shown in Fig 4.4

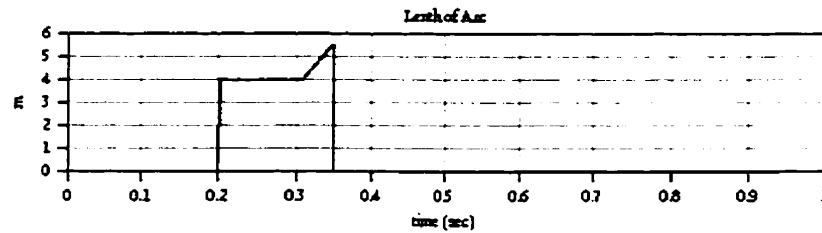


Fig 4.4 Arc Length (Open at t = 0.2 s)

In the above diagram, the arc length will increase linearly as a function of time after 0.3 second then it will terminate at the length of 5.5 meters.

It is possible to figure out the maximum arc length criterion for the specific switch in a particular switch station such that the enlarging arc will not damage other contacts and create the safety problems for the operating staff.

The initial arc length is an input parameter in our model.

Because of the lack of available references, it is derived from the following data:

For the 115 kV switch used in the case study:

Design phase spacing : 10 feet

Horizontal distance between switch contacts : 60 inches

Opening angle : 97 degree from horizontal

The distance of the two terminals of the initial arc would be the hypotenuse of a triangle with a horizontal dimension of 60 inches and a second side, at an angle of 97 degree with a length of 67 inches. This distance is 2.4189 meters. The arc will be created along a curve along this line between the two contacts after the switch is opened. We can set a modification coefficient to roughly estimate the initial arc length. The initial arc length is set at the length of 4.65 meters in our simulation.

The initial arc length is determined by the physical dimension of the switch and also by the voltage level of the system. The smaller the initial arc length, the more difficult to open the circuit.

4.4 IMPROVEMENTS OF THE GUIDELINES

Based on the case study, we have carried out the following simulation hoping to make some improvements on the present guidelines. The variable and parameters are: Z_1 is the impedance in series with the switch, Z_2 is the impedance in parallel with the switch, V_{src} (kV) is the initial line to ground voltage (rms value) of the source, the load is assumed to be composed of resistor R (ohm) and inductor L (Henry), I_{sw} (A) is the switch current to be interrupted and V_{sw} (kV) is the voltage across the switch (line to ground rms value), L_{arc} (meter) is the length of the arc and T_{arc} (ms) is the arc extinction time and the load power factor is 0.8.

In the following simulation, Case a/b/c don't consider the resistance along the path in the loop, while Case d/e/f consider it.

Case a) Changing I_{sw} to find out its influence upon the switch operation, where $Z_1 = Z_2 = 0.18$ H, the simulation results are shown in table 4.1 .

Vsrc	Isw	R	L	Vsw	Larc	Tarc
67.847	35	758.803	1.51	6.572	4.65	21
68.059	40	663.953	1.321	7.487	4.65	32
68.271	45	590.18	1.174	8.396	4.65	48
68.485	50	531.162	1.057	9.299	4.65	57
68.7	52	510.773	1.016	9.659	4.65	73
68.915	53	501.096	0.997	9.838	4.65	98
68.132	55	482.875	0.961	10.196	5.35	115
69.35	56	474.252	0.943	10.375	5.72	123
68.829	58	457.859	0.911	10.732	6.10	132
68.915	60	442.635	0.881	11.088	6.50	140
69.132	65	408.586	0.813	11.973	7.67	165
69.35	70	379.402	0.755	12.852	8.0	173

Table 4.1 The Results Summary for Case a

Case b) $Z1 = 0.26 H$, $Z2 = 0.10 H$, changing Isw, we have the following simulation results as shown in Table 4.2 .

Vsrc	Isw	R	L	Vsw	Larc	Tarc
68.509	35	421.557	0.839	6.636	4.65	23
68.819	40	368.863	0.734	7.571	4.65	34
69.132	45	327.878	0.652	8.502	4.65	60
69.447	50	295.09	0.587	9.43	4.65	81
69.573	52	283.741	0.564	9.8	4.65	97
69.636	53	278.387	0.554	9.958	4.88	105
69.763	55	268.264	0.534	10.354	5.40	116
69.827	56	263.473	0.524	10.539	5.77	124
69.954	58	254.388	0.506	10.907	6.50	140
70.082	60	245.908	0.489	11.275	6.88	148
70.403	65	226.992	0.452	12.193	7.30	157
70.725	70	210.779	0.419	13.107	8.00	173

Table 4.2 The Results Summary for Case b

Case c) $Z1 = 0.10 H$, $Z2 = 0.26 H$, changing Isw we have the following simulation results as shown in Table 4.3 .

Vsrc	Isw	R	L	Vsw	Larc	Tarc
67.195	35	1096	2.182	6.509	4.65	29
67.311	40	959.043	1.908	7.405	4.65	31
67.427	45	852.483	1.696	8.292	4.65	41
67.543	50	767.234	1.526	9.171	4.65	73
67.59	52	737.725	1.468	9.521	4.65	82
67.613	53	723.806	1.44	9.695	4.65	97
67.66	55	697.486	1.388	10.042	5.02	108
67.683	56	685.031	1.363	10.215	5.35	115
67.73	58	661.409	1.316	10.56	6.14	132
67.78	60	639.362	1.272	10.904	6.46	139
67.894	65	590.18	1.174	11.758	7.30	157
68.011	70	548.025	1.09	12.604	7.67	165

Table 4.3 The Results Summary for Case c

The following cases consider resistance along the loop as well and the inductance is 10 times of the resistance in that path.

Case d) $Z1 = Z2 = 0.18H$, the correspondent resistance R1 and R2 all equal to 6.86 ohm, the simulation results are shown in Table 4.4 .

Vsrc	Isw	R	L	Vsw	Larc	Tarc
68.033	35	758.803	1.51	6.588	4.65	19
68.271	40	663.953	1.321	7.503	4.65	22
68.509	45	590.18	1.174	8.412	4.65	37
68.784	50	767.234	1.526	9.314	4.65	72
68.844	52	737.725	1.468	9.673	4.65	97
668.892	53	723.806	1.44	9.852	4.65	98
68.988	55	697.486	1.388	10.21	5.39	116
69.037	56	685.031	1.363	10.388	5.77	124
69.898	58	661.409	1.316	10.745	6.09	131
67.23	60	639.362	1.272	11.1	6.42	138

Table 4.4 The Results Summary for Case d (considering resistance)

Case e) $Z1 = 0.26H$, $Z2 = 0.10 H$, $R1 = 9.802 \text{ ohm}$, $R2 = 3.77 \text{ ohm}$,

the simulation results are shown in Table 4.5 .

Vsrc	Isw	R	L	Vsw	Larc	Tarc
68.775	35	421.557	0.839	6.66	4.65	19
69.122	40	368.863	0.734	7.597	4.65	23
69.471	45	327.878	0.652	8.53	4.65	37
69.822	50	295.09	0.587	9.46	4.65	55
69.963	52	283.741	0.564	9.83	4.65	71
70.033	53	278.387	0.554	10.016	4.65	78
70.175	55	268.264	0.534	10.386	5.25	113
70.245	56	263.473	0.524	10.57	5.58	120
70.387	58	254.388	0.506	10.939	6.32	136
70.529	60	245.908	0.489	11.308	6.789	146

Table 4.5 The Results Summary for Case e (considering resistance)

Case f) $Z_1 = 0.10 \text{ H}$ $Z_2 = 0.26 \text{ H}$, $R_1 = 3.77 \text{ ohm}$, $R_2 = 9.802 \text{ ohm}$,
the simulation results are shown in Table 4.6 .

Vsrc	Isw	R	L	Vsw	Larc	Tarc
67.3	35	1096	2.181	6.517	4.65	17
67.43	40	959.403	1.908	7.411	4.65	23
67.561	45	852.483	1.696	8.295	4.65	37
67.691	50	767.234	1.526	9.171	4.65	47
67.744	52	737.725	1.468	9.519	4.65	63
67.77	53	723.806	1.44	9.692	4.65	71
67.823	55	697.486	1.388	10.037	4.65	97
67.849	56	685.031	1.363	10.21	5.39	116
67.901	58	661.409	1.316	10.533	6.14	132
67.954	60	639.362	1.272	10.895	6.46	139

Table 4.6 The Results Summary for Case f (considering resistance)

Now we'll use the above results to validate the present guidelines and give some improvements toward the guidelines for loop switching.

4.4.1 Critical Switch Voltage

Another possible method to predict the success of switching is to use the voltage across the switch (switch voltage) after switch opening.

The steps are:

- a) perform a load flow with the switch to be opened in open position
- b) Record the voltage magnitude and phase across the switch
- c) Predict the success of switching by comparing the resultant voltage across the switch with the critical switch voltage.

Since the switch voltage can be obtained directly through the EMS/SCADA system, the critical switch voltage can be used as a alarm signal before any loop switching operation.

The relationship of switch voltage V_{sw} v.s arc extinction time T_{arc} can be seen in Fig 4.5, where $vsw1$, $vsw2$ and $vsw3$ represent the data files for Case a, Case b, and Case c respectively. (Note: Arcing time refers to the time need to extinguish the arc.)

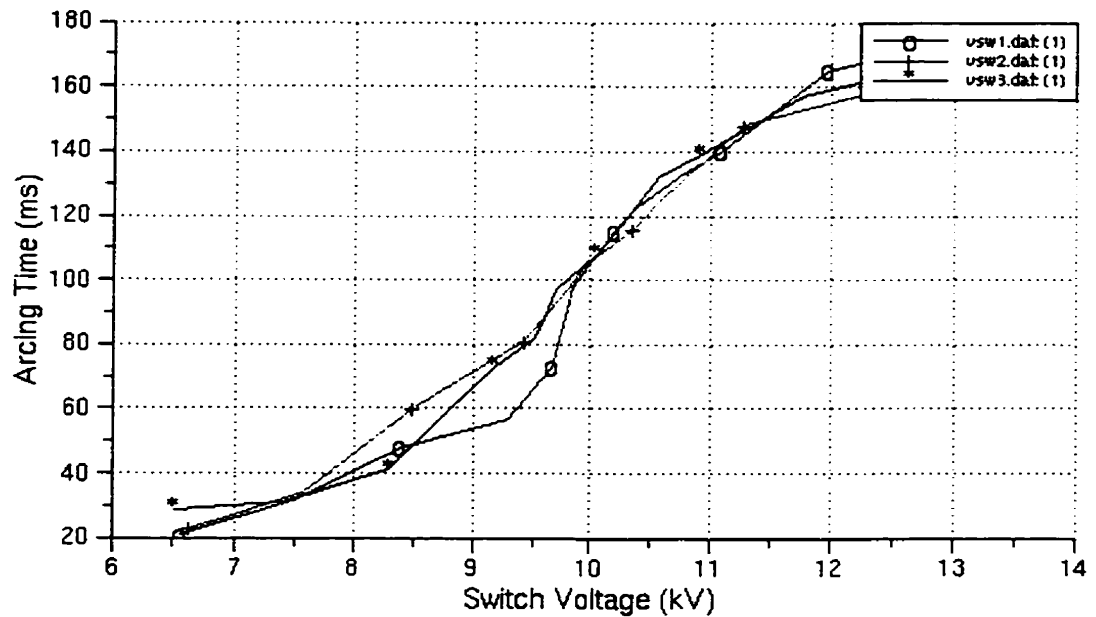


Fig 4.5 The Critical Switch Voltage for Case a/b/c

If the arc can be extinguished in 100 ms from switch opening, there would be no arc enlarging, which can be regarded as a successful interruption, the corresponding switch voltage is the critical switch voltage. From the above diagram, we can implement the loop switching operation when the switch voltage is below 9.8 kV for Case a and Case b, 9.6 kV for Case c. The critical switch voltage for Case a, b and c are little different, it's useful to get the critical switch voltage according to the loop impedance distribution in a certain loop circuit.

When resistance along the path considered as in Case d, e and f, the critical switch voltage seems to be larger than that where resistance hasn't been taken into account (compare Case a) with d), b) with e) and c) with f) .

In Fig 4.6, vsw4, vsw5 and vsw6 represent the data files for Case d, e and f respectively. It shows us that the critical switch voltage for each case is significantly different after considering resistance. This shows that the switch voltage criterion should be used with caution under such circumstances.

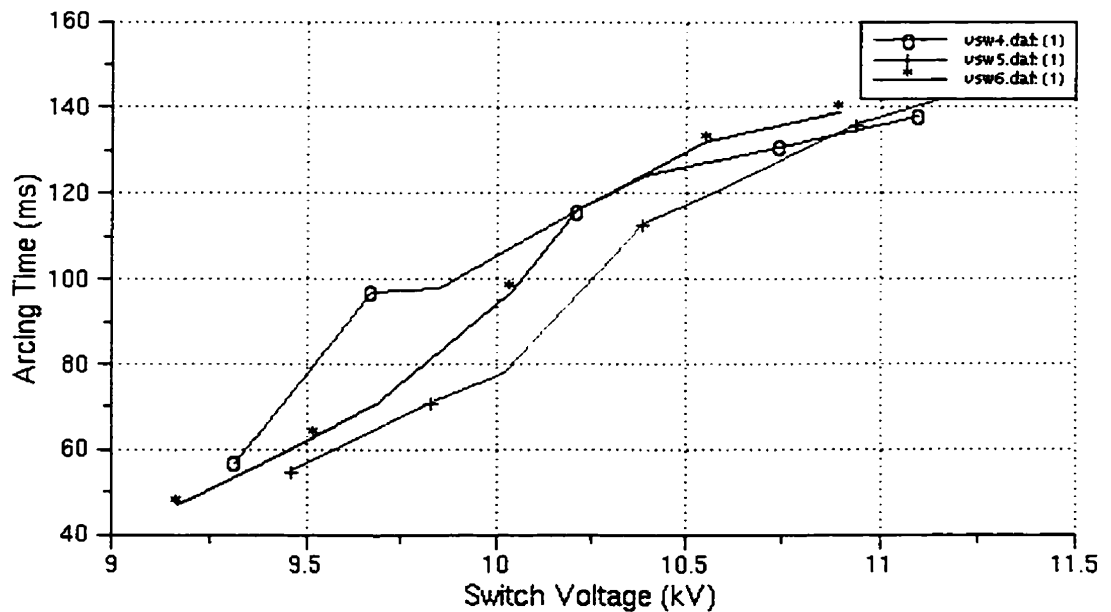


Fig 4.6 The Critical Switch Voltage for Case d/e/f

4.4.2 The Maximum Current to Be Interrupted

Because the current to be interrupted for the next operation mode can be predicted through power flow calculation in advance, we shall use the maximum current that the switch can interrupt based on the above simulation results as another criterion, if the switch current is below that maximum value, the operation is going to be successful.

In Fig 4.7, isw1, isw2 and isw3 refer to the data files for Case a, b and c respectively.

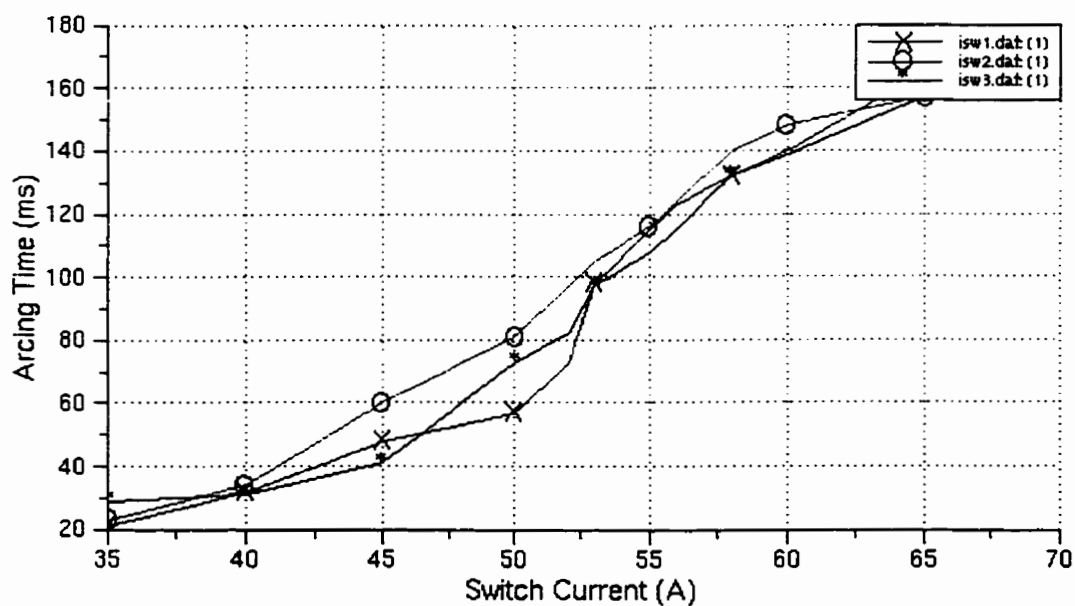


Fig 4.7 The Switch Current for Case a/b/c

The arcing time is especially sensitive to change of the switch current at the range of 50 to 55 amperes when loop impedance is distributed fairly equally. The unequal distribution will reduce this sensitivity. For Case b, the critical switch current is even smaller than that of Case a. So Loop Impedance method is reasonable for near equally distributed loop impedance cases. For those whose impedance is unequally distributed, the loop impedance distribution could be considered for some improved accuracy.

When considering the resistance along the impedance, we have the following result as shown in Fig 4.8 corresponding to the Case d, e and f.

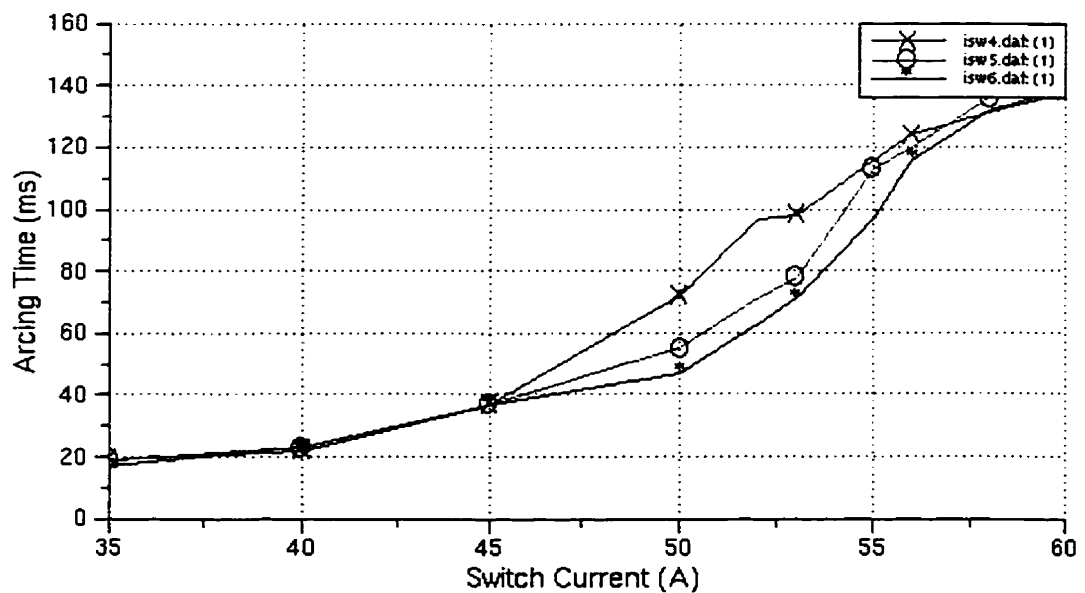


Fig 4.8 The Switch Current For Case d/e/f

From Fig 4.8, when the switch current is less than 45 A or greater than 57 A, the arc behaviour looks nearly the same in all cases. A comparison of Fig 4.7 with Fig 4.8 shows that: the resistance along the path leads to different critical switch current.

A comparison of case a) with case d) shows that the critical switch current are almost the same, the resistance have some influence on the arc behaviour, but after the switch current is greater than the critical switch current, its influence becomes less.

The results of the comparison of Case b) with e) are shown in Fig 4.9, when $I_{sw} < 55$ A, it takes less time to extinguish the arc than Case e. The resistance doesn't has too much influence on arc behaviour when switch current is greater than 55 A. The critical switch current for Case e) is greater than that for Case b).

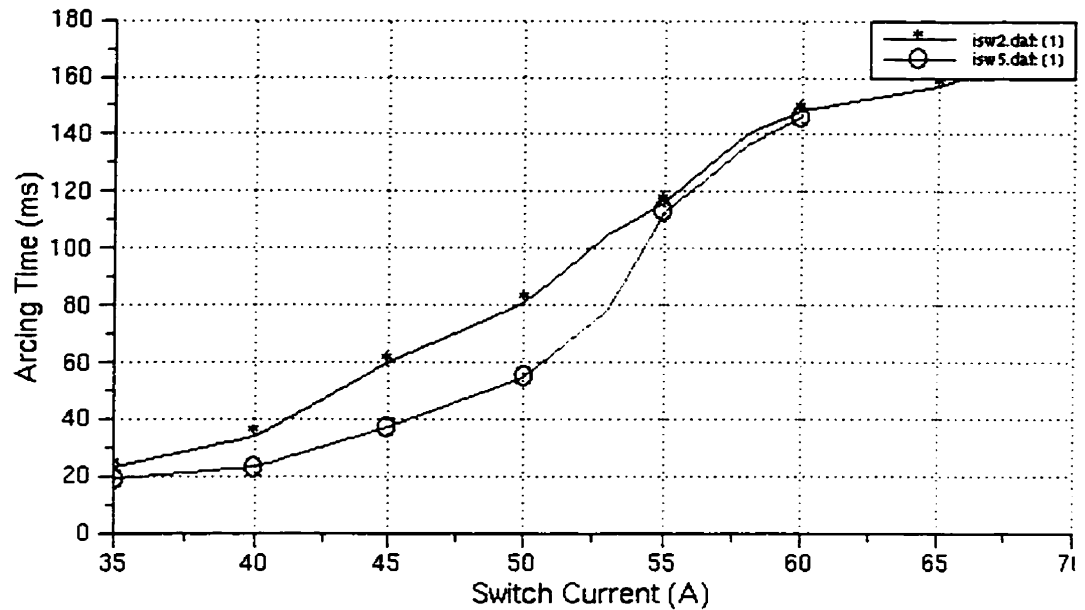


Fig 4.9 The Comparison of Case b vs. Case e

Fig 4.10 shows us that the critical switch current for Case f) is greater than for Case c). The resistance makes the arc behaviour for both cases different before the switch current is less than 57 A. It takes more time to extinguish the arc for Case c) than that for Case f). But after the switch current is over 57 amps, the arc behaviour for both cases are almost the same.

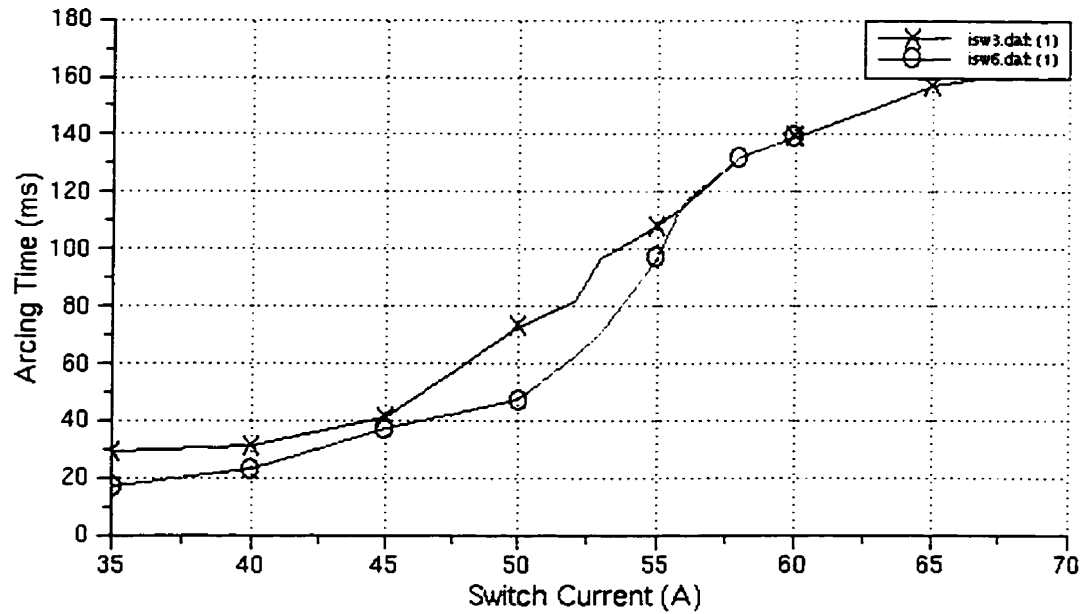


Fig 4.10 The Comparison of Case c vs. Case f

4.4.3 Loop Impedance Distribution and Composition

From the above discussion, we conclude that the loop impedance distribution and composition are two important factors which can be integrated as part of the guidelines for loop switching.

Besides, to predict success of opening switch, it's possible to set the specific critical switch voltage and critical switch current for the switch in a certain circuit.

To roughly predict a successful opening, the present guideline such as Loop Impedance still can be applicable in most cases, but it couldn't be accurate enough in every cases, especially when the impedance configuration and distribution in the loop path are greatly different. On the other hand, the Switch Voltage criterion is somewhat less accurate, particularly when the resistance is considered along the loop path.

The fact that the resistance along the path creates influences upon the loop switching, as discussion in the 4.4.2 suggests us to consider it as the composition factor especially at the initial period of arcing because the resistance has significant impact on the arc behaviour at the initial stage of arcing.

Conclusions

5.1 CONCLUSIONS

The opening of disconnects in a looped networks has been discussed through the arc modelling and simulation in EMTDC/PSCAD to determine the success of an opening operation. The existing guidelines for loop switching have been investigated and the proposed arc model of the air switch gave us some improvements for the guidelines.

The arc behaviour has been studied from the electrical point of view without going through extensive treatment based on physics. The differential-equation mathematical model is used to reflect the experimental voltage-current characteristics of the arc: it is treated as a nonlinear resistor varying with the time. This model is then incorporated into

EMTDC environment to take the advantage of its powerful transient analysis capacity. The empirical guidelines such as loop impedance method are examined through the simulation. An methodology for determining the successful opening of disconnects is presented.

The incorporation of the mathematical model into PSCAD/EMTDC to reflect the arc behaviour of the air switch is possible. The simulation results are consistent with the tests done by Andrew [4]. This validates the model. It was found that the arc behaviour for the same air switch under different operation modes could be different. Loop Impedance method was proved to be valid for most cases. The arc length is suggested as an important parameter for loop switching.

The critical switch voltage and current for a switch under a specific loop switching operation can be obtained through PSCAD/EMTDC simulation. These data can be incorporated with EMS/SCADA systems so that they can be used by operators to predict whether the opening is a successful one or not for a specific switch under a particular operating mode.

In general, the detailed analysis showed that the loop impedance guideline is still reasonably accurate in most cases. Some further improvements could be

accrued with the detailed simulation of the arc model, particularly when the resistance along the loop impedance is considered and the loop impedance is unequally distributed in the loop circuit. It was also seen that the Switch Voltage criterion is less accurate as compared to the Loop Impedance criterion, and it should be used with caution when the resistance along the loop impedance is considered and the loop impedance is unequally distributed in the loop circuit.

5.2 RECOMMENDATIONS FOR FURTHER WORKS

To improve the arc model to develop as a practical criteria, the field tests need to be done to get some experiment data such as the initial arc length, the oscilloscope records for the voltage and current across the switch. This information can be used to modify and upgrade the model to closely reflect the real situation.

The effects of external factors may be examined by the field test and a corresponding criteria or the modification coefficients can be determined. For example, we can examine the wind factor, which has a significant influence on the interrupting capability of the air switch.

Once the arc model is validated, it is possible to incorporate this model and PSCAD/EMTDC into EMS/SCADA. This will give the operator necessary information when determining whether to open a switch or not in a looped network. It's suggested that an interface between PSCAD/EMTDC and EMS/SCADA be created to make this possible.

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```

*****
!
SUBROUTINE arc_tot(SS,I,J,FAULT_LOGIC,L_ARC_INIT,IS,G_ARC,
+      V_IGN,L_ARC_OUT)
!
!      ARC MODEL
!
! Fortran 77  date 20/01/97  ver. 2.0
! This routine uses 9 STOR locations
!
-----
!
! Inputs: SS, I, J  - subsystem and nodes numbers
!      FAULT_LOGIC - fault inception
!              0 - no fault
!              1 - fault
!      BRK      - breaker status
!              0 - close
!              1 - open
!      L_ARC_INIT - the initial length of arc (cm)
!      IP      - the peak value of high current (A)
!              (the value of current when a bolted fault
!              is assumed, before breakers open)
!      IS      - the peak value of low current (A)
!              (the value of current when a bolted fault
!              is assumed, after breakers open)
!
! Output: none
!
-----
!      Variable Declarations
!
-----
INTEGER SS      ! subsystem
INTEGER I      ! node
INTEGER J      ! node
INTEGER FAULT_LOGIC ! fault inception
INTEGER BRK    ! breaker status
REAL  L_ARC_INIT ! initial arc length
REAL  IP      ! peak value of high arc current
REAL  IS      ! peak value of low arc current
!
-----
LOGICAL ZERO_CROS ! is .TRUE. if a current zero has been
! reached and the arc voltage has not
! exceeded reignition voltage
LOGICAL NEW_CAL  ! is .TRUE. when calculation of new value

```

APPENDIX : FORTRAN Code for Air Switch

```

! of g_arc has to be done
INTEGER ITEST ! branch type
REAL GTEST ! branch conductance
REAL ABS ! absolute value function
!
REAL ARC_STATUS ! arc_status: 0 - no arc
! 1 - high current arc
! 2 - low current arc
! 3 - final extinction of arc
REAL V_ARC ! arc voltage
REAL I_ARC ! arc current
REAL I_ARC_PAST ! previous value of arc current
REAL G_ARC ! arc conductance
REAL I_ECS ! current of equivalent current source
REAL G_ECS ! conductance of equivalent current source
REAL I_G_ECS ! current thru conductance of equ. current source
REAL THRESHOLD ! the value which can not be exceeded by the
! current from equivalent current source
REAL THRSHLD_MIN ! minimum value of threshold
!
REAL T ! time constant of arc
REAL I_PEAK ! peak value of arc current
REAL V_GRAD ! voltage gradient of arc
REAL L_ARC ! length of arc taken for calculations
!
REAL VP ! voltage constant per unit length (cm)
! of high current arc
REAL ALPHA ! constant of high current arc
!
REAL VS ! voltage constant per unit length (cm)
! of low current arc
REAL BETA ! constant of low current arc
!
REAL T_PRM_BGN ! time when high current arc is started
REAL T_SEC_BGN ! time when low current arc is started
REAL TR ! time from the initiation of low current arc
REAL TE ! time from the initiation of low current arc
REAL TE ! time from the initiation of low current
! arc to a current zero
REAL V_IGN ! reignition voltage

INTEGER COUNTER !
INTEGER MAX !
REAL FRQ !
REAL L_ARC_OUT !

```

```

REAL L_COR    !
! -----
! ----- Usage of STOR array -----
! -----
! STOR(NEXC+1) - ARC_STATUS
! STOR(NEXC+2) - I_ARC_PAST
! STOR(NEXC+3) - G_ARC
! STOR(NEXC+4) - I_ECS
! STOR(NEXC+5) - G_ECS
! STOR(NEXC+6) - T_PRM_BGN
! STOR(NEXC+7) - T_SEC_BGN
! STOR(NEXC+8) - TE
! STOR(NEXC+9) - ZERO_CROS
! -----
! ----- EMTDC include and COMMON requirements -----
! -----
INCLUDE 'emt.d'
INCLUDE 'emt.e'
!
CHARACTER*72 DURLIN
REAL TIME,DELT,ICH,PRINT,FINTIM
REAL STOR
INTEGER NEXC,MXINV
!
COMMON /S1/TIME,DELT,ICH,PRINT,FINTIM
COMMON /S2/STOR(ND10),NEXC
COMMON /S8/MXINV(ND2)
! -----
! -----
! -----
! ----- Main body of program -----
! -----
DURLIN = '                ' &
&
! -----
! Initialization steps
! -----
IF (TIME .LT. DELT) THEN
! -----
! Test to see if a resistance branch is in data file
! -----

```

```

IF ((I.EQ.0).OR.(J.EQ.0)) THEN
  GTEST = GDACS(I+J,SS)
  ITEST = IBR(I+J,I+J,SS)
ELSE
  IF (I.EQ.J) THEN
    GTEST = GDACS(I,SS)
    ITEST = IBR(I,I,SS)
  ELSE
    GTEST = GDC(L,J,SS)
    ITEST = IBR(I,J,SS)
  ENDIF
ENDIF
ENDIF
IF ((ABS(GTEST).LT.1.0E-12).OR.
+ ((ITEST.NE.1).AND.(ITEST.NE.6))) THEN
  CALL OUTMSG(462,SS,I,J,GTEST,GTEST,DUMLIN)
ENDIF
! -----
! Initial values of STOR variables
! -----
STOR(NEXC+1) = 0.0
STOR(NEXC+2) = 0.0
STOR(NEXC+3) = 20.0
STOR(NEXC+4) = 0.0
STOR(NEXC+5) = 20.0
STOR(NEXC+6) = 0.0
STOR(NEXC+7) = 0.0
STOR(NEXC+8) = 0.0
STOR(NEXC+9) = 0.0
ENDIF
! -----
! Data Recovering
! -----
ARC_STATUS = STOR(NEXC+1)
I_ARC_PAST = STOR(NEXC+2)
G_ARC     = STOR(NEXC+3)
I_ECS     = STOR(NEXC+4)
G_ECS     = STOR(NEXC+5)
T_PRM_BGN = STOR(NEXC+6)
T_SEC_BGN = STOR(NEXC+7)
TE        = STOR(NEXC+8)
ZERO_CROS = .TRUE.
IF (STOR(NEXC+9) .LT. 0.5) ZERO_CROS = .FALSE.
I_G_ECS   = 0.0

```

```

! -----
! Arc Voltage and Current
! -----
IF ((I .EQ. 0) .OR. (J .EQ. 0)) THEN
  V_ARC = VDC(I+J,SS)
  I_ARC = CDC(I+J,I+J,SS)
ELSE
  IF (I .EQ. J) THEN
    V_ARC = VDC(I,SS)
    I_ARC = CDC(I,I,SS)
  ELSE
    V_ARC = VDC(I,SS) - VDC(J,SS)
    I_ARC = CDC(J,I,SS)
  ENDIF
ENDIF

! -----
! Main Loop
! -----
IF (FAULT_LOGIC .LT. 1) THEN
! -----
! Before fault
! -----
  G_ECS   =20.0
  G_ARC   =20.0
  ARC_STATUS = 0.0
  ZERO_CROS = .FALSE.
  T_PRM_BGN = TIME
ELSE
! -----
! After fault
! -----
  NEW_CAL = .FALSE.
  IF (TIME.GT.(T_PRM_BGN+2.0*DELT)) THEN
! -----
! After fault and delay
! -----

  IF (ARC_STATUS.NE.3.0) THEN
    IF (BRK .LT. 1) THEN
! ***** low current arc *****
      IF ((I_ARC*I_ARC_PAST) .LE. 0.0) THEN
        IF (ARC_STATUS .NE. 2.0) THEN

```

```

        ARC_STATUS = 2.0
        T_SEC_BGN = TIME
    ENDIF
ENDIF
! *****
IF (ARC_STATUS .EQ. 2.0) THEN
    TR = TIME - T_SEC_BGN
    IF (TR .LE. 0.1) THEN
        L_ARC = L_ARC_INIT
    ELSE
        L_ARC = 10.0*TR*L_ARC_INIT
    ENDIF
    VS = 75.0*IS**(-0.4)
    BETA = 2.51E-3
    T = (BETA*IS**(1.4))/L_ARC
    THRESHOLD = 0.01*IS*1.00E-3
    I_PEAK = IS
    V_GRAD = VS
    THRSHLD_MIN = 0.000001
! -----
! Detection of current zero crossing
! -----
    IF (TR .GT. (TE+0.001)) THEN
        IF ((L_ARC*L_ARC_PAST) .LE. 0.0) THEN
            IF ((ABS(L_ARC)+ABS(L_ARC_PAST)) &
                .GT.1.0E-10) THEN &
                TE = TR - DELT - DELT*ABS(L_ARC) &
                /(ABS(L_ARC)+ABS(L_ARC_PAST)) &
            ELSE
                TE = TR - 1.5*DELT
            ENDIF
            ZERO_CROS = .TRUE.
            COUNTER = 0
        ENDIF
    ENDIF
! -----
! Check for ignition if current crossed zero
! -----
    IF (ZERO_CROS) THEN
        V_IGN = (5.0 + (1620.0*(TE))/(2.15+IS)) &
            *(TR - DELT - TE)*L_ARC &
        IF (V_IGN .LT. 0.0) V_IGN = 0.0
        IF ((ABS(V_ARC) .GE. V_IGN) &

```

```

&          .AND.((TR-TE) .GE. DELT) THEN
          ZERO_CROS = .FALSE.
          G_ECS = G_ARC
        ENDIF
      ENDIF
!
! -----
!
! -----
      IF (ZERO_CROS) THEN
        G_ECS = 1.0E-9
        COUNTER = COUNTER + 1
        FRQ = 60.0
        MAX = AINT(1.0/(2.0*DELT*FRQ))-1
        IF (COUNTER.EQ.MAX) THEN
          ARC_STATUS = 3
        ENDIF
      ELSE
        NEW_CAL = .TRUE.
      ENDIF
    ENDIF
  ENDIF
! *****
  ENDIF
  ENDIF
  ENDIF
!
! -----
! Calculations of arc conductance & the values of current source
! -----
  IF (NEW_CAL) THEN
!
! -----
! New value of arc conductance
! -----
    G_ARC = G_ARC*(2.0*T-DELT)/(2.0*T+DELT) +          &
&      ABS(I_ARC*1000.0)*2.0*DELT/(V_GRAD*L_ARC*(2.0*T+DELT))
!
! -----
! Current correction and current via gn
! -----
    I_ECS = V_ARC*(G_ECS - G_ARC)
    I_G_ECS = V_ARC*G_ECS
!
! -----
! New value of g_ecs & i_ecs - calculated if necessary
! -----
    IF (ABS(I_ARC).LE.(0.3*I_PEAK*1.00E-3)) THEN
      THRESHOLD = (THRESHOLD-THRSHLD_MIN)*I_ARC*I_ARC/          &
&      (0.3*I_PEAK*1.00E-3*0.3*I_PEAK*1.00E-3)+THRSHLD_MIN
    ENDIF
  
```

```

IF (ABS(I_ECS).GE.THRESHOLD) THEN
  G_ECS = G_ARC
  I_ECS = V_ARC*(G_ECS - G_ARC)
  I_G_ECS = V_ARC*G_ECS
ENDIF
ENDIF

```

```

! -----
! Updating the Current of Equivalent Current Source
! -----

```

```

IF (I .NE. J) THEN
  CCDC(J,I,SS) = - I_ECS
  CCDC(I,J,SS) = - CCDC(J,I,SS)
ELSE
  IF ((I .EQ. 0) .OR. (J .EQ. 0)) THEN
    CCDC(I+J,I+J,SS) = - I_ECS
  ELSE
    CCDC(I,I,SS) = - I_ECS
  ENDIF
ENDIF
ENDIF

```

ENDIF

```

! -----
! Updating the Conductance of Equivalent Current Source
! -----

```

```

IF ((I .EQ. 0) .OR. (J .EQ. 0)) THEN
  IF (ABS(GDCS(I+J,SS)-G_ECS) .GE. 1.0E-8) THEN
    GDCS(I+J,SS) = G_ECS
    MXINV(SS) = I + J
  ENDIF
ELSE
  IF (I .EQ. J) THEN
    IF (ABS(GDCS(I,SS)-G_ECS) .GE. 1.0E-8) THEN
      GDCS(I,SS) = G_ECS
      MXINV(SS) = I
    ENDIF
  ELSE
    IF (ABS(GDC(I,J,SS)-G_ECS) .GE. 1.0E-8) THEN
      GDC(I,J,SS) = G_ECS
      IF (I .LT. J) THEN
        MXINV(SS) = I
      ELSE
        MXINV(SS) = J
      ENDIF
    ENDIF
  ENDIF

```

APPENDIX : FORTRAN Code for Air Switch

```

        ENDIF
        GDC(J,I,SS) = GDC(I,J,SS)
    ENDIF
ENDIF
! -----
! End of main loop
! -----

! -----
! Data Storing
! -----
    STOR(NEXC+1) = ARC_STATUS
    STOR(NEXC+2) = L_ARC
    STOR(NEXC+3) = G_ARC
    STOR(NEXC+4) = L_ECS
    STOR(NEXC+5) = G_ECS
    STOR(NEXC+6) = T_PRM_BGN
    STOR(NEXC+7) = T_SEC_BGN
    STOR(NEXC+8) = TE
    IF (ZERO_CROS) THEN
        STOR(NEXC+9) = 1.0
    ELSE
        STOR(NEXC+9) = 0.0
    ENDIF
!
! NEXC = NEXC + 9
!

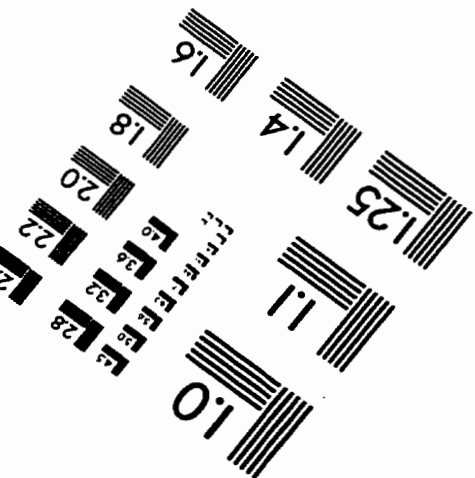
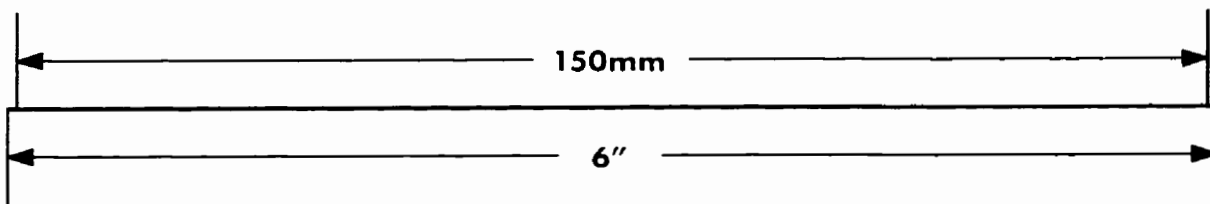
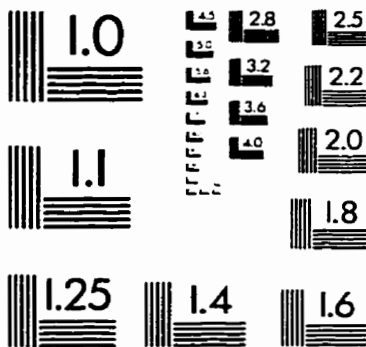
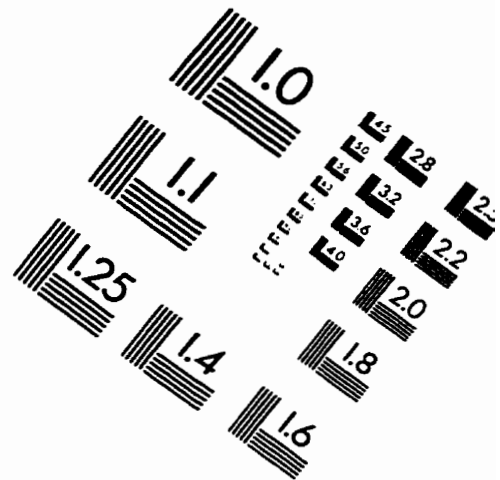
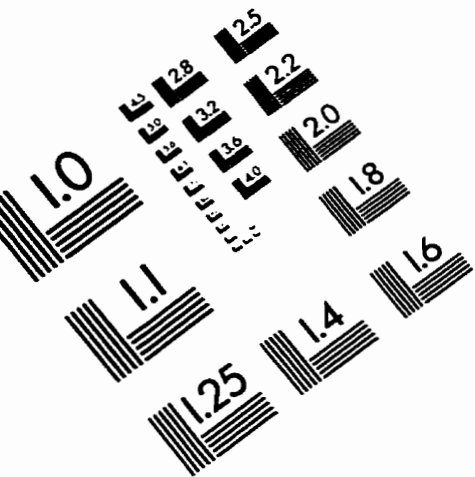
    MAX = AINT(1.0/(2.0*DELT*FRQ))-1
    L_COR = MAX*DELT*10.0*L_ARC_INIT
    IF (L_ARC.LT.(L_ARC_INIT+L_COR)) THEN
        L_ARC_OUT = L_ARC_INIT
    ELSE
        L_ARC_OUT = L_ARC - L_COR
    ENDIF
    L_ARC_OUT = L_ARC_OUT/100.0
    IF (ARC_STATUS.EQ.3.0) L_ARC_OUT = 0.0

    RETURN
    END

! *****
! *****

```

IMAGE EVALUATION TEST TARGET (QA-3)



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