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Development of Diagnostic and Prognostic Algorithms for SF_6 Puffer Circuit Breakers from Transient Waveforms: a Validation Proposal

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Abstract- *This paper presents a validation proposal for development of diagnostic and prognostic algorithms for SF_6 puffer circuit-breakers reproduced from actual site waveforms. The re-ignition/restriking rates are duplicated in given circuits and the cumulative energy dissipated in interrupters by the restriking currents. The targeted objective is to provide a simulated database for diagnosis of re-ignition/restrikes relating to the phase to earth voltage and the number of re-ignition/restrikes as well as estimating the remaining life of SF_6 circuit-breakers. The model-based diagnosis of a tool will be useful in monitoring re-ignition/restrikes as well as predicting a nozzle's lifetime. This will help ATP users with practical study cases and component data compilation for shunt reactor switching and capacitor switching. This method can be easily applied with different data for the different dielectric curves of circuit breakers and networks. This paper presents modelling details and some of the available cases, required project support, the validation proposal, the specific plan for implementation and the propsed main contributions.*

Keywords: *Alternative Transient Program, simulated data, diagnostic and prognostic algorithms developmen, validation.*

1 Introduction

Failure of modern SF_6 puffer circuit breakers during shunt reactor switching have been reported [1] and the high-frequency reignition currents cause 'parasitic arcing' in the circuit breaker nozzle. This phenomenon leads to gradual deterioration of the nozzle that may eventually result in a puncture of the nozzle material and failure of the interrupter [2]. Lots of work has been done on transient disturbances over many years. Nowadays there is an interest in quantifying the distortion and migration measures for power supplier waveforms. This field is referred as "Power Quality". Transient waveform analysis for asset management is proposed a new research direction

For a majority of circuit breakers in service, the point-on-wave of contact opening or closing is a random operation, and transient simulation is initiated because the process under study is complex and it is necessary to simulate the worst-case scenario for estimating the remaining life of the SF_6 circuit breakers. The Modeling process, therefore, using the ATP-EMTP software package is proposed to confirm with site measurement waveforms. The "preventive switching" strategy is performed at the modelling level by using computer-simulation-based observations about the circuit-breaker's behaviour. To assess the behaviour of the SF_6 puffer circuit breaker various scenarios, i) topology changes, ii) switching angle changes and iii) situations involving reignition/restrikes are generated and studied using simulation results. By quantitative simulation of the circuit breaker behaviour for as many as possible scenarios as a database, the knowledge will be acquired and impending problems can be identified.

System voltages monitoring the magnitude and frequency of occurrence of system restrike currents over time using on-line analysis by comparison with values database will be used as the diagnostic algorithm to determine the impending failure. High frequency current magnitude inference from ATP simulations with the prognostic algorithm will determine the remaining lifetime, which may result in an improved expectancy of the SF_6 puffer circuit breakers to reduce its maintenance cost. These are the objectives of this research project. This paper presents modelling details, the validation proposal, requested project support and research methodology for developing diagnostic and prognostic algorithms. The outcome of this research will be a new model for maintenance of circuit breakers which will result in savings and prevention of disruption of electricity supply.

2 Modelling of The SF_6 Circuit Breaker

There are two parts to the SF_6 puffer circuit breaker model: Mayr's Arc Equation [3] as follows:

$$\frac{dG}{dt} = \frac{G}{\theta}\left(\frac{P}{\tau} - 1\right) \quad (1)$$

where G- Arc conductivity

τ - Arc time constant

W- Arc power loss

P- Arc power

Typical values $P=4 \mathrm{x} 10^{6}$ and $\tau = 1.5 \mathrm{x} 10^{-6}$

and Dielectric Recovery model to determine the deterioration of a dielectric strength. Using ATPDraw Mayr's Equation is simulated in a circuit breaker arc model. The mathematical operation of an arc model is done by Transient Analysis of Control System (TACS) function, and feedbacks continuously operate in the simulated system. The modelling arc, the dynamic refreshing function, can get more precise simulating results. In this paper, a circuit breaker arcing effect at opening shunt reactor is simulated by this model. The simulated results are compared with published results to prove the validation of the circuit-breaker model. It is hoped that the measurement of voltage and current waveforms, with the MAYR arc model equation, the voltage and current data can determine the deterioration of the dielectric strength with the equation parameters P and τ of the internal circuit breaker.

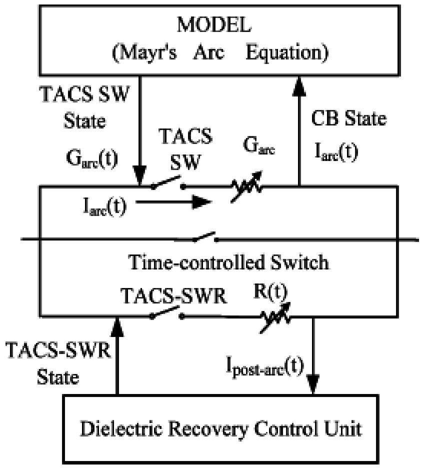

Figure 1 . Schematic diagram of the proposed extended Mayr's equation based arc model including ATP-EMTP TACS SW(Switch) control and dielectric recovery control unit for post-arc monitoring. [3].

It is proposed to use the MODEL language in ATP-EMTP co-ordinating with the TACS switch to simulate the arc dynamics for the Mayr's nonlinear differential equation. In Figure 1, the states of the CB voltage and the arc current input to the Mayr's model are shown. The arc conductance and the TACS switch states are then determined and output to control the CB switch, SW is shown. The time-controlled switch is to control zero current. The upper part is arcing time before zero current and the lower part is post-zero current.

Method

Refer to [4] where the circuit-breaker model is using Transient Analysis of Control System (TACS) by taking off the voltage and current point of the network with Algebraic and Logical variables and Transfer functions .

Steps using ATPDraw
Step 1: Take off the voltage with TYPE 90 and current signal level with TYPE 91
Step 2: Using TYPE 60 to determine if the current is zero or not; if the current is zero i.e. pre-zero period, go to step (A) to find resistance; if the current is not flowing through the circuit i.e. post-zero period, goto step (B) to find the resistance.

Step (A)

1. Using TYPE 98 to calculate V=V1- V2; gj=I /|V|;
2. Using TYPE 98 to calculate P(gj) and г(gj).
3. Using TYPE 58 to calculate Integral gj+1(GG).
4. Using TYPE 98 to calculate Rj+1(RR)

Step(B)

1. Using TYPE 98 to calculate V=V1- V2. For initial value, 0.05 Ω is assumed due to the practical measurement value between 0.02 Ω and 0.06 Ω.
2. Using TYPE 98 to calculate P(gj) and г(gj).
3. Using TYPE 58 to calculate Integral Rj+1(RR).

Step 3: using TYPE 98 to calculate the V arc, then using coupling to electric network for calculation.

The following equations are used for the model:

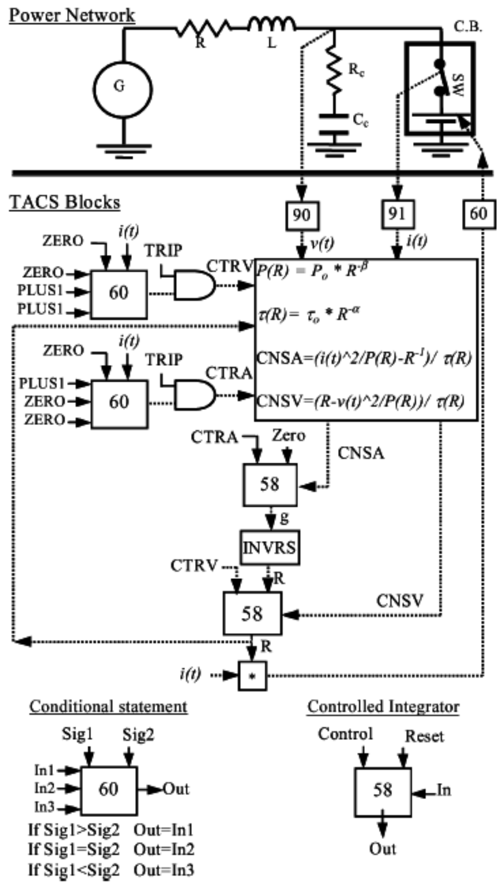

Figure 2. Universal arc representation of modified Mayr's model [4]

$$P(R) = P_0 * g^{\beta} = 4E\text{-}6*g**0.68$$

$$\tau(R) = \tau_0 * g^{\beta} = 1.5E\text{-}6*g**0.17$$

Reset CNSA=(i(t)**2/P(R)-G)/ $\tau(R)$

Reset CNSV=(R- v(t)**2/P(R)/ $\tau(R)$

The second part is circuit-breaker model: the MODEL language in ATP with the TACS switch was used to realise an accumulator and logic operators for the reignition control, where the recovery voltage is larger than the dielectric recovery voltage after the current chopping, a voltage comparator is applied subsequently. A flow chart of the voltage comparator is described below:

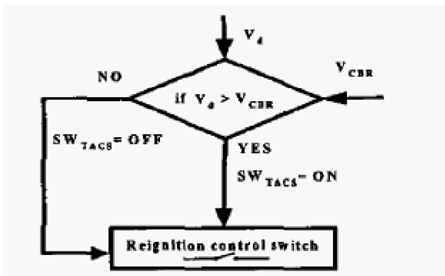

Figure 3. The flowchart of the voltage comparator [5]

A Statistical ATP Model for Dielectric Strength for Calculation of the Probability of Reignition/Restrikes

Considerable data in the old Greenwood papers should assist in the development of a statistical ATP model for MV VCBs and then further development for SF_6 puffer circuit-breakers. In accordance with the statistical theory of breakdown, it is proposed to calculate with a lower breakdown probability for a SF_6 puffer circuit-breaker. This may improve the accuracy of ATP simulation results. A statistical ATP model for dielectric strength will be developed for asset management as an innovation for the accuracy improvement in computer software modelling.

Modelling Dielectric Strength

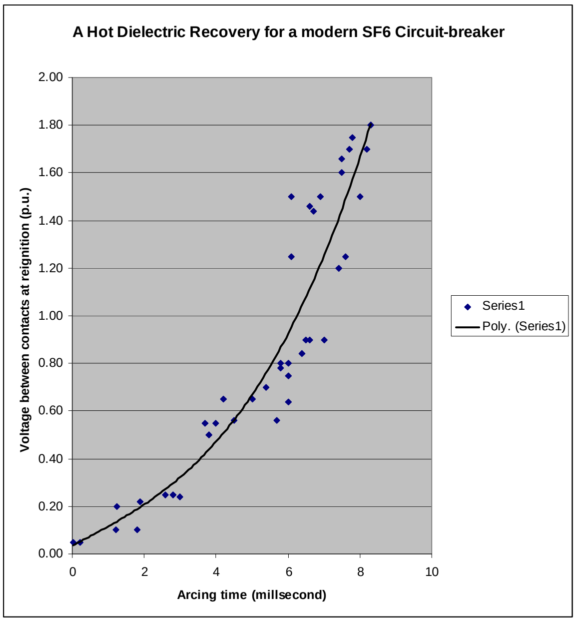

Figure 4. A generalised dielectric breakdown curve derived from the Laboratory dielectric recovery data from Japan[6] and the measured data from Korean experimental results [7]

Table 1. Diagnostic and prognostic algorithms

Features	**SF_6 puffer circuit breaker**
Number of occurrence	Number of restrikes/re-ignition from the voltage waveform by measuring phase to earth voltage
Amplitude	High frequency current magnitudes
Time	Time to breakdown i.e. current zero to re-ignition/restrike
Worn parts	SF_6 gas contamination or particles & Telfon nozzle & contacts
Detection algorithms	Arc Power, Arc Time Constant and Conductivity Phase to earth voltage and the number of re-ignition/restrikes and frequency of occurrence of system restrike/reignition current over time
Statistical model	Dielectric strength variation on the basis of normal distribution for the breakdown voltage

The deterioration is estimated from the cumulative energy dissipated in interrupters by the restriking currents. The method [8] to estimate the remaining lifetime of a circuit breaker is based on interrupting the current magnitude to obtain the erosion characteristics. The test data to see some dependencies of nozzle and contact mass losses on the interrupting current can be in terms of $\int idt$ and $\int i^2 dt$. Cumulative energy/current dissipated in interrupters are indicated for mass loss of nozzle - interrupter wear calculations (curves interpretation).

Mass loss limit=N $_{\text{allowable}}$* Mass loss $_{\text{I breaking}}$ (2)

When the allowable number of interruptions at any percentage of rated short-circuit current is known, the remaining lifetime can be determined [8]

$$\text{Remaining lifetime}(\%)=\left[1-\sum_{i=1}^{n}\frac{N_i I_{SCi}}{N_{allow(\max)} I_{SC(\max)}}\right]x100 \quad (3)$$

where I_{SCi} is any interrupted current.

3 Validation Proposal

Ramli [9] has measured the restrikes/re-igntion during shunt reactor switching using capacitive coupled antennas and active broadband antenna. He completed the single-phase laboratory experiment at Ergon Laboratory, Virginia and three-phase exploratory three-phase capacitor bank switching measurement at Blackwall Substation. We suggest that it should be possible to use waveforms for the validation of the developed dielectric recovery model for the SF_6 circuit-breakers and then extend our research work to provide the validation of the developing diagnostic and prognostic algorithms with further system testing using non-invasive methods for measuring restriking activity. A database will be established using the phase to earth voltage and the number of re-ignition/restrikes for online monitoring of re-ignition/restrikes. The advantage of the simulated input data will have a similar behaviour to the online waveforms. This is only if the presumed independence and Gaussian assumption of the SF_6 dielectric strength is valid. Using the database as a part of an expert system for online monitoring, impending problems can be identified in advance. After services with such condition indicators an improved life expectancy of the SF_6 puffer circuit breakers can be expected.

It is proposed that the research project will cover the following:

(i) Equipment Familization and Data Collection – 1) Substation layouts would be examined in order to enable simple equivalent circuits of the systems to be studied. 2) Tests' reports of the circuit breakers for shunt reactor switching and capacitor switching duty and other relevant conditions would be examined as well as 3) collection of relevant power network data.

(ii) Electromagnetic Transient Simulation Studies -Models of selected installations will be constructed and re-ignition/restriking conditions will be simulated. Special consideration would be given to determining the magnitude of high-frequency restriking current and voltages.

(iii) Site Validation – Results from ATP-EMTP studies using previous site data [10] will be used for exploratory investigation. After estimating the number of the re-ignition and restrikes from the selected installation, the SF_6 circuit-breakers will be internally examined against the calculated deterioration.

4 Project Support

It is proposed that the project would run for 24 months from June 2009. Mr. S. Kam will carry out research and prepare his PhD thesis on the topic 'Development of diagnostic and prognostic algorithms for SF_6 puffer circuit breakers from Transient Waveforms ' under the guidance of Professor G. Ledwich.

The following support is required:

1. Laboratory tests if required to reconfirm the ATP-EMTP simulated results
2. Equipment – power supplies, data acquisition system and test gears
3. Identify test sites
4. Field substation and plant data
5. Arrangement of internal examination of SF_6 circuit-breaker internally after re-ignition/restrikes being detected to confirm and identify any deterioration match with the prediction

5 Specific Plan

A. To estimate the remaining life using energy loss and mechanical damage to the Teflon nozzle after restrikes/reignition.

1. Collect experimental waveforms/data as shown in Figure 5 for normal power frequency and transient voltage and current waveforms for predication of failure in terms of arc energy dissipation.

Target waveforms from experiments:

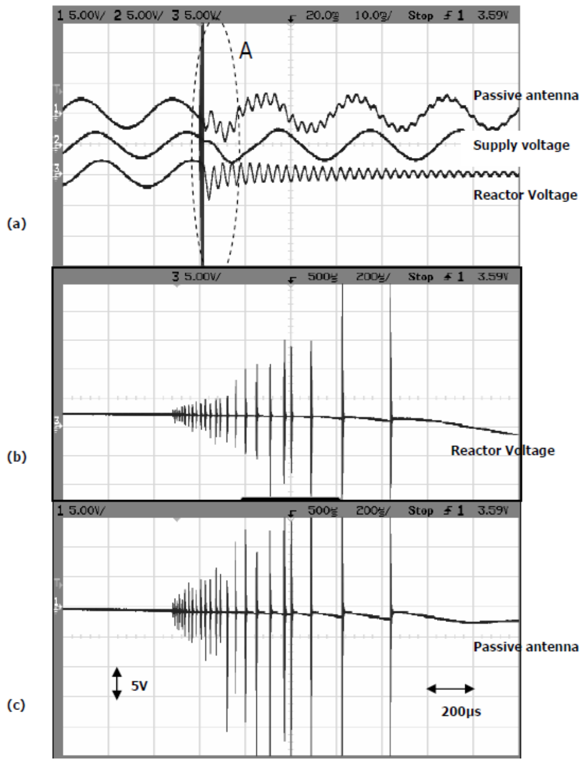

Figure 5: Single-phase reactor waveforms[9]

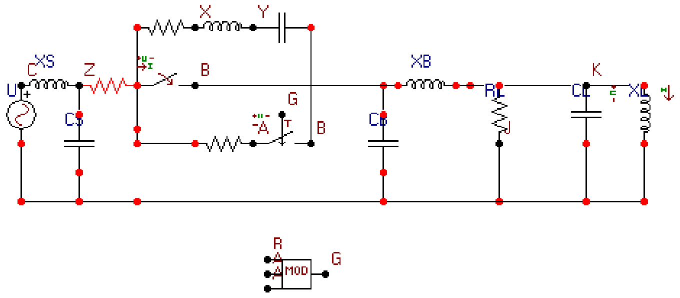

Figure 6. Single-phase Equivalent Circuit with Dielectric Strength Recovery Model.

The used values of the curves and times in the model were taken from literature Data [11]and the network data is taken from with Australian Standard AS4372-1996.
The 400kV with short-circuited current 60kA gives

Inductance= 400/√3x60 = 3.85 Ω or 12.3 mH i.e. less than 10% of shunt reactor inductance

Source capacitance= 0.03 μF i.e more than 10 times load capacitance

Reactor capacitance = 1.9nF

Reactor inductance = 2.55H

Reactor resistance with 173A = 1330 Ω

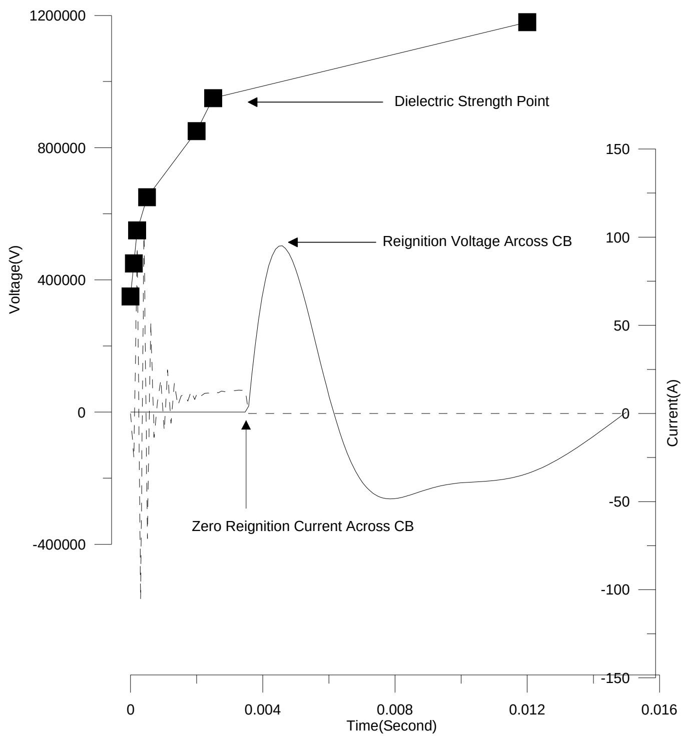

Figure 7. Single Reignition Across Circuit-breaker

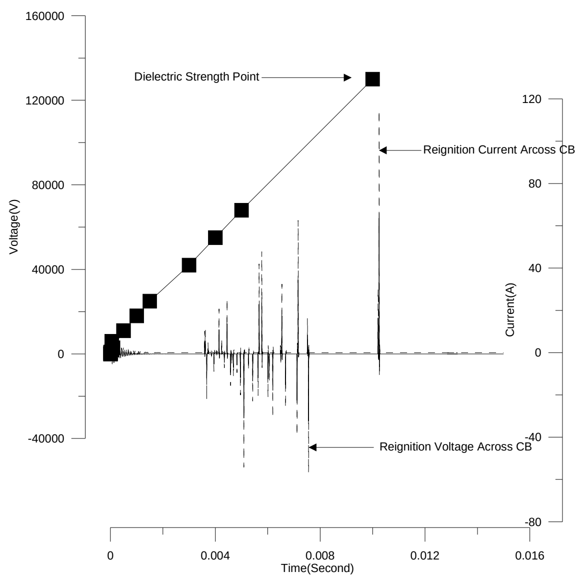

Figure 8. Multiple reignitions Across Circuit-breaker

Phenomena: Depending on the ignition-delay, higher values were reached by a higher rate of the rising of the recovery voltage. Flashover in hot gas between the zero interruption current may cause reignition current for the single-phase case. The multiple reignitions are obtained from the appropriate dielectric curve gradient as shown in Figure 8.

Simulation results and verification: The ATP model described above has been verified using the formulae with the following results:

Table 2: Comparison of calculated and simulated overvoltages and frequency

	Phase-to-ground overvoltage* (kV)	Frequency*(kHz)
ATP simulation	320	28
Using the formulae given in [12]	350	29
% discrepancy	11.8	3.5

* The data refer to the first interruption phase

By adjusting the gradient of the dielectric curve, single and multiple reignitions were obtained as per Table 1 for single-phase shunt reactor switching. With the help of a random generator in ATP, numbers in the interval [0, 1] were defined for the scattering process like chopping current, reignitions and the characteristics of the recovery voltage. By adjusting the gradient of the dielectric curve, single and multiple reignitions were obtained as per Table 2 for single-phase shunt reactor switching.

2. The literature survey on parameters for modelling such as parasitic capacitance and inductance to improve ATP simulation with parameters for ATP modeling shows: C_s=300pF and L_s=5x10^{-5} mH to adjust the simulated waveforms for the actual site measurement waveforms as follows:

Arc Voltage (kV)

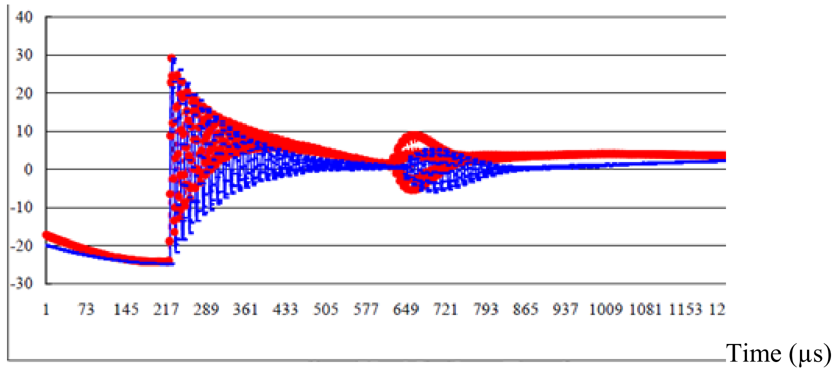

Figure 9. Target simulated ATP waveform (red in colour) and actual site waveform (blue in colour)

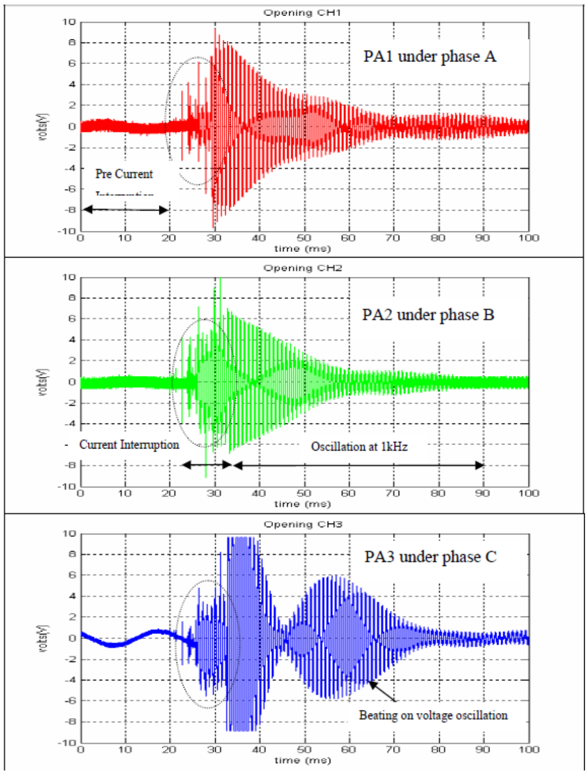

Figure 10. Target site measurement waveform from [9]

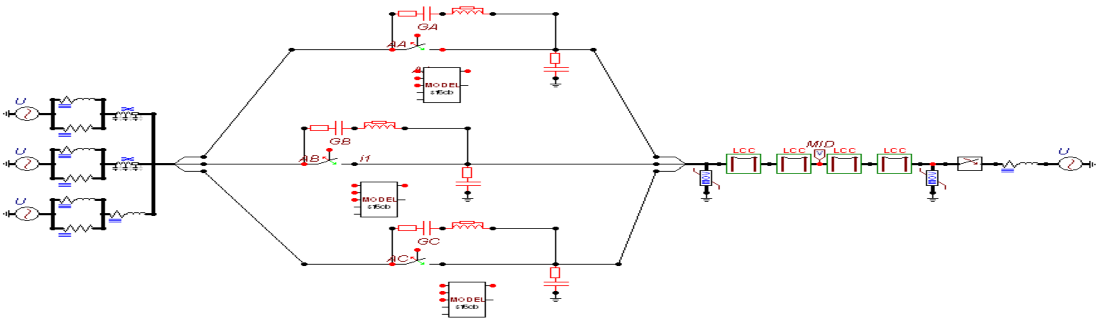

Figure 11. Three-phase simulated circuit for site

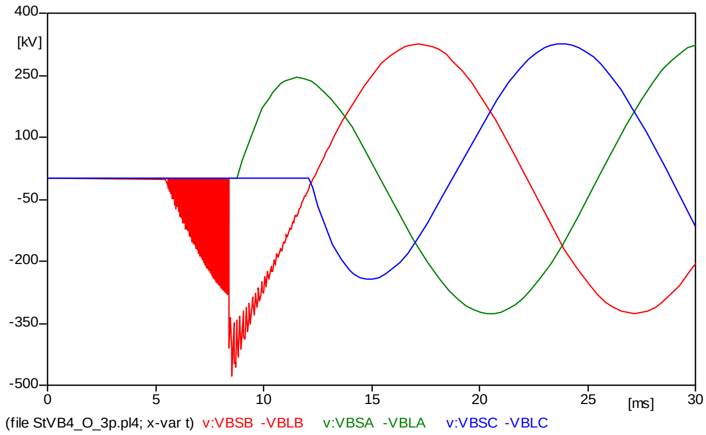

Figure 12: Three- phase simulated reignition voltage

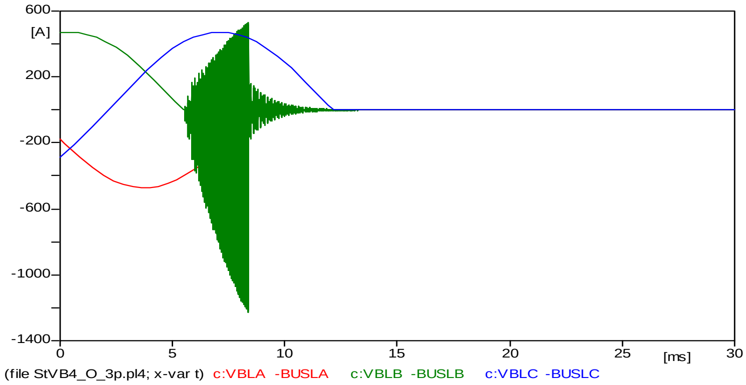

Figure 13:Three-phase simulated reignition current to predict I^2t losses.

3. match using ATP simulations the high frequency current waveform to predict losses.
4. following the paper [13], the remaining life of a Teflon nozzle will be predicted I^2t losses.
5. it will be verified by physical observation of damage done to a Teflon nozzle and wearout (mechanical strength) will be related to the nozzle's remaining life.

B. To estimate the rate of degradation based on the number of restikes/reignition, the following will be addressed:

1. Number of high frequency reignition/restrikes with reference to each phase voltage as shown in Figure 8.

2. Estimate the standard deviation to determine the statistical variation of dielectric strength. With the help of the Monte-carlo capability in Matlab Program is determined to simulate the occurrence of each reignition/restrike.

3. Feed the data into an ATP model to produce a simulated database for on-line system voltage monitoring and restriking current. This will produce a prediction of the impending failure rate and a rate of electrical degradation against experimental measurements and site validation.

6 Proposed Main Contributions

Three main contributions from this research project are proposed:

a. Diagnossis: Development of a database which will show phase-to-earth voltage across a circuit breaker and the numbers of restrikes/reignitions which can be used to diagnose electrical degradation..

b. Prognosis: Use an ATP program to calculate the high frequency magnitude current inside a circuit-breaker to estimate the cumulative energy current inside a circuit-breaker to estimate the cumulative energy inside a circuit-breaker to predict a nozzle's lifetime.

c. Model: Develop an ATP statistical model which will determine the statistical dielectric strength behaviour of a circuit-breaker and improve the accuracy of computer simulations.

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