An Adaptive, Self-checking Algorithm for Controlled Fault Interruption

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Abstract—A method for achieving a controlled arcing time on high voltage (SF_6) circuit breakers during fault interruption is presented. Using least mean squares based regression, a model of a sampled (fault) current is generated. If the model is found to sufficiently match the sampled current, the model is extrapolated to predict current zero times for use as targets for synchronizing the opening command to the circuit breaker so as to achieve a pre-determined optimum arcing time. Prediction of target current zero times within ±0.2 ms have been achieved. Benefits of such controlled interruption include reduction in circuit breaker electrical wear, potential to increase circuit breaker switching ratings and facilitation of new high voltage interruption techniques. Novel aspects of the scheme include the use of an hypothesis test for verification of the accuracy of the modeled current.

Keywords: ***controlled switching, fault interruption, circuit breakers, arcing times, adaptive control***

1. INTRODUCTION

Controlled ("synchronized" or "point-on-wave") switching has become widely used with high voltage (HV) circuit breakers in order to mitigate transients that arise from switching certain well-defined loads. Shunt capacitor and reactor banks are among the more common applications. Power transformer and long line switching are among more recent applications. CIGRÉ working group A3.07 has produced a comprehensive state-of-the-art survey of the conventional application of controlled switching [1],[2].

Unlike conventional controlled load switching that is focused on switching transient mitigation, the method presented here focuses on fault interruption. Specifically attention is on achieving a pre-determined target arcing time during interruption. The most obvious benefit of such arcing time control is reduction in the electrical wear on the circuit breaker. Other benefits may include the possibility to uprate a circuit breaker or facilitate new interruption technologies, including power electronic or "SF_6-free" interrupters.

Little detailed prior research in this specific area is available. Pöltl and Fröhlich [3] proposed a method of controlling the arcing time by targeting so-called "safepoints" that were determined by a rapid estimation of the phase angle of a fault current during the first ¼ to ½ cycle after fault inception. In addition Pöltl further developed a means of single or multiple phase fault identification using an artificial neural network (ANN) so as to enable management of a wide range of "typical" fault cases [4].

While the "safepoint" method offers a relatively fast and conservative means to control arcing times, it lacks some important features. First, consideration must be give to what happens when the control scheme is unable to reach a viable target solution within the protection system response time. Second, for effective data processing it is important to detect the fault inception instant, particularly for any method applying a continuous moving data sampling window. Third, the fault current model for target prediction should ideally be able to manage a wide range of fault behaviours.

2. PROPOSED METHOD – OVERVIEW

The proposed method seeks to address the limitations of the safepoint method described above. What follows is a summary of the initial results of an on-going research project [5].

Figure 1 shows interruption of a single phase asymmetrical fault current using both controlled (CFI) and non-controlled fault interruption (non-CFI).

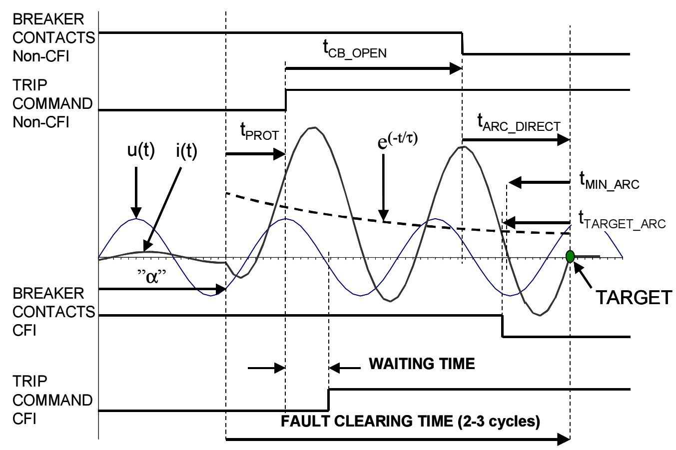

Figure 1: Direct (non-controlled) and controlled fault interruption example

It should be noted that in the context of this work "controlled" interruption means targeting a specific current zero and co-ordinating the trip signal to the circuit-breaker in order to achieve a pre-selected arcing time. As such the control scheme is supplementary to the protection system. The decision whether or not the specific circuit-breaker should be tripped, remains with the protection system. The overall control scheme is described in Figure 2.

In the conventional, non-CFI case the protection system issues the trip command directly to the circuit-breaker as soon as it has determined a fault (within its protection zone requirements) has occurred. After the trip command is sent, the breaker opens and will experience a certain arcing time between the time its arcing contacts first separate and when the current is eventually interrupted at a current zero.

As seen in the example shown in Figure 1 interruption may not necessarily be achieved at the first current zero after arcing contact separation. This is due to the fact that the circuit-breakers exhibit minimum arcing times for which they can achieve interruption.

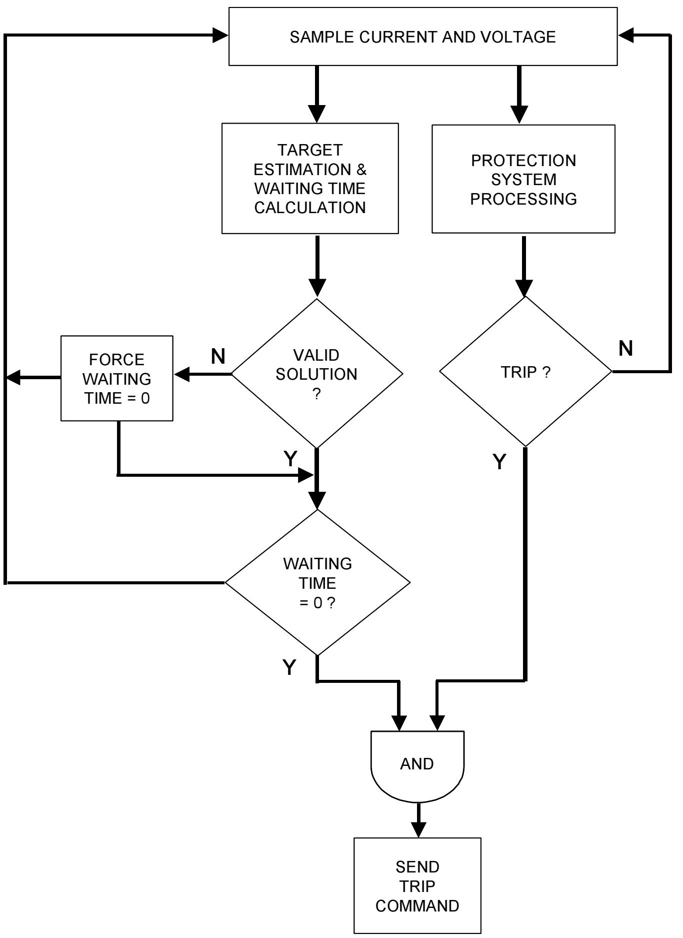

Figure 2: Overall proposed Controlled Fault Interruption scheme

Minimum arcing times vary according to the nature and magnitude of the current interrupted (e.g. capacitive, inductive, load or fault), the resultant transient recovery voltage behaviour, combined with the type of interrupter being used. For fault interruption with modern HV SF_6 circuit-breakers, minimum arcing times in the order of half a cycle are typical.

It can be clearly seen in Figure 1 that the non-CFI arcing time, t_{ARC_DIRECT}, is considerably longer than the minimum arcing time, t_{MIN_ARC}. The additional arcing time beyond the minimum can be considered as being "wasted" arcing, that contributes to additional electrical wear on the breaker without necessarily adding to certainty of interruption. A primary objective of CFI applied to existing interrupter technologies is to minimize such "wasted" arcing time without undue prolongation of the total fault clearing time.

The proposed CFI method seeks to estimate the time of the first viable current zero for which interruption could be achieved and delay the trip command such that the circuit breaker will experience only a near minimum arcing time. The delay of the trip command is represented by the waiting time shown in Figures 1 and 2.

The process of estimating future viable current zeroes is continuous. If at any stage the CFI scheme is unable to reach a valid estimation of the current's behaviour and thus a valid current zero prediction, the waiting time is forced to zero. Hence protection tripping is not unduly delayed by a failure of the CFI scheme. Such an approach naturally assumes that the circuit-breaker can still interrupt with a longer than targeted arcing time.

3. PROPOSED METHOD – DETAILS

The detailed implementation of the proposed method will be described in terms of the major processing components; modelling of the current, determination of key parameters, validation of estimated model, determination of target current zero and waiting time, data sampling window control. The main data processing stages are illustrated in Figure 3.

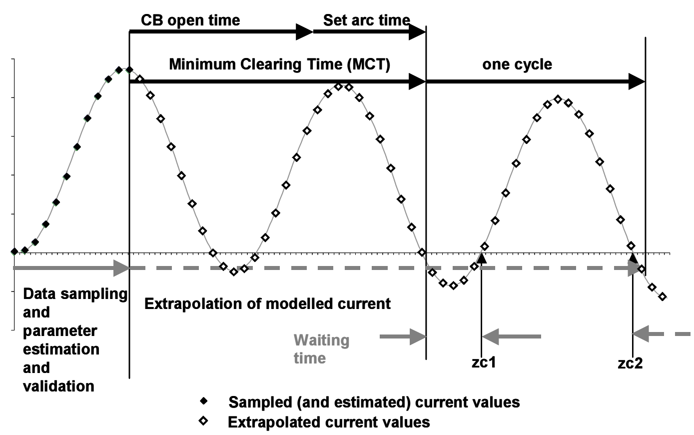

Figure 3: Example of data processing stages

Data is sampled and an estimation of key parameters describing the fault current according to a preset model is made. Estimated and actual current values are compared within the sampling window range and if sufficiently consistent, the estimated current model is extrapolated in order to find the first viable current zeros available for interruption. Parameter estimation and zero-crossing estimation proceeds until the protection trip is active. Once the protection trip is active, the trip signal to the breaker will be sent once the waiting time from the CFI calculation has decremented to zero. Details of these steps are now explained below.

3.1 Fault Current Model

A single phase fault current, i(t), is modelled according to (1), in conjunction with driving source voltage, u(t), defined by (2):

$$i(t) = I_F.(\sin(\omega t + \alpha - \phi) + \sin(\alpha - \phi).e^{(-t/\tau)}) + I_0..e^{(-t/\tau)} \quad (1)$$

$$u(t) = U.\sin(\omega t + \alpha) \qquad (2)$$

where
I_F = peak value of symmetrical fault current
I_{0-} = instantaneous value of pre-fault current at fault start
ω = angular frequency
α = phase angle on source voltage at fault inception
ϕ = fault current phase angle
τ = time constant of fault current asymmetrical component = L / R
L = source-to-fault inductance
R = source-to-fault resistance

3.2 Fault model parameter estimation

The key parameters of the fault current model to be estimated are I_F, α, ϕ and τ. It is assumed that ω can be based on its immediate pre-fault value (e.g. by voltage zero sampling). The fault inception voltage angle, α, can either be determined separately from the fault current estimation, or directly by this process, as will be explained later. I_{0-} is obtained in conjunction with determination of α. Assuming values for α and I_{0-} are known, (1) is reduced and factorized to the orthogonal form in (3) in order to provide a simplified structure for least means square (LMS) estimation of the remaining unknowns.

$$i(t) = K1 .\sin(\omega t) + K2 .\cos(\omega t) + K2.e^{(-t/\tau)} \qquad (3)$$

where

$$K1 = I_F .[\cos(\alpha).\cos(\phi) + \sin(\alpha).\sin(\phi)] \qquad (4)$$

$$K2 = I_F .[\sin(\alpha).\cos(\phi) - \cos(\alpha).\sin(\phi)] \qquad (5)$$

To further enable LMS matrix calculation, the exponential term in equation (3) is replaced by a truncated Taylor series approximation ($e^{(-x)} \approx 1 - x$), resulting in (6)

$$i(t) = X1.\sin(\omega t) + X2 .\cos(\omega t) - X3.1 + X4.t \qquad (6)$$

where

$$X1 = I_F .\cos(\phi) \qquad (7)$$

$$X2 = -I_F .\sin(\phi) \qquad (8)$$

$$\tau = \omega / |X2 / X1| \qquad (9)$$

X1 to X4 are found via a weighted LMS matrix operation. K1 and K2 are then calculated from X1, X2 and the estimated value of α. The estimated current is then calculated according to (10)

$$i_{EST}(t) = K1 .\sin(\omega t) + K2 .\cos(\omega t) + K2.e^{(-t/\tau)} + I_{0-}.e^{(-t/\tau)} \qquad (10)$$

3.3 Validation of estimated current model

In order to ensure reliable target estimation and control it is desirable to verify the validity of the estimated current model. This is done by using a so-called "F0" hypothesis test, which is based on a standard analysis test used in linear regression (see [6]) as per equation (11),

$$F0 = \frac{\left[\sum_{i=1}^{n}(\hat{x}_i - \bar{x})^2\right] \Big/ k}{\left[\sum_{i=1}^{n}(\hat{x}_i - x_i)^2\right] \Big/ (n-p)} \qquad (11)$$

where
n = number of data samples compared
k = number of regression coefficients ("unknowns")
p = number of columns of "A" matrix (= k)
$\hat{x}_i$ = i[th] estimated value
$\bar{x}$ = mean of sampled values
x_i = i[th] actual data value

The higher the F0 result for a specific data set comparison, the more accurate is the estimated current model. Empirical investigation found that a limiting value of F0 could be set such that if the F0 result falls below the limit, the estimation is considered too inaccurate to use and the waiting time is forced to zero, as indicated in Figure 2.

3.4 Target estimation and waiting time calculation

Assuming a valid F0 result has been achieved, the estimated current model is then extrapolated out to a viable interruption current zero crossing search window that extends from the minimum clearing time (t_{MCT}) of the breaker plus one power frequency cycle (as shown in Figure 3). The t_{MCT} constraint is set by the nominal opening time of the circuit breaker plus the targeted arcing time. Normally the targeted arcing time is set to be equal to the minimum arcing time of the breaker plus some margin (e.g. +1ms) to allow for variations in breaker opening and arcing time behaviour, plus some residual error in the zero crossing predictions.

Extending the search window one cycle past t_{MCT} allows for the wide range in possible zero crossing times for asymmetrical fault currents and ensures at least one current zero should be detected for targeting. The earliest viable zero crossing is the normally chosen target.

Once the target zero crossing time, t_{ZC}, has been estimated, the waiting time, t_{WAIT}, required to achieve the target arcing time is easily calculated by (12)

$$t_{WAIT} = t_{ZC} - t_{MCT} - t_{NOW} \qquad (12)$$

3.5 Data sampling window control

At start-up the data sampling window is set at ¼ cycle, then progressively increased to 1 cycle and thence shifted with each new data sample iteration. At fault detection the pre-fault data is discarded and the sampling window reset to ¼ cycle and then progressively expanded to 1 cycle again.

3.6 Estimation of fault inception

Determining the instant the fault transient starts is important as this is used both to determine the phase voltage fault angle, α, and for resetting the data sampling window to discard pre-fault data. A means of utilizing the F0 results from the CFI process has been developed to facilitate such a fault start detection.

If a successive preset number ("N") of F0 results are observed to decrease by a preset factor ("k"), then it is concluded that a fault (or state change) in the current has occurred at the start of the detected trend. The pre-fault sampled current data is then discarded and the data sampling window reset to start from the estimated fault inception instant. The estimated value of α is also updated, being calculated from with respect to the last positive slope voltage zero crossing before the fault inception instant. For CFI start-up, α can be set according to synchronized closing of the circuit-breaker with respect to the source voltage.

The F0-trend method of fault detection has been found to provide reasonably good results for low noise and low sample rate conditions with setting of "N = 8" and "k = 0.85". Further enhancement of the fault inception detection method is planned.

4. SIMULATIONS AND RESULTS

Numerous simulation tests of the proposed method have been conducted using both artificial network data and actual utility disturbance recording data. The simulations have been made using MATLAB® [7].

In order to assess the performance of the CFI scheme, four key performance indicators were defined:

1. Arc current -- time integral savings
2. Error in target zero crossing times
3. Impact on total fault clearing times
4. Success rate of CFI target estimation

The results for arc integral savings are presented in Figures 4 and 5, with respect to a range of time constants, τ, and fault inception voltage angles, α. The arc integral savings indicate the possible reduction in the value of the time integral of the arc current by using CFI compared to "direct" non-CFI tripping.

Note that the arc integral saving results are shown for both "ideal" CFI (not using the estimation method and assuming the target current zeroes are exactly known) and for the proposed algorithm tested with 20 data sets of simulated |20%| white gaussian noise (WGN) per α, τ combination. For each τ-value (or α-value) the maximum, minimum and mean results are shown for the corresponding full range of α (or τ) values simulated.

It can clearly be seen that the proposed algorithm and "ideal" results are closely matched, even for a relatively high level of random signal noise.

It should be noted that in the results shown, it has been assumed α is known "exactly". Simulations using the F0-trend method to estimate α have also been made, but similar results to those above are only gained with a much lower random noise magnitude.

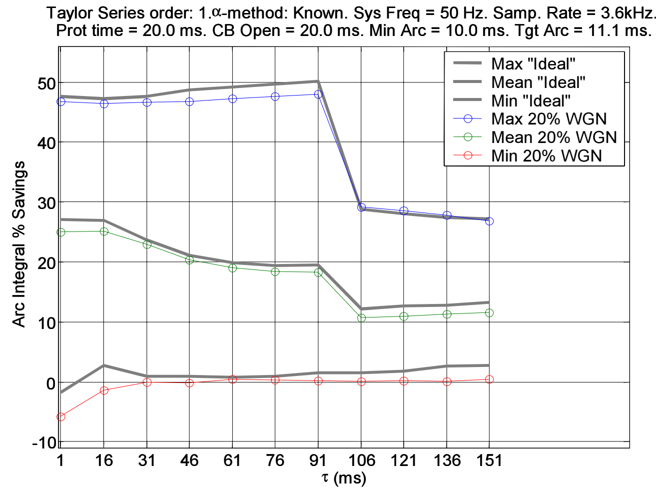

Figure 4: Arc integral savings with respect to time constant, τ

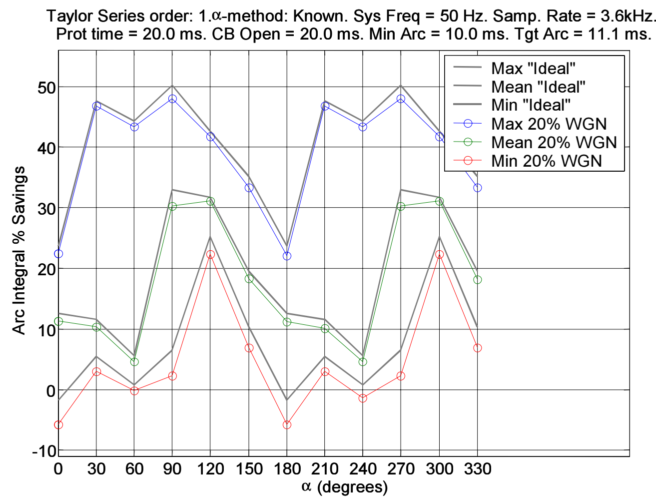

Figure 5: Arc integral savings with respect to fault voltage angle, α

It is also of interest to note the characteristic behaviour of the results with respect to τ and α. The drop in arc integral savings above t = 91ms can be traced to the shift in major/minor current loop behaviour before the interruption current zero for the given combination of protection relay, breaker opening and arcing times used in this case.

Figure 6 shows the corresponding target zero crossing prediction errors by the algorithm w.r.t. α for the same range of parameters. Here the results show the errors for the algorithm with and without |20%| simulated WGN. While there are some relatively large errors within the |20%| WGN results, it can be seen from the mean error results that such extreme errors only form a small percentage of the total results.

Tests with actual HV system fault disturbance recordings also suggest that persistent |20%| WGN is a somewhat extreme test. A more realistic noise simulation could be |10%|, decaying rapidly within the first half-cycle of the fault transient. Nevertheless the mean zero-crossing error performance is quite good, being within ±0.2ms using a reasonably low to moderate sampling rate of 3.6kHz.

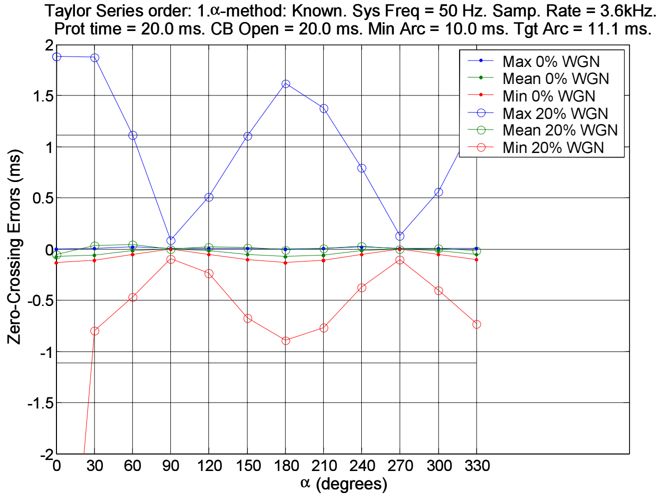

Figure 6: Zero crossing errors with respect to fault voltage angle, α

Figure 7 shows an example of a simulation made with a fault recording from a 50Hz, 400kV network. The data was sampled at a nominal 3.2kHz rate. The protection response, circuit breaker opening and minimum arcing times were artificially set to investigate how fast the algorithm could obtain a viable estimation of the fault current; as such the interruption of the current in the simulation is approximately one cycle ahead of what was originally recorded from actual non-CFI operation.

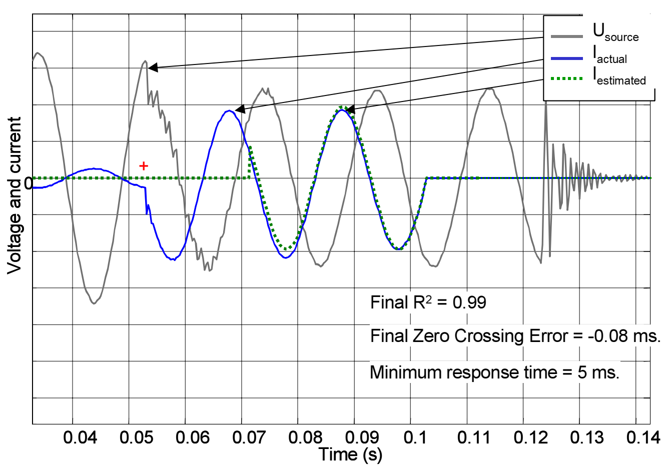

Figure 7: Example of simulation using a fault recording from 50Hz, 400kV network.

In this example the algorithm obtained a very good estimation (dotted line) of the fault current (dark solid line) within 5 ms of fault inception (indicated by the cross "+"), with current zero time errors less than ±0.1ms.

5. CONCLUSIONS AND FUTURE WORK

While the proposed method has so far only been developed and tested as a single phase system, it has shown distinct potential for further development towards a viable CFI method.

The F0-test to verify the validity of the key fault parameters used in the fault current model has been found to provide a useful means of regulating the CFI scheme with respect to protection operation dependability, in addition to facilitating fault inception detection and data sampling window adjustment. As such, some of the limitations of earlier CFI methods are addressed.

The trends observed in arc integral savings and zero-crossing errors with respect to different fault time constants and fault inception voltage angles are important in terms of further development, testing and potential application of the proposed CFI scheme.

Future work is now directed towards high power experiments to quantitatively determine the potential benefits of CFI to the performance of HV SF_6 circuit-breakers, in addition to development of the proposed method to manage the full range of single and multiple phase fault combinations.

Further work is also required to more fully investigate the influence of current measurement systems and signal filtering processes on the accuracy of the algorithm and management of proper time synchronization between primary currents and the processed secondary current signals.

6. ACKNOWLEDGEMENTS

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