Research on Zero-crossing Point Prediction Technology of CFI Based on A New Adaptive LS Algorithm

Xiuming Hu*, Hongyan Wan and Ya Zhou
Huanggang power supply company State Grid, Huanggang 438000, HuBei, China

*Corresponding author e-mail: hbhgsunshine@163.com

Abstract. Fast identification of fault current parameters and accurate prediction of current waveform zero-crossing are the key technologies of controlled fault interruption(CFI). Aiming at the problem that the least squares(LS) algorithm has truncation error, this paper propose a new adaptive least square(LS) algorithm using the change rate of the fault current, avoiding the approximation of the attenuated DC decaying component. Based on the fault current simulated by MATLAB, the results show that the new algorithm has higher accuracy when the noise is not less than 40dB and the data window is more than 10ms. For the actual simulated fault current data by PSCAD, the proposed algorithm also had high accuracy, which can meet the requirements of CFI.

1. Introduction
With the continuous expansion of the power grid and the increasingly close connection, the level of short circuit current continues to approach or even exceed the breaking capacity of existing circuit breakers.

CFI is a useful meas to improve the breakers’ interruption capacity [1]. By controlling the interruption moment when fault occurs, the breaker could be interrupted in the optimal opening interval after a certain arcing time, which can effectively reduce the electrical erosion thus improve the breaking capacity [2]. However, how to accurately predict the zero-crossing point of short circuit current with non-sinusoidal waveform is crucial.

2. Fundamental of CFI

2.1. Breaking Process
The processes of using traditional interruption and CFI were shown in Fig. 1.
When using traditional interruption, a fault occurs at the time $t_0$, the fault is identified after $t_p$, and the circuit breaker opening command is issued at the time $t_1$. Then the contacts act, and the dynamic and static contacts of the circuit breaker are separated at $t_4$, then arc is generated, the arc is extinguished at the supposed ideal breaking point of the current, and the circuit breaker is fully opened at the time $t_6$.

When using CFI technology, the zero-point prediction is completed at the time $t_2$. After waiting time $t_w$, the breaker starts to act at the time $t_3$. Experiencing the same inherent opening time, an arc is generated at $t_5$, and the arc is extinguished during the arcing time $t_{\text{minarc}}$ to achieve full interruption.

### 2.2. LS Algorithm

When fault occurs in 220kV and above power system, a decaying DC component will generate in the short circuit current. The short circuit current $i(t)$ can be expressed as:

$$i(t)=I_m \sin(\omega t+\phi)+I_d e^{-t/\tau} \quad (1)$$

In (1), $I_m$ is the fundamental frequency amplitude, $\omega$ is the fundamental angular frequency, $j$ is the initial angle. $I_d$ is the amplitude of DC decaying component. $t$ is the decaying time constant. Equation (1) contains a non-linear exponential term. Expanding it using Taylor series and ignoring higher-order terms.

$$i(t)=X_1 \sin \omega t+X_2 \cos \omega t+X_3 +X_4 t \quad (2)$$

In (2):
If the sampling interval is $\Delta T$, the sampling current matrix is:

$$\begin{pmatrix}
X_1 &= I_m \cos \varphi \\
X_2 &= I_m \sin \varphi \\
X_3 &= I_d \\
X_4 &= -\frac{I_d}{\tau}
\end{pmatrix}$$

(3)

In (4), $n$ is the number of sampling points. Let coefficient matrix $X = [X_1, X_2, X_3, X_4]^T$, and

$$A = \begin{bmatrix}
\sin \omega t & \cos \omega t & 1 & t \\
\sin \omega (t + \Delta T) & \cos \omega (t + \Delta T) & 1 & t + \Delta T \\
\vdots & \vdots & 1 & \vdots \\
\sin \omega [t + (n-1)\Delta T] & \cos \omega [t + (n-1)\Delta T] & 1 & t + (n-1)\Delta T
\end{bmatrix}$$

(5)

Then there is the short circuit current equation system as:

$$AX = B$$

(6)

Solve the equation (6) to get the parameters $X_1, X_2, X_3, X_4$. The parameters of short circuit current can be calculated.

2.3. New Algorithm

The theoretical error of the commonly used LS algorithm mainly comes from the processing of the attenuated DC decaying component. When the Taylor series is used to expand the attenuated DC decaying component, there is:

$$I_d e^{-\frac{t}{\tau}} = I_d \left[1 - \frac{t}{\tau} + \frac{1}{2!} \left(\frac{t}{\tau}\right)^2 - \frac{1}{3!} \left(\frac{t}{\tau}\right)^3 + \cdots\right]$$

(7)

In order to eliminate the difficulty caused by non-linearity in the calculation, the traditional LS algorithm approximates equation (7), that is, ignoring higher-order terms:

$$I_d e^{-\frac{t}{\tau}} \approx I_d \left(1 - \frac{t}{\tau}\right)$$

(8)

Ignoring higher-order terms will inevitably cause truncation errors, and as can be seen from equation (8), the relative magnitude of this error is related to the decay time constant and sampling interval. To solve this problem, this paper improves the algorithm in principle to reduce the error. If the current is as equation (1), then the change rate of short circuit current $i'(t)$ is:

$$i'(t) = \omega I_m \cos (\omega t + \varphi) + \frac{1}{\tau} I_d e^{-\frac{t}{\tau}}$$

(9)
Combining equation (1) and (9), there is:

\[ i'(t) = \omega I_m \cos(\omega t + \varphi) + \frac{I_m}{\tau} \sin(\omega t + \varphi) - \frac{i(t)}{\tau} \]  

(10)

Change equation (10), there is:

\[ i'(t) = X_1 \sin \omega t + X_2 \cos \omega t + X_3 i(t) \] 

(11)

in (11):

\[
\begin{cases}
X_1 = \frac{I_m}{\tau} \cos \varphi - \omega I_m \sin \varphi \\
X_2 = \frac{I_m}{\tau} \sin \varphi + \omega I_m \cos \varphi \\
X_3 = -\frac{1}{\tau}
\end{cases}
\]  

(12)

Then the short circuit current equation system just as equation (6) can be get:

\[ A \cdot X = B \] 

(13)

In (13):

\[
A = \begin{bmatrix}
\sin \omega t & \cos \omega t & i(t) \\
\sin \omega (t+\Delta T) & \cos \omega (t+\Delta T) & i(t+\Delta T) \\
\vdots & \vdots & \vdots \\
\sin \omega [t+(n-1)\Delta T] & \cos \omega [t+(n-1)\Delta T] & i[t+(n-1)\Delta T]
\end{bmatrix}
\]  

(14)

\[
B = [i'(t) i'(t+\Delta T) \cdots i'[t+(n-1)\Delta T]]
\]  

(15)

Solving (13), the parameters \( I_m, j, t \) of short circuit current can be calculated, and combining with the actual value, the DC decaying component \( I_d \) can be calculated. Then the zero-crossing points of the short circuit current could be predicted, and the CFI technology could be achieved.

3. Simulation Verification

This paper first generated short circuit current data just like (1) using MATLAB and set the sampling frequency 10kHz. In (1), the parameters were set separately as \( I_m=1, j=75^\circ, I_f=0.8, t=0.045s \). When the short circuit current did not contain harmonic components, the data window was 10ms, the fitted current waveform was compared with the real current waveform as shown in figure 2.
Figure 2. Fitted current waveform compared with the real.

It can be seen from Fig. 2 that when using the algorithm proposed in this paper, the fitted short circuit current waveform and the real were very similar. The results show that the error between the first zero-crossing point of the fitted and the real was not more than 0.1 ms, and other zero-crossing points also had very small errors, which reflected very high accuracy. When the short circuit current contained white noise, which was actually the superposition of harmonic components in various frequencies, 40dB noise has been added to the short current, after 1000 calculations, the errors of the first zero-crossing point were shown in figure 3 (a), (b) when the data window was respectively 10ms, 15ms. Due to paper space limitations, the errors of other zero-crossing point were not calculated one by one.
It can be seen from Fig. 4 that when there was 40dB white noise and the data window was 10ms, the first zero-crossing error could be controlled within 1ms. Extended the data window to 15ms, the first zero-crossing error did not exceed 0.1ms. In order to further verify the feasibility of the algorithm in this paper, the PSCAD/EMTDC simulation software was used to build a 500kV double-ended power supply system model with EHV lines as shown in figure 4.

The M-terminal system parameters were: positive sequence impedance $Z_{m1}=15.149 \angle 89^\circ \Omega$, and zero-sequence impedance $Z_{m0}=8.321 \angle 89^\circ \Omega$. While the N-terminal system parameters were: positive sequence impedance $Z_{n1}=30.269 \angle 89^\circ \Omega$, and zero-sequence impedance $Z_{n0}=15.721 \angle 89^\circ \Omega$. The line length is 200km, and it used Bergeron model. The parameters of positive Sequence: $R=0.0124e^{-3}\Omega/m$, $XL=0.275e^{-3}\Omega/m$, $XC=239.2344M\Omega\cdot m$. Zero Sequence: $R=0.1522e^{-3}\Omega/m$, $XL=1.0314e^{-3}\Omega/m$, $XC=380.807M\Omega\cdot m$.

When a single-phase ground fault occurred at 261ms, 30km distance from the M terminal. The data window was only 5ms, the real fault current waveform was compared with the waveform fitted by the algorithm in this paper as shown in figure 6. The result showed that the waveform were very similar and the errors of the zero-crossing point were less than 0.3ms, which can meet the CFI technology.
4. Conclusion
This paper proposed a new LS algorithm using the change rate of short circuit current after analyzing the basic principles of CFI. The results show that when no noise was included and the data window was greater than 10ms, and the error of short-circuit current zero-crossing prediction did not exceed 0.1ms. When 40dB white noise was contained, the error did not exceed 1ms, extended the data window to 15ms, the error also did not exceed 0.1ms. Using simulated data by PSCAD, the data window was only 5ms, the zero-crossing prediction error did not exceed 0.3ms, which further verified the feasibility of the algorithm in this paper and could meet the requirement of CFI technology.

References
[1] Xiongying Duan, Minfu Liao, Fuhua Ding, et al. Application and Key Technology Analysis of Controlled Switching. High Voltage Apparatus, vol.43, no. 2, pp. 113-117, 2007.
[2] Honglei Li, Zhao Yuan, Ying Feng, et al. Comparisons of Three Zero-Point Prediction Algorithms for Controlled Fault Interruption. Power System Technology, vol. 39, no. 4, pp. 1133-1138, 2015.