# RESEARCH ON RESPONSE OF ROGOWSKI COIL ELECTRONIC CURRENT TRANSFORMER TO TRANSIENT SIGNAL

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## ABSTRACT

*During the running process, Rogowski coil ECT will activate protection malfunction due to abnormal waveform caused by transient signal which is generated by switch operation or short-circuit fault. This paper builds a Rogowski coil ECT model, analyzing signal transformation progress between each link in the transformer, and conducting a simulation experiment as well. Both theoretical analysis and simulation experiment results show that, transient signal waveform is distorted in the integration accumulation operation progress after differential and discrete sampling by Rogowski coil ECT. Because transient disturbance signal, which caused by switch operation or short-circuit fault, contains high-frequency components, while the collector sampling rate is low. According to this question, an improvement measure is proposed that using fourth order Bessel Filter to suppress high-frequency signals, applying collector to complete software integration, and improving A/D sampling rate to 100kHz, in which way to help improve running reliability of Rogowski coil ECT.*

## INTRODUCTION

In intelligent substation, electromagnetic disturbance caused by switch operation or short-circuit fault can lead to abnormal operation of Rogowski coil ECT, thus causing incorrect operation of relay protection device. And this become the most difficult problem in actual operation and key factor affecting its widely application. It also becomes the focus of attention. “The experience of electronic transformer operation still needs accumulated. Relevant system files and calibration standards need further optimized. While the operating experience of conventional transformer in substations with various voltage levels has already been mature. Before the electronic transformer getting mature, all the new established substations should apply conventional transformer with merging unit to achieve on-site analog digital conversion, using fiber upload, in which way not only improve the anti-interference and reliability of signal transmission, but also reduce the configuration amount of transformer secondary winding. So as to reduce the transformer volume and imporve its reliability.” stipulated in 2011 [58]th supplementary document signed by Infrastructure Department of State Grid Corporation.

Researchers all over the world have done a lot of studies[1]-[13] on Rogowski coil ECT. But, currently, there are few analyses on Rogowski coil ECT abnormal work caused by electromagnetic disturbance. Ref[14] discusses about the impact of integral part on transformer transient characteristics. Above references do not study in detail on the transmission progress of Rogowski coil ECT between each link, neither point out the primary reason of generating abnormal waveform. This paper will build a Rogowski coil ECT model, analysing signal transmission between each link in transformer and influence mechanism of Rogowski coil ECT differential and integral process on transient electromagnetic disturbance signal, thereby revealing the generating reason of abnormal waveform in Rogowski coil ECT, and finally proposing an improvement measure of using fourth order Bessel Filter to suppress high-frequency signals, applying collector to complete software integration, and improving A/D sampling rate to 100kHz, in which way to help improve the anti-electromagnetic interference ability of Rogowski coil ECT.

## ROGOWSKI COIL ELECTRONIC TRANSFORMER MODEL

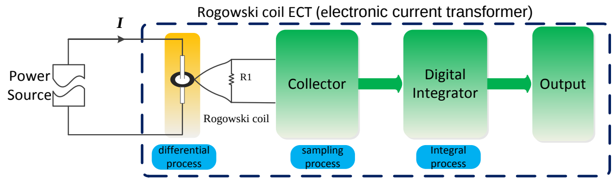



Fig.1 Model of Rogowski coil ECT (electronic current transformer)

Comparing with conventional electromagnetic current transducers, the principle of Rogowski coil electronic current transformer is to measure current by differential and integral. As shown in Fig.1, Rogowski coil electronic current transformer is consisted of Rogowski coil (differential processing), collector (sampling processing) and digital integrator (integral processing).

### Differential Process

Rogowski coil output induced emf equation:

$$e(t) = \mu_0 \cdot N \cdot A \cdot \frac{\partial i(t)}{\partial t} \quad (1)$$

Where $i(t)$ represents primary current, $\mu_0$ represents vacuum magnetic permeability, $N$ represents turns density, $A$ represents single turn area. As equation (1) shown, Rogowski coil transfer characteristics can be regarded as differential on primary signal. From frequency domain point of view, this process only changes the amplitude and phase of the signal, but no effect on the frequency of the original signal. If the primary current contains a large number of higher harmonic, then Rogowski coil output also contains a lot of higher harmonic, and the amplitude of high-frequency component is much larger than that of power-frequency component.

## Sampling Process

To get all information of the signal and restore it in subsequent processing, sampling process should meet the Nyquist Sampling Theory, which means sampling frequency should be greater than twice the highest frequency component of the signal, otherwise, frequency aliasing will occur, resulting in incorrect restoration of signal. Actually, electromagnetic disturbance caused by switch operation or short-circuit fault contains a lot of high-frequency components whose frequency is more than half the sampling frequency, which causes the frequency aliasing in sampling process, generating a lot of DC components and tail current phenomenon.

For illustration, the concept of Sampling Instant Offset is introduced to show the influence of low sampling frequency on signal transmission, and remark it as $\Delta t$ , as Fig.2 shown.

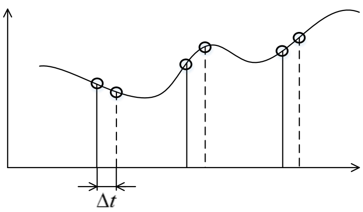



Fig.2 Sketch map for "sampling point offset"

In Fig.2, the solid lines and dotted lines represent two sampling instants for one signal. Although two sampling frequency are the same, the sampling instants on the time axis are different. And this fixed time interval between two instants is called "sampling instants offset", marked as $\Delta t$ .

When sampling frequency meets the Nyquist Sampling Theory, the concept of sampling instant offset will no longer have practical significance, as the signal can be correctly transmitted and finally restored, no matter which signal instant is sampled. Whereas, when sampling frequency doesn't meet the Nyquist Sampling Theory, the concept of sampling instant offset does have practical significance. As frequency aliasing occurs, the generated signals in different sampling instants will be in big difference. So for the same primary currrent, the final output current waveform will be tremdously different with the change of $\Delta t$ .

To correctly analyze the signal change in transmission process in transformer, the influence of "sampling instant offset" can not be ignored. This paper builds the final model as Fig.3 for analysis with adding "time delay" link before sampling to simulate this phenomenon.

With this model, when sampling frequency is constant, the correspondent sampling instant is fixed. In order to simulating "sampling instant offset", the signal waveform from "a" will be translated on the time axis by "time delay", so that to get different point in sampling link by changing time delay. Unless otherwise stated, the signal in subsequent analysis in this section refers to single frequency.

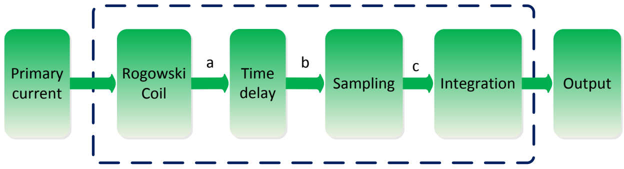



Fig.3 Model for analysis

Firstly, with figure 3, the transfer characteristics of "time delay" link on signal waveform will be analyzed. As mentioned above, "time delay" only translate signal waveform in part "a" on the time axis, and it does not change signal frequency and amplitude. But it changes the signal phase for the following sampling process. Supposed that signal frequency in part "a" is $f_a$ , the signal translation time in "time delay" link is "sampling instant offset", marked as $\Delta t$ , the signal waveform phase in part "a" and "b" respectively labelled as $\theta_a$ and $\theta_b$ , then it can be given by:

$$\theta_b = \theta_a + f_a \Big/ \frac{1}{\Delta t} \bullet 2\pi = \theta_a + 2\pi f_a \Delta t \quad (2)$$

Then, under the condition that sampling process does not meet the Nyquist Sampling Theory, the transfer characteristics of "sampling process" on signal waveform will be analyzed with Fig.3. Different from "time delay", "sampling process" has little effect on signal amplitude, but it can change signal frequency and phase. Supposed signal frequency in part "b" as $f_b$ , sampling frequency as *SF*, the signal frequency after sampling process in part "c" as $f_c$ , then $f_c$ can be obtained by formula (3) (4):

$$n = Int(\frac{f_b}{SF} + 0.5) \quad (3)$$

$$f_c = \left| f_b - nSF \right| \quad (4)$$

Suppose "m" as aliasing times:

$$m = Int(\frac{f}{SF/2}) = Int(\frac{2f}{SF}) \quad (5)$$

Where *Int*() represents round numbers reservation only, that is to say all figures after the decimal point should be discarded.

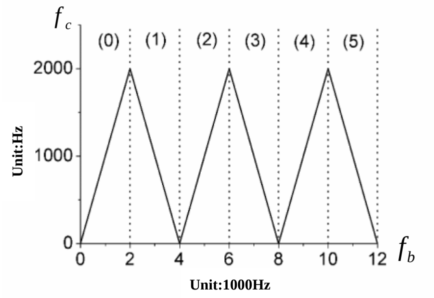



Fig.4 Diagram for frequency alias

Supposed signal phase from part "b" in Fig.3 as $\theta_b$ , sampling frequency as *SF*, sampled signal phase from part "c" as $\theta_c$ :

$$\theta_c = \frac{\pi}{2} + (-1)^m \cdot \theta_b + (-1)^{m+1} \cdot \frac{\pi}{2} \qquad (6)$$

For example, *SF*=4000Hz, then we can figure out that all signal frequency after sampling is not more than 2000Hz and signal frequency aliasing is regular periodic. (as Fig.4) As shown in Fig.4, six sections on horizontal axis, which are divided by dotted line, are used to explain the phase variation of signals with different frequency. The correspondent aliasing times "m" are 0~5 when the signals from sections (0)~(5)generate frequency aliasing. According to formula (6), when $f_c$ figure is in the range of sections (0)(2)(4), the signal phase from "c" and "d" are equal. When $f_c$ figure is in the range of sections (1)(3)(5), the sum of the signal phase from "c" and "d" is $\pi$ .

Finally, based on the above analysis, considering signal from part a in fig.3 contains various frequency components, we take fundamental frequency as example to illustrate signal transfer process from b to c.

In Fig.3, signal contained fundamental sequence from part c can be considered as superposition of two parts. One part is the original contained fundamental sequency from part a, which is less than half the sampling rate and undistorted after transferred to part c. While the other part is distorted from high-frequency signal, such as frequency in Fig.3 that all signal frequency, like 3950Hz, 4050Hz and 7950Hz become 50Hz after sampling process.

## Integral Process

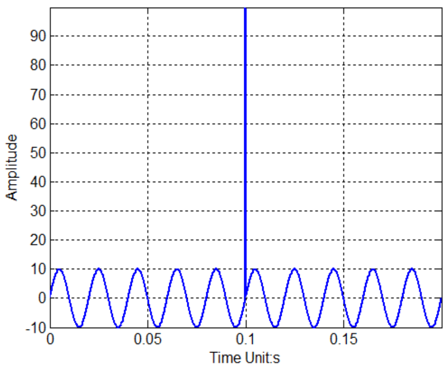
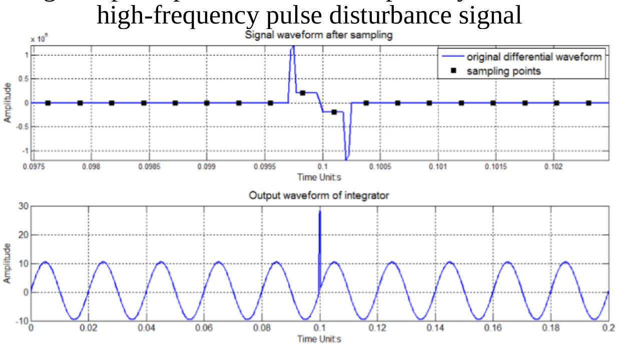
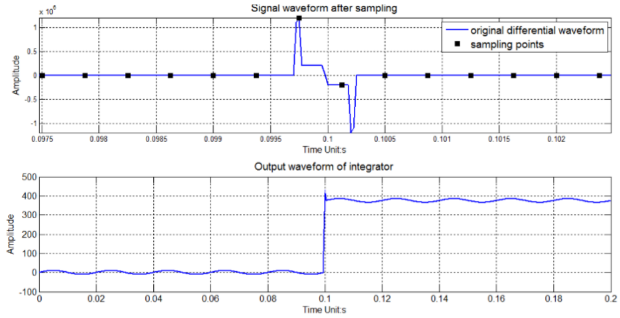



Fig.5 Superimposed waveform of primary current and high-frequency pulse disturbance signal




(a)




(b)

Fig.6 Signal waveform after sampling and output waveform of integrator

As Fig.5 shown, supposed that high-frequency disturbance signal is added to primary current. The continuous curve in Fig.6 represent the differentiated waveform of primary current which is superimposed with high-frequency disturbance signal, and the black blocks represent sampling instants of the collector. It can be seen from Fig.6(a) that the output waveform of integrator is not obviously distorted, as relatively big value of the high-frequency disturbance signal is not collected. While from Fig.6(b), it can be seen that the output waveform of integrator is obviously distorted, as big value of the high-frequency disturbance signal is collected.

## IMPROVING METHOD OF ROGOWSKI COIL ECT SOFTWARE INTEGRATION AND SAMPLING SYSTEM

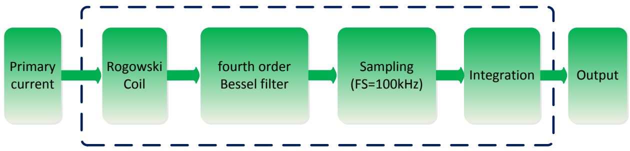



Fig.7 Schematic diagram for rogowski coil electronic transformer (fourth order Bessel filter and Sampling rate FS=100kHz)

To solve the frequency aliasing problem of the higher harmonic integration, the improvement measure is proposed that using fourth order Bessel Filter to suppress high-frequency signals, applying collector to complete software integration, and improving A/D sampling rate to 100kHz, in which way to help improve running reliability of Rogowski coil ECT, as Fig.7 shown.

## Bessel filter

Among the common three lowpass filters, Butterworth type, Chebyshev type and Bessel type, only Bessel filter can make least distortion for input and output waveform, as its phase is linear with frequency in the specific frequency range. But Bessel's frequency response is worse than Butterworth's and Chebyshev's of the same order. In order to get better frequency response, using high-order Bessel filter is necessary. According to electronic transformer application requirement, the cutoff frequency of lowpass filter is chosen to be 2kHz, and the zero frequency group delay of fourth order Bessel filter is less than $0.9\times10^{-4}s$ .The amplitude-frequency characteristics of the fourth order Bessel filter is better than that of the second order RC lowpass filter. Within passband, the phase-frequency characteristics is linear and the normalized group delay is constant.

## Improving sampling rate to 100kHz

The efficient signal frequency looped A/D sampling is controlled within 15kHz after through fourth order Bessel filter. According to Shannon Sampling Theory, it is obvious that frequency aliasing can be eliminated if sampling rate improved to 100kHz.($K$=100/15 ≈ >2). There are three commonly used methods for A/D conversion, successive approximation, sampling and integration, while the latter two converted speed is between a few milliseconds and tens of milliseconds, unable to meet the requirement of relay protection to ECT output characteristic. Thus, using successive approximation A/D chip with high accuracy and fast conversion is a better choice. According to sampling rate calculation, the sampling interval for collector is $T_s$=0.00001s. Triggered timingly by FPGA microprocessor, A/D sampling is activated to complete interruption trigger, and inform FPGA to read A/D conversion data. Considering from the amplitude-frequency characteristics, the approximation degree between its real characteristic and ideal characteristic becomes higher along with the decreasing of $T_s$ value. While $T_s$ value is inversely proportional to sampling spot "N" in a unit time. That is to say, the sampling data become more when the $T_s$ value is smaller, and it brings burden for subsequent data calculation and transformation.

## Simulation experiment

The three-phase line short circuit model is built (as shown in Fig.9. Three phase short-circuit current waveform is shown in Fig.10. At 0.15s, the A phase short-circuit occurs. And after 100ms, the A-phase circuit breaker jumped.

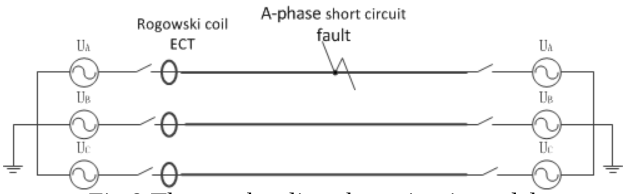
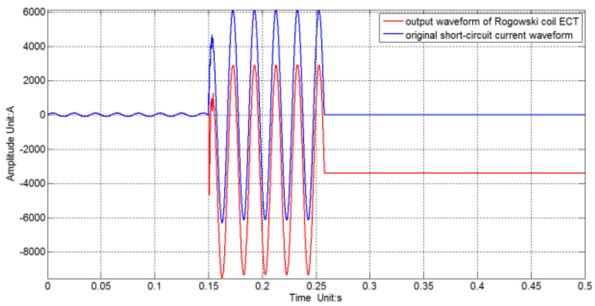
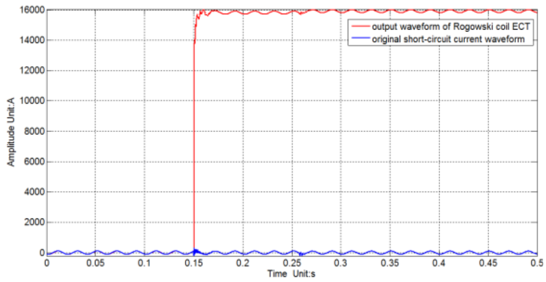


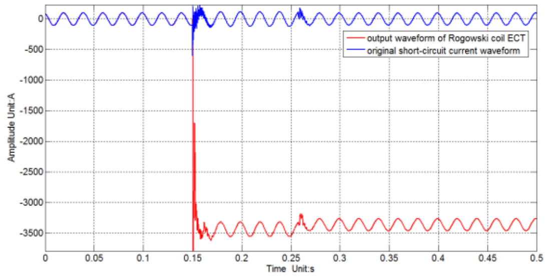

Fig.9 Three-pahse line short circuit model




(a)A phase



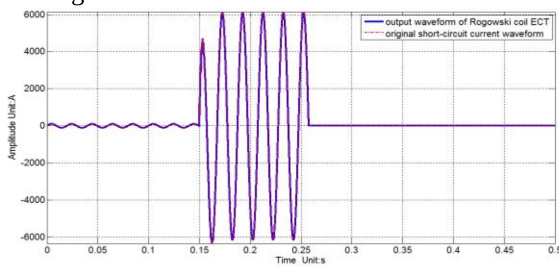

(b)B phase



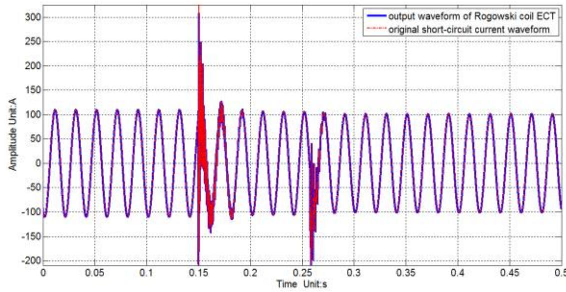

(c)C phase

Fig. 10 The three phase short-circuit waveform and the output waveform of Rogowski coil ECT

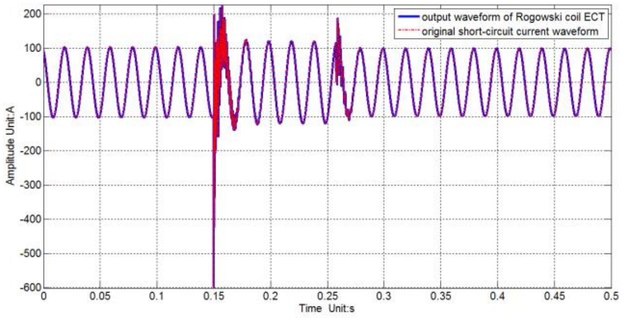
The three phase short-circuit waveform and the output waveform of Rogowski coil ECT are shown in Fig.10. The output waveform is distorted, which is quite different from the original short-circuit current waveform. On short-circuit instant, the short-circuit current contains a lot of high frequency components. The sampling frequency of the collector is relatively low. After sampling and integrating, the output of Rogowski coil ECT is distorted. After using fourth order Bessel filter and improving sampling rate to 100kHz, the output waveform of Rogowski coil ECT is shown as Fig.11. Bessel filter will filter out the high-frequency components before signal enter the collector, then improving sampling rate to 100kHz. And the original waveform will be well restored after integration.




(a)A phase




(b)B phase




(c)C phase

Fig.11 The three phase short-circuit waveform and the output waveform of Rogowski coil ECT (using fourth order Bessel filter and improving sampling rate to 100kHz)

## CONCLUSION

In this paper, Rogowski coil ECT model is built, and signal transformation between each link in transformer is analyzed, simulated analysing the impact mechanism of Rogowski coil ECT differential and integral process on transient electromagnetic disturbance signal. Besides, solutions are proposed finally, and the main conclusions are as follows:

1. The transient electromagnetic disturbance signal caused by switch operation or short-circuit fault is a significant reason for abnormal waveform generated by Rogowski coil ECT.

2. Reducing cut-off frequency of the filter can decrease the amplitude of transferred signal high-frequency components, reducing frequency aliasing extent after sampling process, so as to eliminate abnormal waveform.

3. Improving sampling rate in sampling process can enlarge the right transferred signal frequency range, reducing signal distortion degree, and the output signal tends to be ideal. At the same time, it can be considered as filter matching with sampling. As the simulation experimental results show in this paper, tail current can be eliminated when filter cut-off frequency is 8 harmonic and sampling rate is 10kHz. When the cut-off frequency becomes 60 harmonic, the sampling rate should be improved to more than 100kHz.

4. Signal delay time on the scene is uncontrollable, and its coincident value is a necessary but not sufficient condition for generating abnormal waveform. When the filter cut-off frequency matches relatively well with the sampling frequency, the variety of signal delay time will have little effect on the final results.

5. It is a feasible improvement method by using fourth order Bessel filter to suppress high-frequency signal, improving A/D sampling rate to 100kHz and finishing software integration by collector. And it will help improve the running reliability of Rogowski coil ETC.

### Acknowledgments

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