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# An Analog Low Pass Filter Design of RCD

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The residual current operated protective device (RCD) as a protection facility for the safe operation of the power grid, prevent personal electric shock casualties, and reduce fires, and so on. Currently, the RCD has maloperation, low operation rate and other problems. The reason, most of the RCDs cannot really identify the signal of the biologic shock branch. By the built RCD physical shock test system platforms, collected more than 1,000 groups of shock fault related electrical signals. Through the shock signal spectrum analysis, observed each harmonic variation law. According the signal characteristics of electric shock, selected 1kHz as the analog low pass filter cutoff frequency, using the design idea of Butterworth analog low pass filter calculate the transfer function, design the second-order low pass filter circuit to meet the filtering requirements. It is a foundation for the future analog filter circuit design of electric shock signal in intelligent detection board.

## 1. Introduction

Electric shock is one of the common serious accidents, have the features of high sudden, high personal injury rate, etc. With the rapid increase in industrial production, agricultural production and users electricity consumption, even caused casualty due to current damage (Baskerville, 2002). As important measures to prevent from biologic electric shock or equipment leakage accidents in recent years, RCD has been widely used and promoted in rural low-voltage power grids. But, the residual current device has mis-operation, low operation rate and other problems. The reason, one is affected by the outside interference as installation site environmental, and the other is existed problems of protective device signal detection and setting method of operation value. Currently, the residual current device action or not is based on the detected total leakage current in voltage circuit is greater than the setting values (Li et al., 2011; Guan et al., 2013b), most can not really identify the biologic shock branch current signal, so its principle of operation is defective.

Therefore, to prevent the occurrence of leakage accidents in grid must solve the RCD nuisance tripping and refuse operation issues, requires not only the proper use, but also need to develop self-adaptive RCDs based on the biologic shock current (Han et al., 2014). Many scholars have discussed the leakage signal detection and processing of RCD. Taylor et al. (1995), Kendall (1997) and Martinez et al. (2004) improved the materials and processes of residual current transformer, which is sensing element of the residual current protection device. Li et al. (2008a), Chen et al. (2007) and Liu et al. (2008) chose the good performance microcontroller. Consideration of environmental factors such as temperature, humidity, etc, Li et al. (2008b) corrected the leakage action threshold, and designed an adaptive leakage protection model. Li et al. (2008c) and Wu (2008) proposed leakage protection theory based on residual current variation. These methods improve the technical performance of the RCD to some extent, but do not relate to the detection shock branch current signal, cannot solve the problems of nuisance tripping and refusal operation fundamentally. Li et al. (2010), Guan et al. (2013a) and Han et al. (2014) try to establish the shock current detection model by intelligent calculation, provide a theoretical basis for the development of the new generation of self-adaptive residual current device based on biologic electric shock current component. To detect and identify biologic shock current signal is one of the key issues of RCD nuisance tripping and refusal operation. So, in order to get more accurate shock current signal, it must be filtered before the signal acquisition. The observed signal get from experiment will first to filter some ingredients and interference by the prepositive analog filter, thus obtaining analog signals. It sampled the analog signal by the setting sample frequency, gets the discrete signal post-processing needs and then digital signal processing. By the built residual current device physical shock test system platforms (Li et al., 2010; Han et al., 2014), it collected more than 1,000 groups of electrical signals relate to shock fault.

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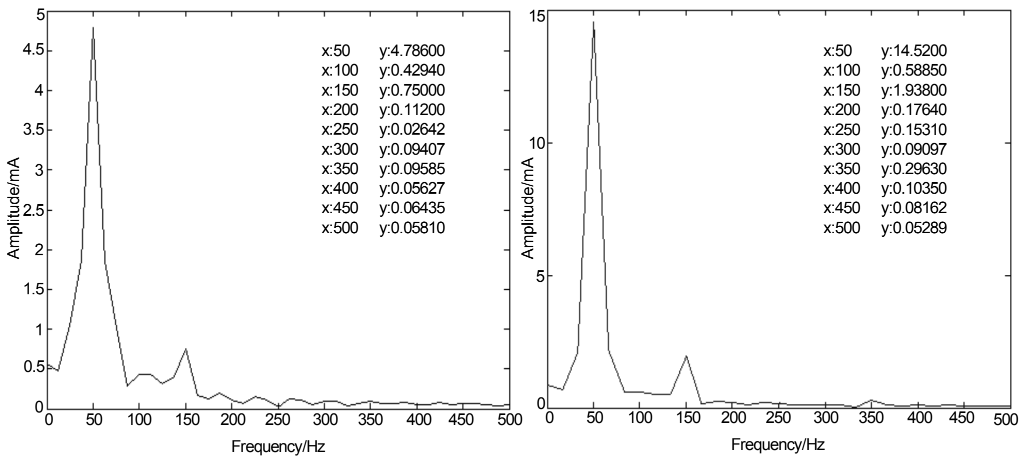
In this paper, analysis of the shock signal spectrum, observed each harmonic variation rule. According to the electric shock signal characteristics, it selected the cutoff frequency. Using the design idea of Butterworth analog low pass filter calculates the transfer functions, using the transfer function gets the circuit element parameters. The hardware circuit implementation could meet the filtering effectiveness and accuracy.

## 2. Shock signal spectrum analysis

Shock signal from the shock physics experiments is discrete time domain signal. For the spectral characteristics and waveform characteristics complexity of the biologic shock fault residual current transient signal, using FFT (Fast Fourier Transform) to analyze its spectral characteristics, and grasp the change process of DC component, fundamental and harmonic components in electric shock fault.

### 2.1 FFT-based leakage current spectrum analysis

Based on the residual current operated protective device physical shock test system platform, large limbs mammals as experimental subjects, taken directly tied electric shock scenarios human electric shock. Experiment subjects is the residual current form biologic shock fault process, the physics experiment platform acquired. Due to the experimental electric shock signal acquisition in time domain waveform, signal characteristics can not be analyzed, only the signal changes into the frequency domain spectrum, the signal can be quantitative interpretation. Use Matlab Fast Fourier Transform subfunction $y = fft(x)$ , transferred shock currents in the program, you can get an electric shock current and total leakage current of the magnitude spectrum. The interception of 0 to 500 Hz amplitude spectral image was shown in Figure 1.




a) Electric shock current b) Total leakage current

*Figure 1: Magnitude spectrum image*

It can be seen that, the amplitude spectrum of an electric shock current and total harmonic leakage current has similar trend of magnitude, in which the maximum amplitude is the third harmonic, with the growth of the frequency, although higher harmonic reduced, but still exists. Each harmonic of the total leakage current changes slowly, compared with the shock current, amplitude slightly larger.

### 2.2 Harmonic scale drawing at different times

Using ZH-102 Portable Power Disturbance analyzer (Wuhan Zhongyuan Huadian Science & Technology Co., Ltd, China) internal software analyzes the shock signal harmonic, which can obtain harmonic analysis diagram, as shown in Figure 2, the harmonic scale drawing of the total leakage before the current shock, shock time and after shock.

Shock current and total leakage current have the similar harmonic scale drawing. Before the electric shock, the total leakage current harmonic has the similar characteristics with power system harmonic, almost only has odd harmonics, which the fifth harmonic larger. In shock moment, even harmonics surge, the amplitude of each higher harmonic was significantly increased.

After the shock, when the circuit reaches a steady state, the higher harmonics amplitude has been reduced compared with the electric shock time

Observed the harmonic analysis diagram of a periodic from electric shock time and after shock by Fault Recorder, we can see the 2nd harmonic is the maximum amplitude of the first half periodic, it begins to decrease after the half periodic, each harmonic amplitude value is also significantly reduced, after a periodic, the total leakage current harmonic components remained unchanged, the maximum amplitude is the 3rd harmonic. Biologic shock impacts the circuit total leakage current, not only increases the amplitude of the current, but also affect the current harmonic components.

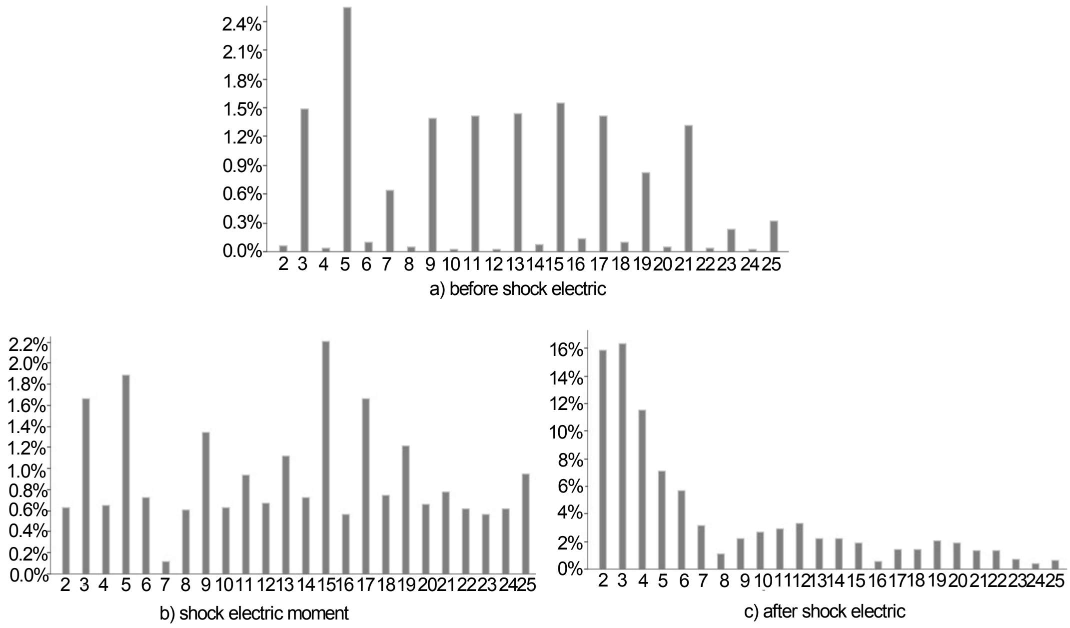



*Figure 2: The proportion of 2 to 25 times harmonic of the total leakage current at different times*

## 3. Low-pass filter designs

Due to the high harmonic amplitude surge at the shock moments, in order to meet the requirements of the sampling theorem, the maximum frequency of the input signal must be limited. It is necessary to design an analog low-pass filter suitable for shock current signal detection. In front of the digital system, usually there is an analog filter for weak signal pre-processing. Before sampling quantify, need to restrict the highest frequency of processing signal by the analog filter. Commonly used analog low-pass filter includes Butterworth low-pass filter, Chebyshev low-pass filter and Bessel low-pass filter. Considering the shock current signal almost in mA level, it belongs to the weak current signal, and has many high frequency components, waveform is very complex, so chosen the best performance Butterworth analog low-pass filter do the signal processing.

Butterworth low-pass filters with maximally-flat frequency response characteristics, and having a good linear phase characteristics and so on. Higher-order Butterworth filter frequency response approximates an ideal low-pass filter. Butterworth low-pass filter magnitude squared function as

$$\left|H(j\Omega)\right|^2 = \frac{1}{1+(\Omega/\Omega_c)^{2N}} \tag{1}$$

Where, *N* is a positive integer, representing the order of the filter; $\Omega_c$ called the cutoff frequency, i.e., the frequency of -3dB as amplitude is decreased. Set filter pass band frequency $\Omega_p$, pass band gain $\alpha_p$; stop band frequency $\Omega_s$, stop-band attenuation $\alpha_s$. According to formula (1) can be obtained

$$\begin{cases} \left|H(j\Omega_p)\right|^2 = \dfrac{1}{1+(\Omega_p/\Omega_c)^{2N}} \\ \left|H(j\Omega_s)\right|^2 = \dfrac{1}{1+(\Omega_s/\Omega_c)^{2N}} \end{cases} \tag{2}$$

Let $\alpha_p = -20\lg(\left|H(\Omega_p)\right|)$ and $\alpha_s = -20\lg(\left|H(\Omega_s)\right|)$ in (2), obtained

$$N = \frac{\lg\sqrt{\dfrac{10^{\Omega_p/10}-1}{10^{\Omega_s/10}-1}}}{\lg(\Omega_p/\Omega_s)} \tag{3}$$

Solve for $\Omega_c$ , its pole is

$$s_k = \Omega_c \cdot \exp[j(\frac{1}{2}+\frac{2k-1}{2N})\pi] \quad (4)$$

The $s$ plane left half plane poles conferred $H(s)$ , as

$$H(s) = \frac{\Omega_c{}^N}{\prod_{k=0}^{N-1}(s-s_k)} \quad (5)$$

To the power frequency grid, electric shock frequency signal will not exceed 1 kHz, and higher than 20 times harmonics the shock exist, large amplitude. Therefore, the analog low-pass filter cutoff frequency set at 1 kHz. The test study found that the first-order filter frequency characteristics decline rate is too slow, poor filtering effect. Compared with 2nd-order, 3rd and higher-order has no obvious improvement in the effect of filtering out noise from the shock signals, and that it increases the hardware cost and technical difficulty. Taken together, chosen the 2nd-order analog filter of 1 kHz cut-off frequency to filter out shock signals noise as noise filters. Filter transfer function

$$H(s) = \frac{3.9478\times10^7}{s^2+8.8858\times10^3 s+3.9478\times10^7} \quad (6)$$

The magnitude-frequency characteristics and phase-frequency characteristics shown in Figure 3, the filter cutoff frequency is 999 Hz, meet the design requirements.
Use resistance R, inductance L and capacitance C constitute a simple 2nd-order passive analog filter. The transfer function can be as

$$H(s) = \frac{1}{LCs^2+RCs+1} \quad (7)$$

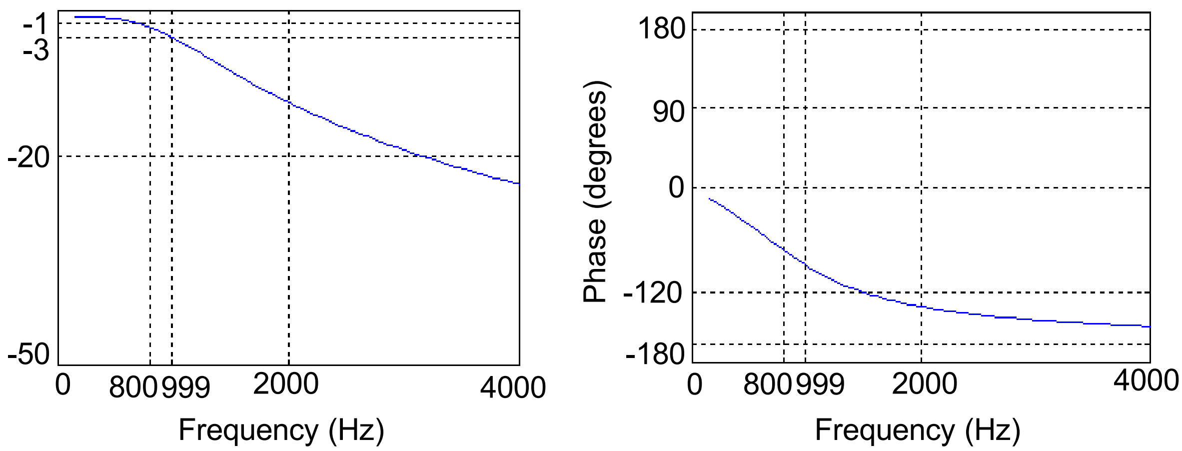



*Figure 3: Magnitude-frequency and phase-frequency characteristic curve of 2nd-order filter*

Contrast to formula (6), given the capacitance as C, you can solve for the inductance L and resistance R. Since difficult to obtain accurate inductance element, can choose 2nd-order active low-pass filter circuit, shown in Figure 4. In order to calculate conveniently, general admission $R_1 = R_2 = R$ , $C_1 = C_2 = C$ .

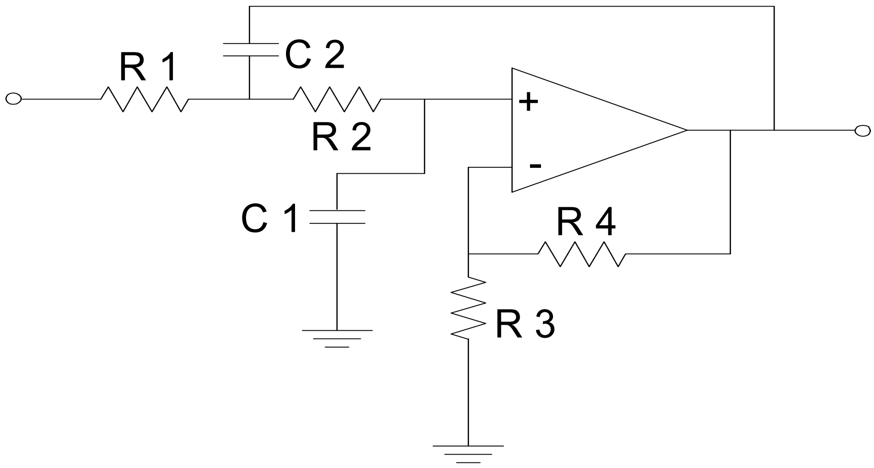



*Figure 4: 2nd-order active low-pass filter circuit*

The transfer function model of 2nd order active low-pass filter circuit can be written as

$$A(s) = \frac{A_0 \omega_n{}^2}{s^2 + \frac{\omega_n}{Q} s + \omega_n{}^2} \tag{8}$$

Where $\omega_n = \frac{1}{RC}$, $Q = \frac{1}{3 - A_{VF}}$. $\omega_n$ is 3dB cut-off frequency.

As the highest shock signal frequency does not exceed 1 kHz, so the upper cut-off frequency is $f_H = \frac{1}{2\pi RC} = 1kHz$.

When Q=0.707, it is called a Butterworth filter, can be obtained $A_{VF} = 1.586$.

Typically, capacitance C is in microfarads order of magnitude or less, so let $C = 0.01\mu F$, then $R = \frac{1}{\omega_n C} = 15.9k\Omega$.

Since $A_{VF} = 1 + \frac{R_4}{R_3} = 1.586$, as well as the two inputs external resistors of the operational amplifier must be balanced, $R_4 // R_3 = 2R$, then $R_3 = 86k\Omega$, $R4 = 50.4k\Omega$.

By building the circuit, the filter was tested, the results showed that when the input frequency high, the designed filter circuit could meet the filtering validity and accuracy.

## 4. Conclusions

Using Fast Fourier Transformation principle, programming with Matlab, the shock signal spectrum was analyzed. By the amplitude spectrum graphics and harmonic proportion figure shows that, the higher harmonic amplitude was significantly increases in the electri shock time, and the biologic shock had an impact on harmonic amplitude and the components of the total leakage current. According the shock signal frequency is not higher than 1 kHz, as a cut-off frequency, calculated Butterworth low-pass filter transfer function, designed 2nd-order passive and active low-pass filter circuit, met the design requirements, it is a foundation for the future analog filter circuit design of electric shock signal in intelligent detection board.

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**References**

Baskerville, J. R. 2002. Focal lingual dystonia, urinary incontinence, and sensory deficits secondary to low voltage electrocution: case report and literature review. Emergency Medicine Journal, 19(4), 368-371.

Chen, K., Ouyang, J., & Yin, K. 2007. Study on intelligent leakage protective instrument based on DSP. Yangtze River, 38(8), 158-159.

Guan, H.O., Du, S.H., Li, C.L., Su, J., Liang, Y., Wu, Z.C., & Shao, L.M. 2013a. Recognition of electric shock signal based on fir filtering and RBF neural networks. Transactions of the Chinese Society of Agricultural Engineering, 29(8), 187-194.

Guan, H.O., Du, S.H., Su, J., Ouyang, Y.P., Zhu, J.J., Liang, Y., Li, C.L., & Shao, L.M. 2013b. An automatic and quick detection model of electric shock signals. Power System Technology, 37(8), 2328-2335.

Han, X.H., Du, S.H., Su, J., Guan, H.O., & Shao, L.M. 2014. Determination method of electric shock current based on parameter-optimized least squares support vector machine. Transactions of the Chinese Society of Agricultural Engineering, 30(23), 238-245.

Kendall, D. 1997. Development of high permeability cores for earth leakage protection devices. Proceedings of the 1997 5th International Conference on Factory 2000- The Technology Exploitation Process. Stevenage, Herts, UK: IEE Conference Publication, 34-36.

Li, C.L., Du, S.H., Su, J., Xia, Y., & Huang, J. 2011. A novel detecting method of electric shock signal based on wavelet transform and chaotic theory. Power System Protection & Control, 39(10), 47-52.

Li, C.L., Su, J., Du, S.H., Xia, Y., Zhang, J.J., & Zhang, L.M. 2010. Detecting model of electric shock signal based on wavelet analysis and BP neural network. Transactions of the Chinese Society of Agricultural Engineering, 26(supp.2), 130-134.

Li, K.C., Liu, J.F., Huang, H.Y., & Zhang, C.H. 2008a. Research on digital residual current operated protective device based on single chip microcomputer of msp430. Relay, 36(8), 64-67.

Li, K., Lu, J.G., Wu, Y., Yue, D.W., Hou, S.M., Yuan, J.L., & Zhang, G.Y. 2008b. Adaptive technology of leakage current operation protection and its application. Transactions of China Electrotechnical Society, 23(10), 53-57.

Li, K., Lu, J.G., Yue, D.W., Wang, Y., Gu, Q.L., & Lin, Y.Z. 2008c. Identification technology of leakage current and its method. Low Voltage Apparatus, (23), 1-4.

Liu, Z.X., Li, G.S., Zhang, C.Y., & Huang, T. 2008. Selective leakage protection for underground distribution networks based on DSP. Safety in Coal Mines, (3), 26-29.

Martinez, L., Rakowski, R., & Cecelja, F. 2004. Design of a magneto-optic residual current device using aqueous ferrofluid as the sensing material. Proceedings of the 21st IEEE Instrumentation and Measurement Technology Conference. Piscataway, New Jersey, USA: IEEE, 804-807.

Taylor, C. J., Twynham, S. C., Powell, S. C., Adl, P., & Rakowski, R. T. 1995. A magnetoresistive residual current sensor. IEE Colloquium on Advances in Sensors. Stevenage, UK: IET, 5/1-5/6.

Wu, Y., Li, K., Yue, D.W., Chi, C.C., & Li, Z.H. 2008. Theory and method of eliminating operating dead zone of residual current protection. Transactions of China Electrotechnical Society, 23(6), 44-49.