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The Grid Voltage's Asymmetrical Fault Detection Method based on Variable-Step LMS Adaptive Notch Filter Algorithm

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Abstract. For wind turbine systems (WTS), the grid voltage fault detection algorithm determines the response speed of WTS to grid voltage fault. This paper proposed a sort of voltage asymmetrical fault detection method, to detect negative-sequence component in grid voltage, variable-step (VS) least mean square (LMS) adaptive notch filter (ANF) is applied to eliminate the 2nd-harmonic frequency component. The application of ANF can separate negative-sequence component from grid voltage, therefore the voltage asymmetrical fault can be detected; the self-tuning of controllable parameters of ANF can be realized by the LMS adaptive algorithm, which is convenient and efficient in practical application; furthermore, because the variable step size adjustment is adopted, the contradiction between convergence rate and steady-state error of ANF can be solved. The MATLAB/Simulink simulation and FFT analysis results are in conformity with the theoretical analysis, which proves the feasibility of the method.

1. Introduction

The grid voltage fault detection method is significant for research of WTS. Through the continuous efforts of scientists, a variety of the grid voltage's asymmetrical fault detection algorithms have been proposed. Several conventional voltage fault detection methods are elaborated to achieve grid voltage fault detection, such as RMS method, peak voltage method and fundamental component method^[3]. The existing modified voltage asymmetrical fault detection methods are listed as follows: The voltage sag detection method based on dq-PLL is proposed, and a sequence separation method based on second-order generalized integral is adopted^[1]. The novel integrated morphology-dq transportation is adopted to separate the negative-sequence component of grid voltage^[2]. The voltage sag detection based on short time Fourier transform has been proposed, which can increase the accuracy^[4]. The voltage fault detection method based on soft PLL algorithm is proposed^[5]. The voltage sag detection method based on least error square (LES) filter is proposed to increase the response speed^[6]. Nevertheless, the calculation of these modified algorithms is complex, which is adverse to promoting the efficiency. This paper proposed a sort of voltage asymmetrical fault detection method. The method converts three-phase voltage into a negative sequence synchronous coordinate system, in order to detect the negative-sequence component, the VS-LMS ANF is adopted to remove the 2nd-harmonic frequency component.



The ANF algorithm is applied into the electrical engineering domains widely, such as harmonic component detection, power measurement and active power filter (APF)^[11-14]. Due to the adoption of VS LMS ANF in this method, the parameters of the digital ANF can achieve the self-tuning by LMS algorithm, which is convenient and effective in practical application. Due to the adoption of variable-step adjustment algorithm in ANF, the step size can be tuned adaptively by the error signal of ANF, and the contradiction between the convergence rate and steady-state error of the ANF can be solved.

2. Negative-order synchronous rotation coordinate transform

The proposed method is suitable for the detection of multi-kind voltage asymmetrical fault, and this paper takes single-phase voltage fault for example to elaborate. The principle of negative-order synchronous coordinate transform is to distil negative sequence component of grid voltage according to Eq. (2)^[9], and it can be utilized into the voltage asymmetrical fault detection by detecting negative sequence-component of grid voltage. When grid is under A-phase voltage asymmetrical fault, the three-phase grid voltage can be expressed as Eq. (1). The σ in Eq. (1) is the fault's level of grid voltage^[7].

$$\begin{cases} u_A = (1 + \sigma)|u_p|\sin(\omega_p t) \\ u_B = |u_p|\sin\left(\omega_p t - \frac{2\pi}{3}\right) \\ u_C = |u_p|\sin\left(\omega_p t + \frac{2\pi}{3}\right) \end{cases} \quad (1)$$

$$\begin{cases} u_\alpha = \frac{2}{3}(u_a - \frac{1}{2}u_b - \frac{1}{2}u_c) \\ u_\beta = \frac{2}{3}(\frac{\sqrt{3}}{2}u_b - \frac{\sqrt{3}}{2}u_c) \end{cases} \quad \begin{cases} u_d = \cos\left[-(\omega_p t - \frac{\pi}{2})\right]u_\alpha + \sin\left[-(\omega_p t - \frac{\pi}{2})\right]u_\beta \\ u_q = -\sin\left[-(\omega_p t - \frac{\pi}{2})\right]u_\alpha + \cos\left[-(\omega_p t - \frac{\pi}{2})\right]u_\beta \end{cases} \quad (2)$$

According to symmetrical component method, the positive-sequence, negative-sequence and zero-sequence component of the 3-phase voltage (1) can be expressed as Eq. (3). Substitute (3) into (2), the result of the negative-order synchronous transform can be calculated, which is expressed as Eq.(4).

$$\begin{cases} u_{A+} = \frac{3+\sigma}{3}|u_p|\sin(\omega_p t) \\ u_{B+} = \frac{3+\sigma}{3}|u_p|\sin\left(\omega_p t - \frac{2\pi}{3}\right) \\ u_{C+} = \frac{3+\sigma}{3}|u_p|\sin\left(\omega_p t + \frac{2\pi}{3}\right) \end{cases} \quad \begin{cases} u_{A-} = \frac{\sigma}{3}|u_p|\sin(\omega_p t) \\ u_{B-} = \frac{\sigma}{3}|u_p|\sin\left(\omega_p t + \frac{2\pi}{3}\right) \\ u_{C-} = \frac{\sigma}{3}|u_p|\sin\left(\omega_p t - \frac{2\pi}{3}\right) \end{cases} \quad \begin{cases} u_{A0} = \frac{\sigma}{3}|u_p|\sin \omega_p t \\ u_{B0} = \frac{\sigma}{3}|u_p|\sin \omega_p t \\ u_{C0} = \frac{\sigma}{3}|u_p|\sin \omega_p t \end{cases} \quad (3)$$

$$\begin{cases} u_d = u_{d+} + u_{d-} + u_{d0} = -\frac{3+\sigma}{3}|u_p|\cos 2\omega_p t + \frac{\sigma}{3}|u_p| \\ u_q = u_{q+} + u_{q-} + u_{q0} = -\frac{3+\sigma}{3}|u_p|\sin 2\omega_p t \end{cases} \quad (4)$$

According to Eq. (4), in negative-order synchronous rotation coordinate d-axis, the positive-sequence component is transformed into 2nd-harmonic frequency component u_{d+} , and the negative-sequence component is transformed into dc component u_{d-} . Therefore, the 2nd-harmonic frequency component u_{d+} in Eq. (4) need to be removed to achieve voltage asymmetrical fault detection function.

3. The application of variable-step LMS ANF in voltage asymmetrical fault detection

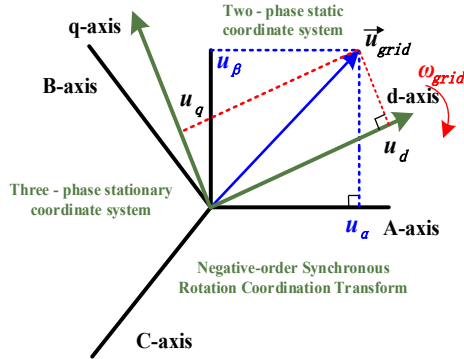


Figure 1. Negative-order synchronous coordinate

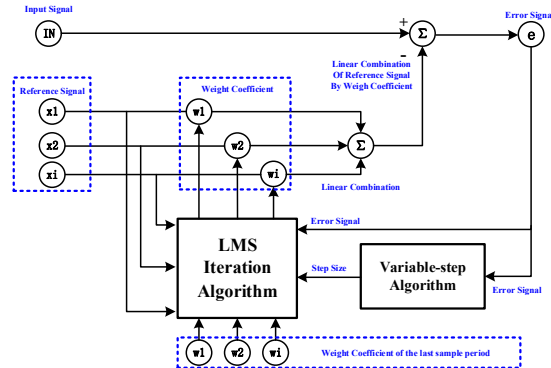


Figure 2. Principal diagram of LMS-ANF

This paper adopted VS-LMS ANF algorithm to achieve the detection of voltage asymmetrical fault.

The structure block diagram of the ANF is shown as Figure 2. By the tuning of weight coefficient according to LMS iteration algorithm, when the algorithm converges, the error signal is minimum, and the linear combination of reference signals has the similarly characteristics to input signal of the ANF, therefore the specific frequency component of input signal can be eliminated [8].

Due to the composition of input signal u_d component according to Eq. (4), the reference signal $x_1(t_k)$, $x_2(t_k)$ is set to 2nd-harmonic frequency, and fundamental frequency $\omega_p(t_k)$ of the grid voltage can be acquired from PLL. The t_k represents time of the k th sampling period. The reference signal $x_3(t_k)$, $x_4(t_k)$ is set to dc frequency. The reference signal of ANF is expressed as Eq. (5).

$$x_1(t_k) = \sin[2\omega_p(t_k)] \quad x_2(t_k) = \cos[2\omega_p(t_k)] \quad x_{3,4}(t_k) = 1 \quad (5)$$

The error signal of the ANF is expressed as Eq. (6), the $x(t_k)$ is the input signal of ANF.

$$e(t_k) = x(t_k) - \sum_{i=1}^4 w_i(t_k)x_i(t_k) \quad (6)$$

The ANF's weight coefficient's self-tuning procession based on LMS algorithm is as Eq. (7), which is decided by step size, corresponding reference signal and the error signal [8].

$$w_i(t_k) = w_i(t_{k-1}) + 2\mu(t_{k-1})x_i(t_{k-1})e(t_{k-1}) \quad (i=1,2,3,4) \quad (7)$$

The $\mu(t_{k-1})$ in Eq. (8) is the step size of the ANF. It is noticeable that fixed step has its defects. The adoption of large step can increase the convergence speed of the system, while it would cause the oscillation. Nevertheless, the adoption of small step size can reduce the oscillation, but the convergence speed is also decreased. Therefore, the variable-step adjusting is adopted, and the formula between step size and error signal ANF is expressed as Eq. (8). When error signal is large, the large step size would be adopted to increase convergence speed, while the error is small, the small step size is adopted to reduce the oscillation and decrease steady-state error. In contrast with fixed-step adjusting, the variable step size settles the contradiction between convergence rate and the steady-state error^[10].

$$\mu(t_k) = \beta[1 - \exp(-\alpha|e(t_k)|^2)] \quad (8)$$

The Eq. (9) is the dc component of input signal, which can be used as desired detection signal of voltage fault detection. When ANF system is stable, the (9) can be regarded as dc component in Eq. (4).

$$x_d(t_k) = w_3(t_k)x_3(t_k) + w_4(t_k)x_4(t_k) \quad (9)$$

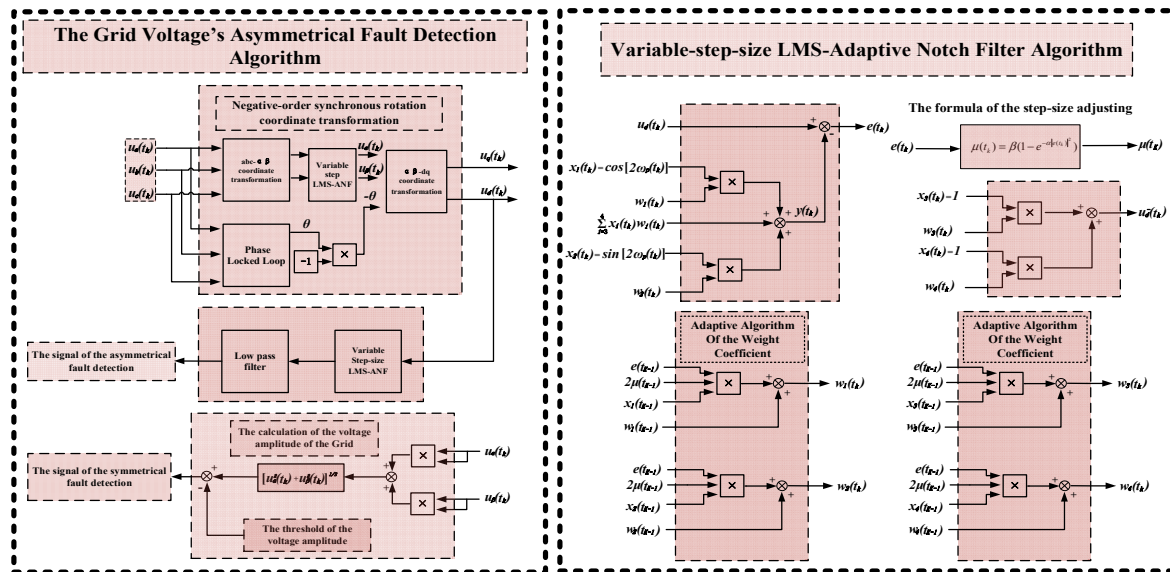


Figure 3. The schematic diagram of the voltage asymmetrical fault detection algorithm

According to Eqs. (4) to (9), the schematic diagram of grid voltage asymmetrical fault detection method is shown as Figure 3. The parts of this proposed method are as follows: (1) Negative-sequence synchronous dq-coordinate transform part; (2) variable-step LMS-ANF part; (3) Asymmetrical grid voltage fault detection part.

4. Simulation results and analysis

The MATLAB/Simulink model based on Figure 3 has been built. The time of voltage asymmetrical fault is set to 1s, and the time of the fault recovery is set to 3s. The sample period of the simulation is set to 200 μ s. The parameters of the variable-step adjustment are set as: $\alpha=0.01$, $\beta=0.02$, the original value of the weight coefficient is set as 0.1. The MATLAB/Simulink simulation results of the grid voltage asymmetrical detection method based on Figure 1 are shown as Figure 4, Figure 5 and Figure 6.

4.1. The simulation results of voltage asymmetrical fault detection method

In Figure 4, picture (a1), (a2) show the waveform of grid voltage. Picture (b1), (b2) show the negative-order synchronous coordinate transform results of grid voltage, and there are both 2nd-harmonic frequency component and dc component in it under the voltage asymmetrical fault. The (c1), (c2) in Figure 4 show that the linear combination curve of reference signal can fit the curve of ANF's input signal well. The (d1), (d2) in Figure 4 show the results of the grid voltage asymmetrical fault detection algorithm, and the 2nd-harmonic frequency component is eliminated by VS-LMS ANF algorithm.

The (d1), (d2) in Figure 4 indicate that the grid voltage asymmetrical detection method can achieve the detection of negative-order component in three-phase grid voltage. It can be seen in (d1), (d2) in Figure 4, while the grid is during normal operation, the negative-order component is approximate zero, and while the grid is under the three-phase asymmetrical fault operation, the negative-order component of the voltage is related to fault severity.

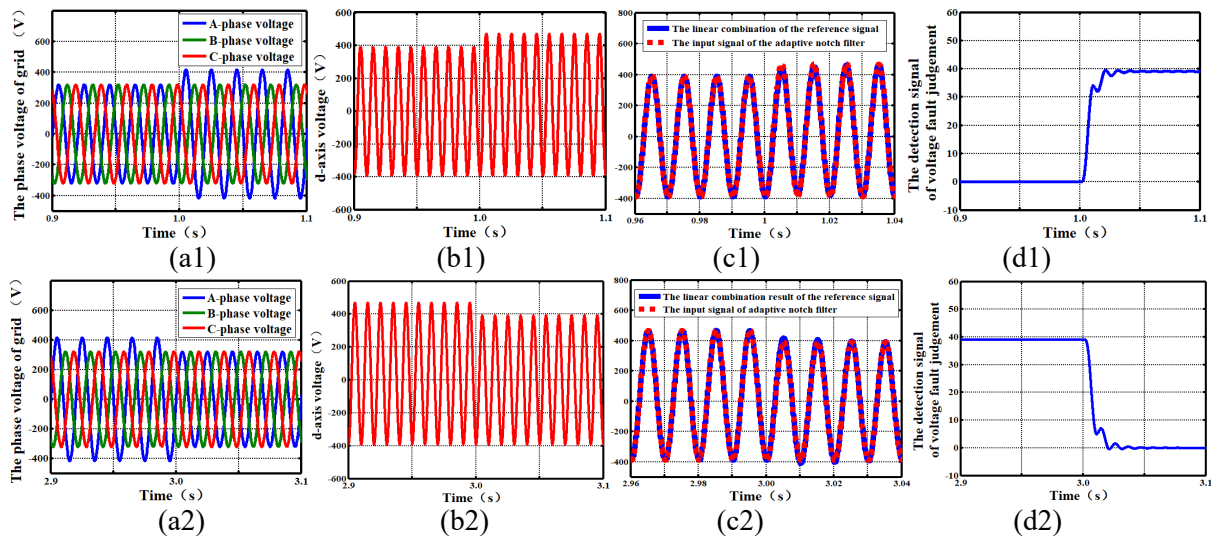


Figure 4. The simulation results of the voltage asymmetrical fault detection

4.2. The simulation results of weight coefficients of LMS-ANF

The simulation results of weight coefficients of LMS-ANF are shown in Figure 5, it can be seen in (e1), (e2), (f1), (f2), (g1), (g2), (h1), (h2) that the weight coefficients of the ANF can be tuned adaptively by LMS algorithm, which is convenient and efficient in practical application of this method.

The parameters w_1 and w_2 represent the weight coefficients of the 2nd-harmonic frequency reference signals $x_1(t_k)$, $x_2(t_k)$, and the parameters w_3 , w_4 represent the weight coefficients of the dc frequency reference signals $x_3(t_k)$, $x_4(t_k)$, and the parameter w_3 is equal to parameter w_4 . It can be seen that the weight coefficients change dramatically at the time of fault occurring and recovering, and it is beneficial to system's rapid response to transient state process according to Eq. (6).

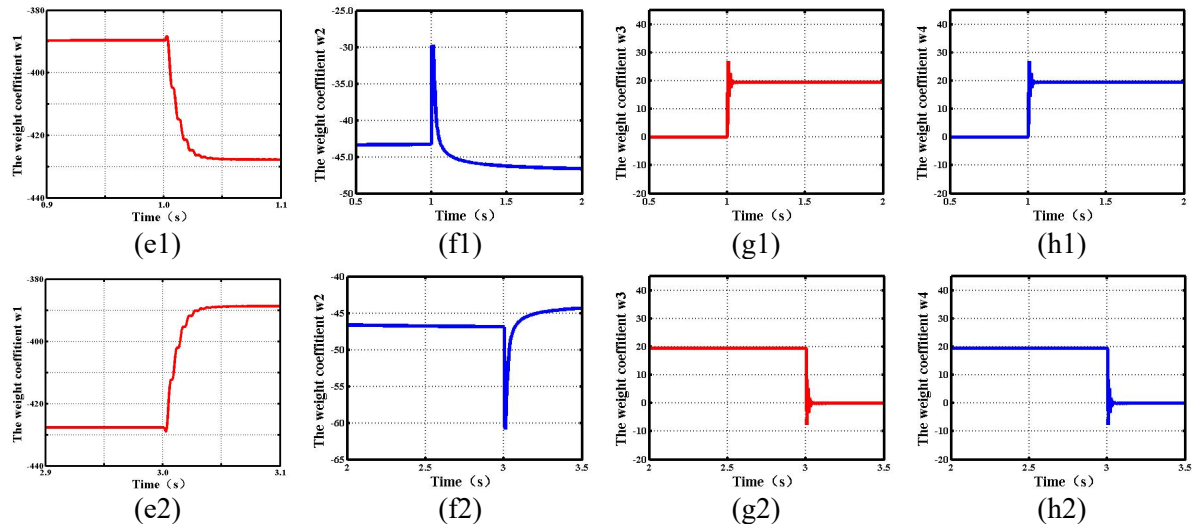


Figure 5. The simulation results of the weight coefficient of the ANF's system

4.3. The simulation results of variable step size adjustment of LMS-ANF

The (i1), (i2), (j1), (j2) of Figure 6 show that the step size of the ANF system can be tuned by the error signal of ANF adaptively. The (i1) demonstrates the error signal while A-phase voltage swell fault occurs, and (j1) demonstrates the step size signal of ANF while the fault occurs. Due to the adoption of the variable step size, while error signal of ANF is large, the large step is adopted; while the system is stable, the error signal is small, and the small step size is adopted to prevent the oscillation of the

system. Therefore, the contradiction between step size and steady-state error of system is solved by variable step size adjustment algorithm. The (i2), (j2) demonstrate the error signal and step size while A-phase voltage swell fault recovers, and the analysis of them is same as (i1) and (j1) in Figure 6.

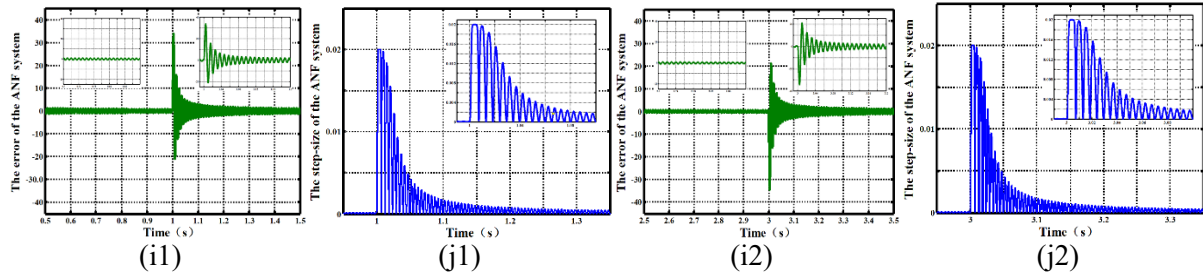


Figure 6. The simulation results of the error signal and step size of ANF

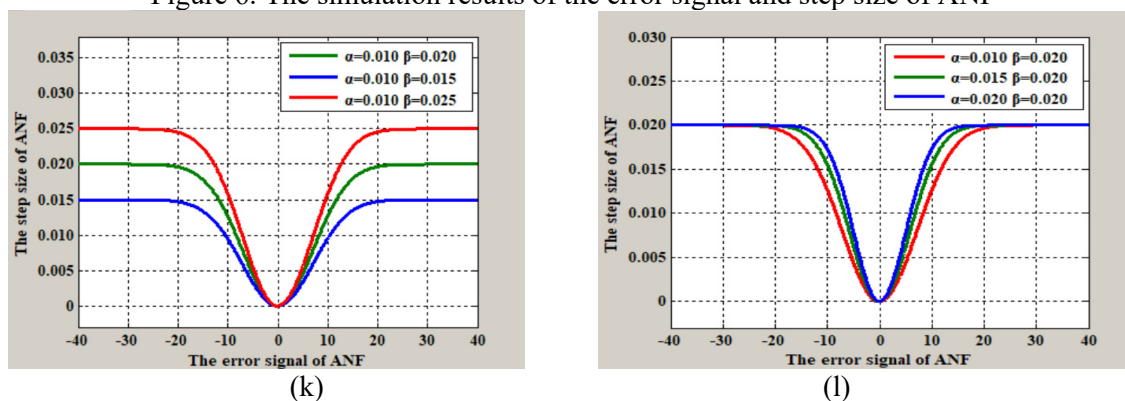


Figure 7. The function graph of the error signal and step size of ANF

The Figure 7 indicates the function graph of the error signal and step size in ANF based on Eq. (8). The upper limit value of the step size is determined by parameter β ; the change rate of step size with error signal is determined by parameter α . It can be seen in Figure 7, if the parameters of Eq. (8) are determinate, when algorithm approximately converges, the change rate of step size is small, which can reduce the oscillation when the system is entering a steady state. When the error signal of the system is large, the relationship between the step size and error signal is approximately linear in Figure.7, which can increase the sensitivity of algorithm step size to error signal's rate of change.

4.4. The FFT analysis results

The Figure 8 demonstrates the results of fast Fourier transform (FFT) analysis of the d-axis voltage u_d and the detection signal u_{d-} in MATLAB/Simulink. According to Figure 8 (m1), when grid is under normal operation, there is only 2-nd frequency component in d-axis voltage u_d . The (n1) demonstrates that there are both 2-nd harmonic frequency component and dc component in d-axis voltage when the grid voltage is under asymmetrical fault. The picture (o1) shows that the 2-nd frequency component in d-axis voltage u_d is eliminated due to the application of VS-LMS ANF algorithm.

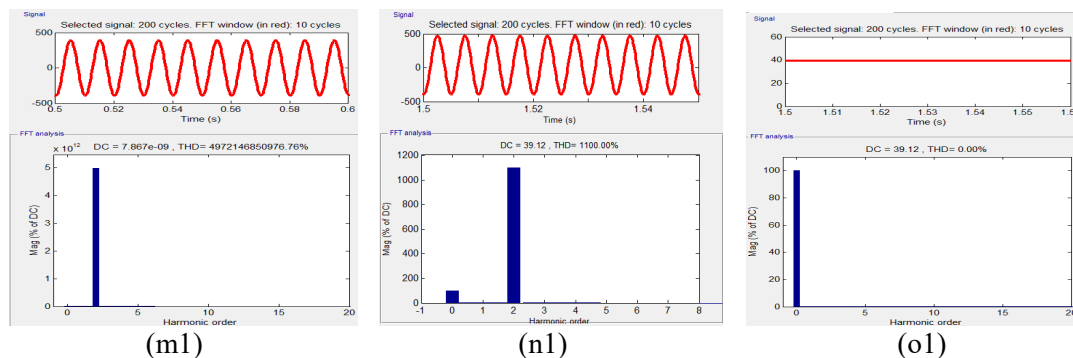


Figure 8. The fast Fourier transform analysis of A-phase voltage swell fault ($\sigma = 0.3$)

To verify the function of this fault detection algorithm in different kinds of voltage asymmetrical fault, the simulation research and FFT analysis under two-phase grid voltage swell fault are also accomplished. The Figure 9 is the fast Fourier transform analysis results of BC-phase voltage asymmetrical swell fault. The picture (o2) shows that the 2-nd frequency component u_{d+} in d-axis is eliminated by VS-LMS ANF algorithm, which can increase the responsibility of the voltage asymmetrical fault detection method. In conclusion, the proposed grid voltage fault detection algorithm can achieve the detection of the multi-kind voltage asymmetrical fault, and it is convenient and efficient.

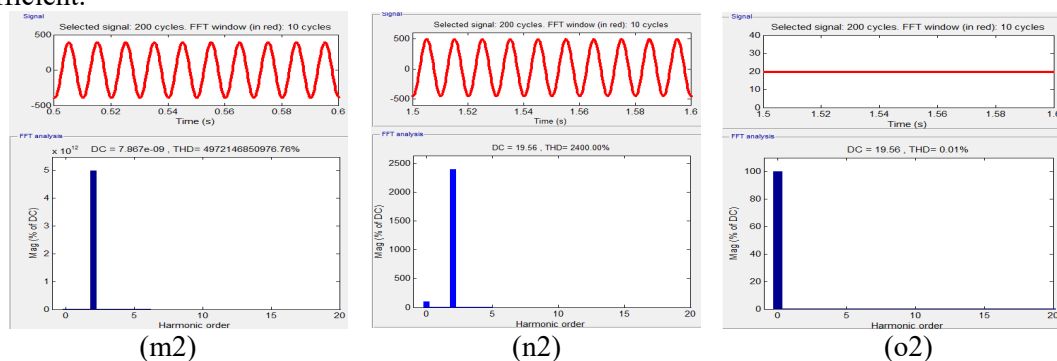


Figure 9. The fast Fourier transform analysis of BC-phase voltage swell fault ($\sigma = 0.3$)

5. Conclusion

Based on negative-sequence synchronous rotation coordinate transform method, a sort of voltage asymmetrical fault detection method is proposed in this paper, and the variable-step LMS ANF is applied into grid voltage asymmetrical detection method. Due to the adoption of VS-LMS ANF algorithm, the negative-sequence component in grid voltage can be detected. Therefore, the grid voltage asymmetrical fault can be detected in this way. The weight coefficients of ANF can achieve self-tuning by LMS algorithm, which is convenient and efficient in practical application. The variable-step adjustment algorithm can achieve the self-tuning of step size by the error signal of the ANF. Therefore, the contradiction between the step size and steady-state error of the ANF can be solved. The MATLAB/Simulink simulation and the FFT analysis results are in conformity with the theoretical analysis, which proves the feasibility of the voltage asymmetrical fault detection method.

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