Design of Multi-frequency Analog Transmitter of Magnetic Source Based on Selective Harmonic Elimination Technology

Zhang Yutong¹, Liu Yi², Cai Shiqing³ and Wang Shilong¹*

¹College of Instrumentation & Electrical Engineering, Jilin University, Changchun, 130000, China
²College of Instrumentation & Electrical Engineering, Jilin University, Changchun, 130000, China
³College of Instrumentation & Electrical Engineering, Jilin University, Changchun, 130000, China
*Corresponding author’s e-mail: wangshilong@jlu.edu.cn

Abstract. Electromagnetic waves of different frequencies penetrate formations at different depths, so the frequency component of the transmitted waveform determines the detection range of electromagnetic exploration. The selective harmonic elimination pulse width modulation technology was originally used for harmonic elimination. In this paper, SHEPWM is used for harmonic enhancement and the control of harmonics. In addition, the current SHEPWM technology mostly uses various heuristic algorithms, which are not ideal for solving higher-order nonlinear equations. This paper uses the third-order convergence arithmetic mean Newton iteration method to solve the nonlinear equations. The number of solving nonlinear equations can reach 41, and the controllable energy ratio can reach 40% to 50%. Finally, the amplitude and phase of each frequency component of the current waveform can be controlled, which provides a reference for the SHEPWM technology to enhance harmonics.

1. Introduction

In electromagnetic exploration, electromagnetic waves of different frequencies penetrate strata of different depths and the accuracy of frequency control directly affects the effect of detection. With the development of science and technology, transmitted waves are no longer simple waves such as sinusoidal wave, triangular wave and square wave but multi-frequency wave with easy identification of frequency components and good detection effect. Literature[1] applies pseudo-random sequence signals to electromagnetic exploration, which has a good system identification and noise suppression capability, but it needs to emit multiple sets of signals to increase the required frequency points. Unlike using pseudo-random sequence signals, some scholars have studied selective harmonic elimination techniques. In literature[2], SHEPWM is applied to electromagnetic exploration technology. The literature[3] improves emprle competition algorithm for solving nonlinear equations with SHEPWM. In literature[4], ant colony algorithm is applied to the control of three level inverter. But the above heuristic algorithms can only solve small number of switch Angles and take a long time. The effect is not ideal for solving higher order nonlinear equations. As for different buried depth of exploration target, it’s unable to provide any band,any waveform, any phase of the optimal frequency ratio and launch. In this paper, we use the Newton iterative method to solve the nonlinear equations and the Newton iteration method up to the third order. Finally we get better convergence properties.
On the basis of solving full cycle SHEPWM high order nonlinear system of equations, the frequency and phase control of the transmitted waveforms needed for high-precision detection of specific depth targets are realized.

2. Principle and method of selective harmonic elimination pulse width modulation

The basic idea of SHEPWM's control of single-phase inverter circuit is to set the amplitude, phase and DC components of the waveform's first harmonic wave, then solve the switching Angle at each moment. The calculated switching Angle is used as the time point for the switching of two h-bridge arms. In this paper, the full period asymmetric SHEPWM waveform with N being an even number of times is adopted. The waveform is shown in figure 1.

![Figure 1. Full cycle asymmetric SHEPWM waveform when N is even](image)

When N is even, the nonlinear equations of full-period asymmetric SHEPWM signal are shown in Equation (1) [5]:

\[
\begin{align*}
\alpha_i &= \frac{2U_i}{m} \left[ \sum_{l=1}^{N} (-1)^l \cos(i\alpha_l) \right] = A_i \cos \theta_i \\
\beta_i &= \frac{2U_i}{m} \left[ \sum_{l=1}^{N} (-1)^l \sin(i\alpha_l) \right] = A_i \sin \theta_i , \quad i=1,2,3,\ldots \\\n\alpha_0 &= \frac{2U_i}{\pi} \left[ N + \sum_{l=1}^{N} (-1)^l \alpha_i \right] = \frac{2}{T} \int_{0}^{T} x(t) dt \\
0 < \alpha_1 < \alpha_2 < \cdots < \alpha_N < 2\pi
\end{align*}
\]

The full period asymmetric SHEPWM waveform equations are more numerous and more complicated to solve, but the odd harmonic, even harmonic and phase can be controlled simultaneously.

3. Basic flow of Newton iteration method

Basic steps of average Newton iteration method:

1. Given equation parameters: set order N, given initial value vector \( \alpha^{(0)} \), set the constant vector \( A_0, A_1, \theta_0 \).
2. Find the value of each equation \( f^{(0)} \).
3. Calculate the Jacoby matrix:

\[
J_{\alpha} = \begin{bmatrix}
\frac{\partial f_1(\alpha)}{\partial \alpha_1} & \frac{\partial f_1(\alpha)}{\partial \alpha_2} & \cdots & \frac{\partial f_1(\alpha)}{\partial \alpha_n} \\
\frac{\partial f_2(\alpha)}{\partial \alpha_1} & \frac{\partial f_2(\alpha)}{\partial \alpha_2} & \cdots & \frac{\partial f_2(\alpha)}{\partial \alpha_n} \\
\vdots & \vdots & \ddots & \vdots \\
\frac{\partial f_n(\alpha)}{\partial \alpha_1} & \frac{\partial f_n(\alpha)}{\partial \alpha_2} & \cdots & \frac{\partial f_n(\alpha)}{\partial \alpha_n}
\end{bmatrix}
\]

4. Calculate an increment and make the following calculation:

\[
\beta^{(k)} = \alpha^{(k)} + \Delta t \times J^{-1} f^{(k)}
\]

The \( \Delta t \) is the iteration step length. In theory, \( \Delta t \) convergent solution can be obtained when it’s small enough, but when the equation convergence good circumstances, it can get fast convergent results by adjusting the step length.

5. Let's compute the Jacoby matrix again
Calculate the second increment

\[
\alpha^{(k+1)} = \alpha^{(k)} + \Delta t \left( J + \frac{J J^T}{2} \right) f^{(k)}
\]  

(5)

Calculate the current function value

\[
f^{(k+1)} = f\left( \alpha^{(k+1)} \right)
\]  

(6)

Judge the convergence condition. If it does not converge, step (3) will be jumped back; if it converges, it will end [6].

The flow chart of Newton iteration method is shown in Figure 2:

*Figure 2. Newton iteration method flow chart*

In terms of Newton iterative method of initial value selection, we have two ways, the first is the application of MATLAB toolbox fmincon () function, it gives initial value. The second way is taking points in a limited time interval. The use of the optimal solution in the form of the equation under the condition of small order can get accurate solution, but if the equations are nonlinear, the efficiency is low and easy to fall into local optimum. The second method is simple and can satisfy the basic nonlinear constraint conditions of the equation. If the iteration step size is properly adjusted, the iteration speed can be obtained quickly.
4. Simulation verifies the results of full-cycle asymmetric SHEPWM control

In order to verify full-cycle asymmetric SHEPWM's ability to control frequency information, we use MATLAB as a tool to carry out computer simulation research, in which the M function of MATLAB was used to achieve the average Newton iteration method. Then the waveform was verified to meet the initial conditions of the equation through SIMULINK simulation platform. The harmonic amplitude and phase Angle not covered in this paper are all set to 0, and the convergence precision is set to $1 \times 10^{-4}$. According to the practical application of electromagnetic exploration, the precision of the switching Angle is set to 0.005.

Single-phase inverter circuit controlled by SHEPWM wave is built by Simulink, as shown in Figure 3:

![Figure 3. Simulink simulation SHEPWM controlled single-phase inverter simulation circuit diagram](image)

4.1 The amplitude of the fundamental, second and fourth harmonics of the voltage waveform is equal and the phase is controllable

In order to improve the controllable energy ratio, reduce the number of switching angles, and reduce the order of the equation to order 10, the highest controllable harmonic is 4. The setting voltage ratio is 1:1:1, and the specific information is shown in Table 1

| Order N of equation | 10 | Fundamental frequency f/Hz | 16 |
|---------------------|----|-----------------------------|----|
| Controlled frequency /Hz | 16 | 32 | 64 |
| Set amplitude /V | 0.5774 | 0.5774 | 0.5774 |
| Set phase /rad | 0 | 0 | 0 |

| Table 2. N=10 full cycle asymmetric SHEPWM switching angle/rad |
|-----------------|
| Full cycle switching angle (rad) |
| 1.2346 | 1.4286 | 2.1569 | 2.5961 | 2.8432 | 3.3016 | 4.0039 | 4.7514 | 4.9770 | 6.2795 |

The voltage waveform and spectrum at both ends of the load are obtained through simulation, as shown in Figure 4 and 5:

![Figure 4. Voltage waveform](image)
The coil current waveform and spectrum are shown in Figure 6 and 7:

Figure 5. Voltage spectrum

Figure 6. Current waveform

Figure 7. Current spectrum

The data of spectrum in Figure 5 are shown in Table 3:

| Frequency | Harmonic number | Fundamental wave | 16 | 32 | 64 |
|-----------|-----------------|------------------|----|----|----|
| 16        | Preset voltage amplitude /V | 0.5774 | 0.5774 | 0.5774 |
| 32        | Simulation voltage amplitude /V | 0.5771 | 0.5771 | 0.5772 |
| 64        | Preset phase angle /rad | 0 | 0 | 0 |
| 64        | Simulation phase angle /rad | 0.0002 | 0.0002 | 0.0001 |
| 64        | Maximum number of controllable harmonics / Secondary | 4 |
| 64        | Controllable energy ratio /% | 49.96 |

Through the above analysis, it can be obtained that the number of switching angles can be reduced, that is, the order of nonlinear equations can be reduced, the number of controllable frequency harmonics can be reduced, but the controllable energy ratio can be improved.

4.2 The fundamental, 7th and 10th harmonics of the current waveform are equal in amplitude and controllable in phase

Increasing the order of the equation to 28, we control the amplitude and phase of the first 13 harmonics, and set the ratio of amplitude of voltage at each frequency to be the same as that of harmonic impedance. Specific input parameters are shown in Table 4:
Table 4. The input parameters corresponding to the full cycle asymmetric SHEPWM current controlled frequency point amplitude equal

| Order N of equation | 28 | Fundamental frequency f/Hz | 16 |
|---------------------|----|-----------------------------|----|
| Controlled frequency /Hz | 16 | 112 | 160 |
| Set amplitude /V | 0.1959 | 0.5438 | 0.7530 |
| Set phase /rad | 0 | $\frac{\pi}{4}$ | $\frac{\pi}{2}$ |

According to the input parameters in Equation (1) and Table 4, the nonlinear equations with full-period asymmetric SHEPWM need to be solved. The numerical solutions of the equations obtained are shown in Table 5:

Table 5. N=28 full cycle asymmetric SHEPWM switching angle/rad

| Full cycle switching angle (rad) |
|----------------------------------|
| 0.2241 | 0.4612 | 0.6200 | 0.7621 | 0.9486 | 1.0712 | 1.3793 | 1.6695 | 2.1116 | 2.3865 |
| 2.5805 | 2.6803 | 2.8674 | 3.0265 | 3.2289 | 3.5570 | 3.8518 | 3.9245 | 3.9706 | 4.3433 |
| 4.6051 | 4.8647 | 5.0096 | 5.2474 | 5.3372 | 5.4916 | 5.7627 | 6.1533 |

The voltage waveform and spectrum at both ends of the load are obtained through simulation, as shown in Figure 8 and 9:

Figure 8. Voltage waveform

Figure 9. Voltage spectrum

The coil current waveform and spectrum are shown in Figure 10 and 11:

Figure 10. Current waveform
Figure 11. Current spectrum

The data of spectrum is summarized in Table 6:

| Frequency | 16  | 112 | 160 |
|-----------|-----|-----|-----|
| Harmonic number | Fundamental wave | 7 | 10 |
| Preset voltage amplitude /V | 0.1959 | 0.5438 | 0.753 |
| Simulation voltage amplitude /V | 0.1958 | 0.5428 | 0.7529 |
| Preset phase angle /rad | 0 | $\frac{\pi}{4}$ | $\frac{\pi}{2}$ |
| Simulation phase angle /rad | -0.0003 | 0.7859 | 1.5708 |
| Preset current amplitude /A | 0.05193 | 0.05192 | 0.05192 |
| Simulated current amplitude /A | 0.05190 | 0.05191 | 0.05192 |
| Maximum number of controllable harmonics / Secondary | 13 |
| Controllable energy ratio /% | 45.00 |

It can be obtained through analysis: We can get the right solution of nonlinear SHEPWM equations by using the Newton iteration method. Except that the amplitude of fundamental, 7th and 10th harmonics is the set value and the phase is the set value, the amplitude of other frequencies is 0, and the current amplitude obtained in the inductor is the same. It is proved again that the full-period asymmetric SHEPWM can control the amplitude and phase of harmonics, and the SHEPWM scheme can be used to solve the problem of multi-frequency wave emission.

5. Conclusion

According to the analysis and argument of this article, we verify the SHEPWM advantages in the field of multifrequency wave emission. Compared with the similar m-sequence of pseudo random waveform, SHEPWM can control the amplitude and phase of the corresponding frequency points, and it is easier to distinguish these waveforms in electromagnetic exploration. It also has more accurate control over detection depth and detection medium. The third-order convergent average Newton iterative method used in this paper can obtain a more accurate solution. Compared with the heuristic algorithm used in other articles, the energy controllable ratio can reach about 55%, and the number of equations is less, basically 5 to 7. The number of equations calculated by the third-order average Newton iterative method can reach 41, and the controllable energy ratio can reach 40% to 50%. Under the premise of a large number of equations, although the controllable energy ratio does not reach the limit, it can still meet the requirements of electromagnetic exploration.

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