Comprehensive Evaluation Method of Energy-saving Effect for Frequency Conversion System Based on Total Harmonic Components

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Received 12 April 2021; Accepted 23 April 2021;
Publication 06 July 2021

Abstract

With the development and application of frequency conversion technology, the types of frequency conversion equipment are becoming more and more diverse, and the corresponding energy efficiency testing and evaluation methods are different, which leads to inconsistencies in the selection of equipment and the operation analysis and evaluation of the frequency conversion system. It is urgent to find an effective solution. By analyzing the problems of the current energy-saving test and evaluation methods of the frequency conversion system, the energy-saving evaluation index system and calculation method based on the total harmonic components are proposed. Establish a harmonic evaluation index system covering 9 indicators. On this basis, 6 core harmonic indicators are selected, and the comprehensive harmonic influence coefficient and weight matrix are introduced to establish a comprehensive

Distributed Generation & Alternative Energy Journal, Vol. 36_3, 239–268.
doi: 10.13052/dgaej2156-3306.3633

evaluation method for energy-saving effects based on harmonic total components and weighted matrix model. On this basis, 15 different working conditions of the energy-saving test and analysis evaluation experiments for of frequency conversion system have been carried out. The results show that the total harmonic components analysis method proposed in this paper can reflect the energy efficiency level of the frequency conversion system and its equipments more realistically on the premise of meeting the analysis and actual operation requirements on site. At the same time, the established comprehensive evaluation method of energy saving effect can comprehensively and reasonably analyze the impact of harmonics on the performance of the frequency conversion system. In addition, it provides theoretical guidance for reasonably determining the optimal operating conditions of the system and equipment, and taking corresponding harmonic prevention measures to effectively improve the quality of power transmission and the actual energy-saving effects of frequency conversion technology.

Keywords: Frequency conversion system, energy-saving indicators, total harmonic components, energy-saving effect, comprehensive evaluation, weighted matrix.

1 Introduction

In recent years, frequency conversion technology and related products have been widely used in key energy-consuming fields such as electric power, machinery and petrochemicals, etc. However, the harmonics generated by the inverter during the working process will reduce the power transmission quality and utilization efficiency of the system. In addition, the operating parameters such as the power and equipment efficiency of the electrical equipment will also be affected by the harmonics to a certain extent. At present, the research on the testing, analysis and evaluation of the frequency conversion system and harmonics has become a hot issue [1, 2], but the analysis and research on the energy saving effect of the frequency conversion system are still relatively few. On the basis of existing research, we should start from the overall frequency conversion system, comprehensively consider the performance of the frequency conversion equipment and the influence of harmonics on the system, and establish an analysis and evaluation method for the energy saving effect of the frequency conversion system, in order to analyze and evaluate the energy-saving effect of frequency conversion technology more comprehensively and reasonably, and promote the technology to realize real green energy-saving and popularization and application.

2 Energy Saving Test and Evaluation Status of Frequency Conversion System

At present, the energy-saving test of the frequency conversion system and the quality inspection of the frequency conversion speed control equipment are mainly according to the relevant regulations of GB/T 14549 [3], GB/T 30843.2 [4], GB/T 30844.2 [5], SY/T 6834 [6, 7] and other standards. The electrical energy testing instruments used mainly include HIOKI 3169/3390, Fluke Norma 5000, etc.

2.1 Energy-saving Test and Index Analysis of Frequency Conversion System

The energy-saving indicators of the frequency conversion system are mainly refers to the efficiency of the frequency conversion equipment, frequency conversion speed regulation device and the system. The current standards, such as GB/T 14549 [3], GB/T 30843.2 [4], GB/T 30844.2 [5], SY/T 6834 [6, 7] and other related standards stipulate the testing, analysis and calculation methods of the power factor, efficiency, harmonics and other indicators for the input side of the frequency converter and the variable frequency speed regulation drive system. However, from the perspective of overall analysis, there is still no unification in terms of indicator definitions, test and calculation methods, and on-site actual operations, which affects the reasonable selection of frequency conversion equipment and the accurate evaluation of equipment performance.

At present, under the condition of variable frequency, the definition and calculation method of active power and apparent power of the system have been widely recognized and unified. Active power is the sum of the active power of the DC component, the fundamental wave component and the harmonic component. The apparent power is the product of the effective value of voltage and current. However, the calculation methods for indicators such as power factor and efficiency are different.

2.1.1 Analysis and calculation of power factor

At present, the quality inspection and testing of the frequency converter are mainly carried out according to the regulations of GB/T 30843.2 and GB/T

30844.2. The power factor at the input side (grid side) of the inverter is the ratio of active power to apparent power, which is the full-wave effective value [4, 5]. But in the relevant test work of the actual variable frequency speed regulation drive system on site, the active power and apparent power set in the test instrument are both fundamental wave power. It means that the calculation method in the current standard is inconsistent with the method used by the test instrument.

Petroleum companies mainly follow the regulations of SY/T 6834 to analyze and calculate the power factor of the frequency converter. On the basis of the currently generally recognized definitions and calculation methods of active power and apparent power, SY/T 6834-2011 [6] stipulated the calculation method of power factor for the first time, which refers to the ratio of fundamental active power and apparent power on the input side of the inverter. With the revision of the standard, the current standard SY/T 6834-2017 [7] further comprehensively considers the influence of each harmonic component on the inverter and the system, and the calculation method of the power factor on the input side of the inverter is given basing on the combination of fundamental wave and full wave, but the output side is not clear.

2.1.2 Analysis and calculation of efficiency

Take the core equipment (frequency converter) of the frequency conversion system as an example for illustration. Currently, there are many types and styles of inverters, the most common inverters are mainly AC-DC-AC types. According to statistics, the efficiency of the inverter is generally 86.4% to 96% when running under rated conditions, and the efficiency will increase as the power increases [8]. Similar to the case of power factor, there are also two main methods for testing and calculating the inverter efficiency. In the current standard GB/T 30844.2-2014, the inverter efficiency is the ratio of the output active power to the input active power and the full-wave effective value is taken [5]. The quality test of the frequency converter complies with the regulations of GB/T 30844.2, and the effective value of the full wave is used for efficiency analysis and calculation. However, for the test and analysis of the variable-frequency drive system, the effective value of the fundamental wave is used to calculate the efficiency of the variable-frequency equipment.

The definition of inverter efficiency refers to its own conversion efficiency, which also belongs to the category of efficiency analysis of electrical equipment. From a macro perspective, the inverter efficiency should be the ratio of the effective output power of the equipment to the total input power. However, due to the existence of harmonics, the effective output power and input power of the system should comprehensively consider the effects of harmonic components. The above-mentioned two methods separately analyze the fundamental wave and the full wave respectively, and neither can comprehensively reflect the conversion efficiency of the inverter under the influence of harmonics.

In addition, according to incomplete statistics, the calculation methods of basic performance indicators such as equipment efficiency listed in the nameplate information for inverter devices of different manufacturers, types, styles, and models are also different. Therefore, in order to further unify and clarify the definition and calculation methods of equipment performance parameters and important indicators, it is necessary to comprehensively consider the actual needs of the equipment manufacturers and users on the basis of the existing standards.

2.2 Harmonic Test and Analysis Evaluation

At present, harmonic testing and analysis and evaluation work are mainly carried out in accordance with the provisions of relevant standards. Internationally, it mainly refers to standards such as IEC 61000, IEEE519, EN 50160, NORSOK-001/2, etc. [9–12], and domestically, it is mainly according to GB/T 14549 [3], GB/T 17626 [13]. Related energy fields, such as the oil and gas industry, mainly carry out specific work in accordance with SY/T 6834 [7]. The application shows that, in view of the requirements of on-site operating conditions and working conditions, the harmonic testing, calculation and evaluation methods in the current standards are not completely applicable. The main reason is: Reference [7] SY/T 6834 only focuses on the harmonics on the input side of inverter. In essence, the harmonics generated by the frequency converter not only act on the input side (grid side), but also on the output side, which in turn affects the performance of the connected motor and the drag load.

The survey shows that the current research on harmonic testing and evaluation is still mainly focused on the detection and analysis of harmonics, and domestic and foreign scholars have carried out a lot of research work on the extraction of harmonic components. For example, Platas, Fang Guo-zhi and others have proposed more traditional power system harmonic detection methods such as TFT, FFT, wavelet packet transformation, and EEMD in [14–19]. Later, Xiao Zhu-li, Zou Pei-yuan and others proposed improved S-transform, full-phase spectrum refinement correction based on traditional FFT, as well as from the perspectives of windowing, interpolation, and neural network algorithms, methods to suppress leakage and improve the accuracy of component extraction are proposed, such as iterative windowing, a combination of various improved interpolation methods, etc. [20–27]. These improvement methods mainly focus on improving the accuracy of the harmonic detection results, but for the on-site test and analysis work, technical feasibility and the promotion of actual engineering applications should be considered comprehensively, and combined with actual working conditions, test conditions and accuracy, etc., to determine a reasonable and feasible method.

3 Energy-saving Evaluation Index Calculation of Frequency Conversion System Based on Total Harmonic Components

Under the conditions of ensuring the feasibility of the test method and the ease of operation of the test instrument, comprehensively considering the influence of each component of the harmonic on the performance of the frequency conversion system and equipment, a calculation method of energy saving index for the frequency conversion system based on the total harmonic components is proposed on the basis of the uniformly recognized definitions of active power and apparent power.

This method uses a combination of filtering and FFT to extract each harmonic component within the 40th order, and considers the influence of each harmonic component on the input side and output side of the inverter comprehensively, then uses the total harmonic components method to analyze and calculate the energy efficiency on the basis of fundamental wave and full wave effective value.

3.1 Energy-saving Evaluation Index System of Frequency Conversion System

The energy-saving evaluation index of frequency conversion system includes 6 indicators. The definition and calculation method of each index are shown in Table 1.

The calculation method of each index in Table 1 is shown as follows:

$$\lambda_{\text{in}} = \frac{P_{\text{in1}}}{S_{\text{inf}}} \tag{1}$$

$$\lambda_{\text{out}} = \frac{P_{\text{out1}}}{S_{\text{outf}}} \tag{2}$$

Table 1 Energy-saving evaluation index system of frequency conversion system

Category	No.	Index	Symbol	Definition	Formula
Frequency conversion equipment	1	Power factor on the input side of the inverter	λ_{in}	The ratio of the total fundamental active power to the full-wave apparent power on the input side of the inverter	(1)
	2	Power factor on the output side of the inverter	λ_{out}	The ratio of the total fundamental active power to the full-wave apparent power on the output side of the inverter	(2)
	3	Inverter efficiency	η	The ratio of the effective output power of the fundamental wave to the total input power of the full wave	(5)
Drive equipment	4	Motor efficiency	η_{mr}	The ratio of the output power of the motor to the input fundamental active power	(7)
Drag device	5	Frequency conversion speed control device efficiency	η_{d}	The ratio of the output power of the motor to the total input power of the full wave	(8)
Frequency conversion system	6	Frequency conversion system efficiency	η_{s}	The ratio of the output power of the variable frequency speed regulation drive system to the total input power of the full wave	(9)

where:

P_{in1} – the total fundamental active power on the input side of the inverter, as shown in Equation (3)

P_{out1} – the total fundamental active power on the output side of the inverter, as shown in Equation (3)

S_{inf} – full-wave apparent power on the input side of the inverter, as shown in Equation (4)
S_{outf} – full-wave apparent power on the output side of the inverter, as shown in Equation (4)

$$P_{\text{in1}} = P_{\text{in01}} + P_{\text{in02}} + P_{\text{in03}} \quad \text{and} \quad P_{\text{out1}} = P_{\text{out01}} + P_{\text{out02}} + P_{\text{out03}} \tag{3}$$

$$S_{\text{inf}} = \sum_{i=1}^{3} (U_{\text{in}rms} \cdot I_{\text{in}rms})_i \quad \text{and} \quad S_{\text{out}f} = \sum_{i=1}^{3} (U_{\text{out}rms} \cdot I_{\text{out}rms})_i \tag{4}$$

where:

P_{in01}, P_{in02}, P_{in03} – fundamental active power of each phase on the input side
P_{out01}, P_{out02}, P_{out03} – fundamental active power of each phase on the output side, which is the product of the effective value of the fundamental voltage, the current, and the displacement factor.
U_{inrms} – the effective value of each phase voltage on the input side of the inverter
U_{outrms} – the effective value of each phase voltage on the output side of the inverter
I_{inrms} – the effective value of each phase current on the input side of the inverter
I_{outrms} – the effective value of each phase current on the output side of the inverter

$$\eta = \frac{P_{\text{out1}}}{P_{\text{inf}}} \times 100\% \tag{5}$$

where:

P_{inf} – full-wave active power on the input side (grid side) of the inverter, as shown in Equation (6).

$$P_{\text{inf}} = P_{\text{inf1}} + P_{\text{inf2}} + P_{\text{inf3}} \quad \text{or} \quad P_{\text{inf}} = S_{\text{inf}} \cos \varphi_{\text{in}} \tag{6}$$

where:

P_{inf1}, P_{inf2}, P_{inf3} – full-wave active power of each phase on the input side of the inverter, which is the product of the effective value of the voltage, current and the displacement factor

$\cos\varphi_{in}$ – total displacement factor, which is the average value of the three-phase displacement factors

$$\eta_{\mathrm{mr}} = \frac{T \cdot n_{\mathrm{mr}}}{9550 P_{\mathrm{cout1}}} \times 100\% \tag{7}$$

$$\eta_{\mathrm{d}} = \frac{T \cdot n_{\mathrm{mr}}}{9550 P_{\mathrm{1f}}} \times 100\% \tag{8}$$

$$\eta_{\mathrm{s}} = \frac{P_{\mathrm{sout}}}{P_{\mathrm{1f}}} \times 100\% \tag{9}$$

where:

T – the motor output shaft torque, Nm
n_{mr} – the actual speed of the motor, r/min
P_{cout1} – the fundamental active power on the output side of the inverter, kW
P_{sout} – the output power of the variable frequency speed regulation drive system, kW

3.2 Harmonic Evaluation Index System of Frequency Conversion System

Based on the analysis of the current situation, this article comprehensively considers the actual production characteristics of the project and the requirements of on-site test conditions, and establishes a multi-index harmonic evaluation system for the variable frequency speed control drive system, which includes a total of 9 indicators on the input/output side of the inverter [28]. Combining the existing harmonic analysis methods, power quality analysis and testing equipment, signal processing and harmonic component extraction methods, the calculation methods of 9 indicators are determined and shown in Table 2.

The meanings of symbols in the formulas in Table 2 are explained as follows:

$U_{\mathrm{I}h}$ – the effective value of each harmonic voltage on the input side
U_{I1} – the effective value of the fundamental voltage on the input side
h – harmonic order, h = 2,3,4,...,40
I_{Ih} – the effective value of each harmonic current on the input side
I_{I1} – RMS value of fundamental current on input side
$V_{\mathrm{I}ab}, V_{\mathrm{I}bc}, V_{\mathrm{I}ca}$ – RMS value of input side line voltage

Table 2 Harmonic evaluation index system of frequency conversion system

Category	No.	Index	Symbol	Unit	Formula
Input	1	Total distortion rate of harmonic voltage	V_{THDI}	%	$V_{\mathrm{THDI}} = \sqrt{\sum_{h=2}^{40} \left(\frac{U_{\mathrm{I}h}}{U_{\mathrm{I}1}}\right)^2} \times 100\%$
	2	Total distortion rate of harmonic current	I_{THDI}	%	$I_{\mathrm{THDI}} = \sqrt{\sum_{h=2}^{40} \left(\frac{I_{\mathrm{I}h}}{I_{\mathrm{I}1}}\right)^2} \times 100\%$
	3	Unbalance of three-phase voltage	V_{unbI}	%	$V_{\mathrm{unbI}} = \frac{\mathrm{Max}(\lvert V_{\mathrm{I}ab} - V_{\mathrm{I}avg}\rvert, \lvert V_{\mathrm{I}bc} - V_{\mathrm{I}avg}\rvert, \lvert V_{\mathrm{I}ca} - V_{\mathrm{I}avg}\rvert)}{V_{\mathrm{I}avg}} \times 100\%$
Output	1	Total distortion rate of harmonic voltage	V_{THDO}	%	$V_{\mathrm{THDO}} = \sqrt{\sum_{h=2}^{40} \left(\frac{U_{\mathrm{O}h}}{U_{\mathrm{O}1}}\right)^2} \times 100\%$
	2	Total distortion rate of harmonic current	I_{THDO}	%	$I_{\mathrm{THDO}} = \sqrt{\sum_{h=2}^{40} \left(\frac{I_{\mathrm{O}h}}{I_{\mathrm{O}1}}\right)^2} \times 100\%$
	3	Unbalance of three-phase voltage	V_{unbO}	%	$V_{\mathrm{unbO}} = \frac{\mathrm{Max}(\lvert V_{\mathrm{O}ab} - V_{\mathrm{O}avg}\rvert, \lvert V_{\mathrm{O}bc} - V_{\mathrm{O}avg}\rvert, \lvert V_{\mathrm{O}ca} - V_{\mathrm{O}avg}\rvert)}{V_{\mathrm{O}avg}} \times 100\%$
	4	Harmonic voltage factor	*HVF*		$HVF = \sqrt{\sum_{n=2}^{k} \frac{U' n^2}{n}} \le 0.02$
	5	Harmonic current factor	*HCF*		$HCF = \sqrt{\sum_{n=2}^{k} I' n^2} \le 0.05$
	6	Harmonic current allowable value	I_L	A	Maximum allowable current of each harmonic

$V_{\mathrm{I}avg}$ – average value of three-phase line voltage on input side
$U_{\mathrm{O}h}$ – the effective value of each harmonic voltage on the output side
$U_{\mathrm{O}1}$ – RMS value of fundamental voltage on output side
I_{Oh} – the effective value of each harmonic current on the output side
I_{O1} – RMS value of fundamental current on output side
$V_{\mathrm{O}ab}, V_{\mathrm{O}bc}, V_{\mathrm{O}ca}$ – RMS value of output side line voltage
$V_{\mathrm{O}avg}$ – average value of three-phase line voltage on the output side
n – frequency, for three-phase AC motors, 3 and multiples of 3 are not included
U_n' – the ratio of the effective value of the harmonic voltage to the rated voltage
I_n' – the ratio of the effective value of the harmonic current to the rated current

Currently, the three indicators of *HVF*, *HCF* and current allowable value have specific limit requirements in IEC 61000, IEEE 519 and EN 50160, NORSOK-001/2 standards [9–12]. The other 6 indicators in the system should be considered comprehensively to give a reasonable evaluation method to analyze the impact of harmonics on system performance and energy-saving effects.

4 Comprehensive Energy-saving Evaluation Method Based on Weighted Matrix Model

4.1 Harmonic Index Weighted Matrix Model

According to the above analysis, we take multiple variable frequency speed regulation systems under the same power frequency as an example. Firstly, select 6 indicators on the input and output side of the inverter from the index system: total voltage distortion rate, total current distortion rate, and three-phase voltage unbalance. Secondly, establish a weighted matrix model through the analysis of the influence weight of each indicator [29]. Finally, a comprehensive evaluation method of harmonic influence based on the weighted matrix model is determined.

4.1.1 Harmonic comprehensive influence coefficient

The 6 harmonic indicators are respectively recorded as: $f_1, f_2, f_3, f_4, f_5, f_6$, there are Z systems, and the 6 indicators corresponding to each system can be recorded as: $f_{ss1}, f_{ss2}, f_{ss3}, f_{ss4}, f_{ss5}, f_{ss6}$, $ss = 1, 2, \ldots, Z$. K_F is the comprehensive influence coefficient of harmonics, and K_{Fss} is the comprehensive influence coefficient of harmonics for each system. The calculation method is as follows:

$$K_{\mathrm{F}ss} = \frac{f_{1\min}}{f_{ss1}} + \frac{f_{2\min}}{f_{ss2}} + \frac{f_{3\min}}{f_{ss3}} + \frac{f_{4\min}}{f_{ss4}} + \frac{f_{5\min}}{f_{ss5}} + \frac{f_{6\min}}{f_{ss6}}$$
$$\begin{cases} f_{1\min} = \mathrm{Min}(f_{11}, f_{21}, \ldots, f_{i1}, \ldots, f_{z1}) \\ f_{2\min} = \mathrm{Min}(f_{12}, f_{22}, \ldots, f_{i2}, \ldots, f_{z2}) \\ \quad \vdots \quad \vdots \\ f_{6\min} = \mathrm{Min}(f_{16}, f_{26}, \ldots, f_{i6}, \ldots, f_{z6}) \end{cases} \tag{10}$$

For a certain system, the larger K_F is, the closer the 6 indicators are to the minimum values of the corresponding indicators in the system, which means that the harmonic comprehensive effect on the system performance is smaller.

4.1.2 Weighted comprehensive evaluation function

- Weight matrix *A*

$$A = \left[\frac{P_1}{P_\Sigma} \cdots \frac{P_i}{P_\Sigma} \cdots \frac{P_m}{P_\Sigma}\right] \tag{11}$$

where:

m – the number of equipment categories included in a system, $m \geq 2$.
P_i – the sum of the rated power of *i*-th equipment in the system, kW
P_Σ – the sum of the rated power of all devices in the system, kW

- Calculation matrix of each sub-item *B*

For various types of equipment in a system, each sub-matrix is calculated as follows:

$$B = [b_1 \cdots b_i \cdots b_m]^{\mathrm{T}}$$
$$b_i = \left[\frac{P_{i1}}{P_i} \cdots \frac{P_{ij}}{P_i} \cdots \frac{P_{iq}}{P_i}\right] \cdot \left[\frac{\eta_{i1}}{\eta_{i01}} \cdots \frac{\eta_{ij}}{\eta_{i0j}} \cdots \frac{\eta_{iq}}{\eta_{i0q}}\right]^{\mathrm{T}} \tag{12}$$

where:

b_i – efficiency weighted value of the *i*-th equipment
P_{ij} – rated power of the *j*-th unit in the *i*-type equipment, kW

q – the number of a certain type of equipment in the system
j – variables corresponding to the number of equipment for a certain type, $j = 1, 2, \ldots, q$
η_{ij} – the actual operating efficiency of the *j*-th unit in the *i*-type equipment, %
η_{i0j} – the efficiency qualified value of the *j*-th unit in the *i*-type equipment, %

- Weighted comprehensive evaluation function *C*

For a variable frequency speed regulation drive system, the weighted comprehensive evaluation function *C* of the harmonic influence can be calculated according to the following Equation (13).

$$C = K_{\mathrm{F}ss} AB = K_{\mathrm{F}ss} \left[\frac{P_1}{P_\Sigma} \cdots \frac{P_i}{P_\Sigma} \cdots \frac{P_m}{P_\Sigma} \right] \cdot [b_1 \cdots b_i \cdots b_m]^{\mathrm{T}} \tag{13}$$

4.2 Comprehensive Evaluation Method of Energy-saving Effect

For multiple variable frequency speed regulation systems with the same frequency, the steps for the weighted comprehensive evaluation of the harmonic influence of each system are as follows:

- Comprehensive evaluation function calculation: Analyze the *Z* systems separately, and calculate the weighted comprehensive evaluation function of each system's harmonic influence according to the calculation method in 4.1.2: $C_1, C_2, \ldots, C_Z$;
- Sorting: sort all *C* values of *Z* systems from high to low;
- Comprehensive evaluation of influence: According to the calculation method analysis of K_{Fss}, matrix *AB*, and evaluation function *C*, it can be seen that the changing trends of the three are the same. The smaller the influence of harmonics, the higher the equipment efficiency and the larger the system comprehensive evaluation value *C*;
- System improvement: For Z systems, find the corresponding C_{max} according to the third step above, then analyze the system's various harmonic indicators, system structure, and operating parameter settings, and take reasonable improvements measures to effectively suppress and reduce the adverse harmonic effects on system performance.

This method is also suitable for the adjustment and determination of a reasonable or optimal working condition of a frequency conversion system.

5 Energy-saving Test and Evaluation Experiment of Frequency Conversion System Based on Total Harmonic Components

5.1 Experimental Platform Establishment

The Energy-saving test and evaluation experimental platform for frequency conversion system includes the following 4 parts:

- Frequency converter: SB70, 37kW;
- Drive motor: three-phase asynchronous motor, Y-2809-8, 37kW, Δ, 740r/min;
- Production machinery: Considering that most of the production machinery driven by the current variable frequency speed regulation system is generally a constant load (such as pumps and other equipment, the load is basically constant during normal operation), so the DC motor is used as a simulated load instead of actual production Machinery, Siemens DC motor is selected for this test bench;
- Virtual test instrument and analysis system: It is composed of PC-side LabVIEW software platform, data acquisition card, power-side electrical signal test instrument (voltage, current transformer, etc.).

The frequency converter used in this experiment is a PWM inverter commonly used in oil fields, and the simulated load is mainly realized by the way of two motors driving each other [28, 30]. The Energy-saving test, analysis and evaluation of frequency conversion system are completed by the combination of the test instrument Norma5000 and the LabVIEW harmonic analysis software platform. Figure 1 shows the experimental platform established for testing and analyzing the inverter energy efficiency and harmonic impact on the system.

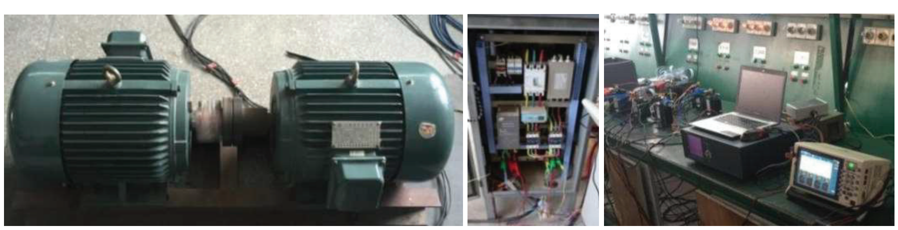


Figure 1 Energy-saving test and evaluation experiment platform.

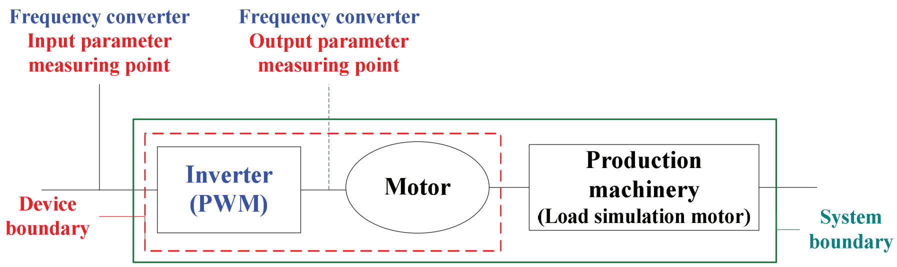


Figure 2 The measuring points arrangement.

5.2 Experimental Conditions and Parameter Settings

The settings of the experimental conditions as follows:

- Power frequency: 30 Hz, 40 Hz, 50 Hz;
- Simulated drag load: 50 N·m, 100 N·m, 200 N·m, 300 N·m, 400 N·m;
- Test parameters: electrical parameters of the input side (grid side) and output side of the inverter, the arrangement of the measuring points is shown in Figure 2;
- Analysis and calculation indicators: The power factor of the inverter input/output side, inverter efficiency listed in Table 1, and the harmonic indicators listed in Table 2.

5.3 Energy-saving Test and Analysis Experiment Process

Figure 3 shows the energy efficiency test and analysis process of the inverter for this experimental system.

5.4 Experimental Results and Analysis

According to the experimental conditions and parameter settings, a total of 15 different operating conditions of the frequency conversion system energy saving test, and the analysis and calculation of the influence of harmonics on the performance and energy saving effect of the inverter have been carried out. First of all, the voltage and current waveforms and the full harmonic components extraction results under each working condition are obtained. On this basis, the active power, apparent power, power factor, inverter efficiency and various harmonic indicators are calculated according to the calculation methods given in the article.

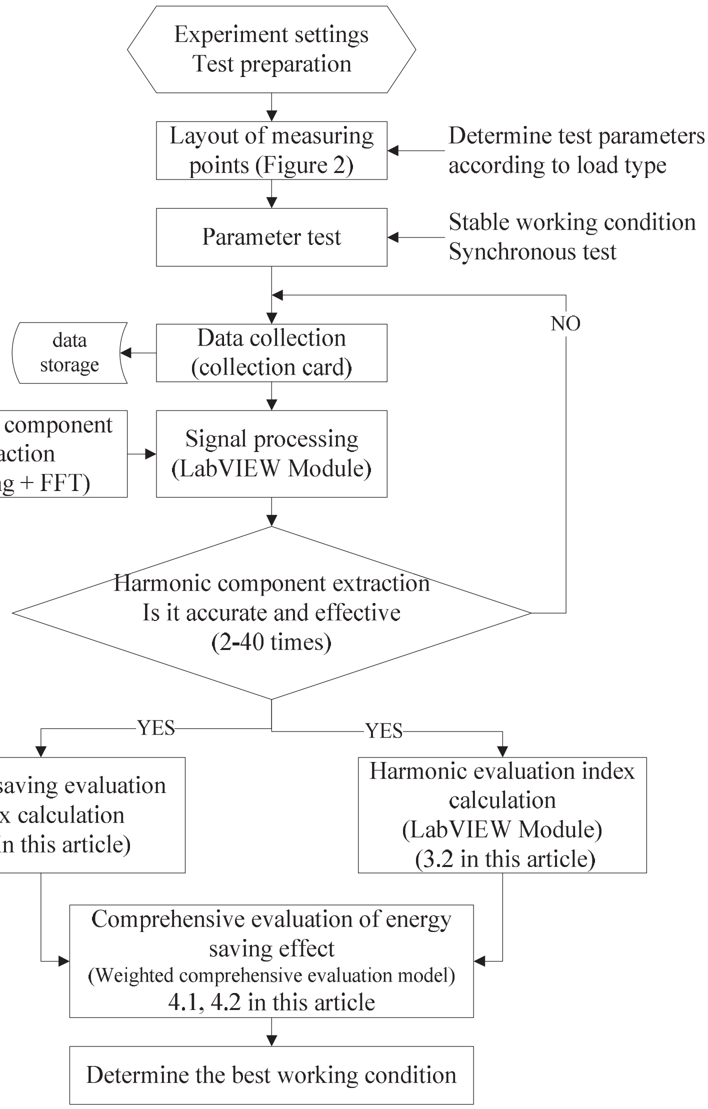


Figure 3 Flow chart of energy-saving test and evaluation experiment.

5.4.1 Basic waveforms

Figure 4 shows the voltage and current waveforms under the working condition of 30 Hz and 200 Nm, and the corresponding harmonic component extraction results are shown in Figure 5.

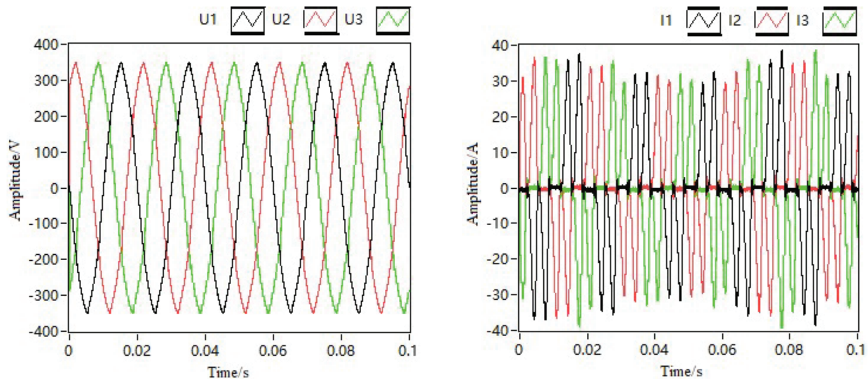


Figure 4 Waveforms of voltage & current.

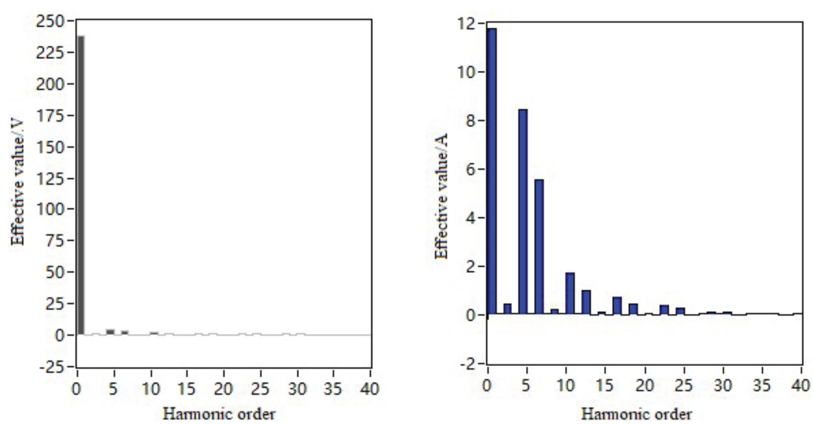


Figure 5 Harmonic components extraction of voltage & current.

5.4.2 Electrical parameter test and calculation results

The test and calculation results of the voltage, current, active power, apparent power on the input and output sides of the inverter under 15 different working conditions are shown in Tables 3 and 4.

5.4.3 Calculation results and analysis of the inverter energy efficiency index

In order to analyze and express clearly, the method in GB/T 30844.2 is recorded as method 1, the method used by the field test instrument is recorded as method 2, and the total harmonic components method proposed in this paper is recorded as method 3. The comparison of the calculation results of

Table 3 Test and calculation results of electrical parameters for inverter input

Condition No.	Frequency/ Hz	Load N·m	Input – Full-wave Parameters				Input – Fundamental Parameters			
			Voltage RMS/V	Current RMS/A	Active Power/kW Average Value	Apparent Power/kW Average Value	Voltage RMS/V	Current RMS/A	Active Power/kW Average Value	Apparent Power/kW Average Value
1	30	50	226.72	9.14	1240.68	2071.65	226.60	5.69	1274.77	1290.33
2	30	100	226.54	14.07	2050.74	3187.33	226.41	9.28	2082.02	2101.20
3	30	200	225.89	23.57	3691.51	5324.36	225.72	16.69	3737.87	3767.21
4	30	300	225.76	33.18	5397.83	7489.93	225.55	24.48	5471.56	5522.27
5	30	400	225.37	42.81	7191.39	9647.39	225.13	32.69	7292.65	7359.75
6	40	50	226.07	11.26	1595.10	2545.66	225.96	7.26	1624.32	1640.10
7	40	100	225.89	17.83	2667.56	4027.34	225.76	12.14	2717.48	2741.58
8	40	200	225.49	29.89	4890.17	6740.16	225.31	22.29	4981.90	5023.00
9	40	300	224.08	42.03	7054.20	9416.75	223.85	32.32	7175.70	7235.44
10	40	400	224.26	53.79	9384.70	12062.83	224.00	42.85	9515.13	9598.29
11	50	50	225.25	12.64	1776.63	2846.30	225.14	7.89	1754.56	1776.80
12	50	100	225.17	21.13	3601.20	4757.87	224.96	14.71	3284.09	3309.08
13	50	200	224.78	36.32	5980.82	8164.36	224.55	27.31	6081.41	6131.22
14	50	300	224.69	50.63	8770.29	11375.10	224.41	39.95	8887.80	8965.59
15	50	400	223.98	65.13	11581.08	14587.17	223.68	52.89	11723.37	11829.57

Table 4 Test and calculation results of electrical parameters for inverter output

Condition No.	Frequency/ Hz	Load N·m	Output – Full-wave Parameters				Output – Fundamental Parameters			
			Voltage RMS/V	Current RMS/A	Active Power/kW Average Value	Apparent Power/kW Average Value	Voltage RMS/V	Current RMS/A	Active Power/kW Average Value	Apparent Power/kW Average Value
1	30	50	215.20	32.71	1122.99	7045.77	150.54	32.34	996.54	4874.79
2	30	100	214.44	34.79	1926.10	7464.29	150.18	34.43	1807.38	5173.17
3	30	200	213.81	42.69	3542.24	9130.81	150.00	42.36	3385.21	6354.42
4	30	300	213.17	54.01	5210.79	11519.55	149.65	53.75	5095.88	8051.31
5	30	400	212.40	67.74	6941.99	14398.22	149.36	67.54	6820.49	10099.84
6	40	50	249.46	32.89	1595.10	8210.99	201.03	32.64	1460.53	6565.27
7	40	100	249.05	35.12	2537.00	8751.71	200.72	34.84	2386.67	6995.94
8	40	200	247.94	43.30	4718.33	10746.25	200.39	43.16	4628.09	8658.07
9	40	300	246.45	54.19	6847.70	13373.99	200.12	54.06	6729.75	10828.63
10	40	400	245.96	67.66	9125.47	16651.79	199.86	67.44	9034.57	13489.86
11	50	50	280.36	33.38	1657.82	9368.41	251.24	33.12	1521.73	8329.42
12	50	100	279.44	35.79	3461.38	9980.38	250.98	35.56	3007.84	8910.82
13	50	200	277.76	43.61	5815.26	12134.29	249.42	43.49	5802.27	10865.46
14	50	300	277.36	54.80	8543.84	15204.95	249.69	54.69	8512.09	13662.82
15	50	400	276.41	67.95	11303.97	18824.79	249.63	67.75	11203.49	16953.06

the inverter energy efficiency index corresponding to the 3 methods under 15 different working conditions is shown in Table 5, and the comparison diagrams are shown in Figures 6 and 7.

The comparative analysis of the above results shows that:

- Power factor: It changes in direct proportion to the power frequency and torque. Due to the different test methods used on the input side and the output side, the numerical rules are different, and the input side is generally higher than the output side;
- Input side: Method 1>Method 3>Method 2, the value range of the method in this article is 0.61∼0.8;
- Output side: Method 1>Method 2>Method 3, the value range of the method in this article is 0.14∼0.59;
- Inverter efficiency: It changes in direct proportion to the power frequency and torque. The numerical law of the three methods is: Method 1>Method 3>Method 2. The efficiency range of the calculation method based on the total harmonic components proposed in this paper is 80% to 97%, which is more in line with the actual situation of the equipment;
- Method recommendation: Based on the above analysis, the total harmonic components method proposed in this paper can not only analyze the fundamental wave's effect reasonably, but also comprehensively consider the full-wave effect under the influence of harmonics. Therefore, it is recommended to use the method proposed in this article to calculate the actual operating efficiency and power factor of variable frequency equipment or system.

5.4.4 Calculation results and analysis of harmonic index and comprehensive evaluation function

Under 15 different working conditions, the calculation results of harmonic index on the input and output sides of the inverter and the comprehensive evaluation function are shown in Table 6.

According to the data in Table 5, the distribution and sequences of the comprehensive evaluation function *C* for the influence of harmonics on system and equipment performance under 15 different working conditions are shown in Figure 8.

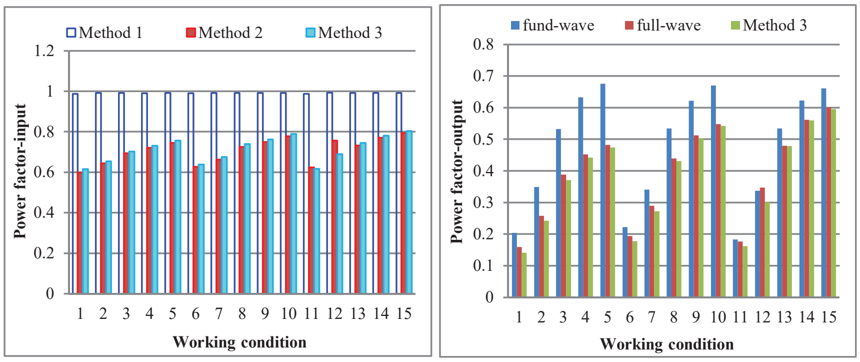
According to the comprehensive analysis of Table 5 and Figure 8, In other words, the best working condition is 40Hz, 300Nm among the 15 working conditions. In other words, for the constant load variable-frequency speed regulation system given in the experiment, the system will have the best

Table 5 The calculation results and comparative analysis of the inverter energy efficiency

Condition No.	Frequency/ Hz	Load N·m	Power Factor – Input			Power Factor – output			Inverter Efficiency/%		
			Method 1 Fund-wave	Method 2 Full-wave	Method 3	Fund-wave	Full-wave	Method 3	Method 2 Fund-wave	Method 1 Full-wave	Method 3
1	30	50	0.9879	0.5989	0.6153	0.2044	0.1594	0.1414	78.17	90.51	80.32
2	30	100	0.9909	0.6434	0.6532	0.3494	0.2580	0.2421	86.81	93.92	88.13
3	30	200	0.9922	0.6933	0.7020	0.5327	0.3879	0.3707	90.57	95.96	91.70
4	30	300	0.9908	0.7207	0.7305	0.6329	0.4523	0.4424	93.13	96.54	94.41
5	30	400	0.9909	0.7454	0.7559	0.6753	0.4821	0.4737	93.53	96.53	94.84
6	40	50	0.9904	0.6266	0.6381	0.2225	0.1943	0.1779	89.92	100.00	91.56
7	40	100	0.9912	0.6624	0.6748	0.3412	0.2899	0.2727	87.83	95.11	89.47
8	40	200	0.9918	0.7255	0.7391	0.5345	0.4391	0.4307	92.90	96.49	94.64
9	40	300	0.9917	0.7491	0.7620	0.6215	0.5120	0.5032	93.79	97.07	95.40
10	40	400	0.9913	0.7780	0.7888	0.6697	0.5480	0.5426	94.95	97.24	96.27
11	50	50	0.9875	0.6242	0.6164	0.1827	0.1770	0.1624	86.73	93.31	85.65
12	50	100	0.9924	0.7569	0.6902	0.3375	0.3468	0.3014	91.59	96.12	83.52
13	50	200	0.9919	0.7326	0.7449	0.5340	0.4792	0.4782	95.41	97.23	97.01
14	50	300	0.9913	0.7710	0.7813	0.6230	0.5619	0.5598	95.77	97.42	97.06
15	50	400	0.9910	0.7939	0.8037	0.6609	0.6005	0.5951	95.57	97.61	96.74
	Ranges		0.98~0.99	0.59~0.79	0.61~0.8	0.18~0.67	0.15~0.6	0.14~0.59	78~95	90~100	80~97
Comparison recommendation			×	×	√	×	×	√	×	×	√

Table 6 Calculation results of harmonic index and comprehensive evaluation function

			Input			Output					Comprehensive
Condition No.	Frequency/ Hz	Load N·m	V_{THDI} %	I_{THDI} %	V_{unbI} %	V_{THDO} %	I_{THDO} %	V_{unbO} %	HVF 10^{-2}	HCF 10^{-2}	Evaluation Function C
1	30	50	1.91	125.22	0.34	2.91	2.86	5.14	0.10	1.07	1.1264
2	30	100	2.29	113.00	0.31	3.05	2.42	1.88	0.11	0.93	1.3754
3	30	200	2.62	98.92	0.26	2.89	2.06	5.70	0.12	0.95	1.5877
4	30	300	3.08	91.17	0.32	3.28	1.40	3.28	0.15	0.78	1.4603
5	30	400	3.60	84.37	0.42	2.96	0.97	5.44	0.16	0.65	1.4269
6	40	50	2.17	117.38	0.29	2.08	2.79	4.12	0.08	1.10	1.6045
7	40	100	2.19	107.09	0.24	2.01	2.50	1.77	0.12	1.04	1.6771
8	40	200	3.01	89.62	0.31	2.11	1.79	5.66	0.15	0.91	1.7313
9	40	300	3.63	83.36	0.28	2.02	1.34	0.16	0.22	0.85	1.6225
10	40	400	4.11	75.53	0.49	2.19	1.03	2.81	0.18	0.79	1.4357
11	50	50	1.91	119.08	0.27	0.33	2.44	5.24	0.10	1.03	1.5789
12	50	100	2.54	101.69	0.29	0.39	1.95	0.31	0.13	0.88	1.5908
13	50	200	3.34	87.92	0.31	0.67	1.50	0.06	0.20	0.83	1.6802
14	50	300	3.91	77.74	0.17	0.69	1.25	0.20	0.23	0.87	1.4786
15	50	400	4.42	71.10	0.33	1.02	1.02	5.16	0.38	0.88	0.8917



6a) Input side 6b) Output side

Figure 6 Comparison of power factor calculation results.

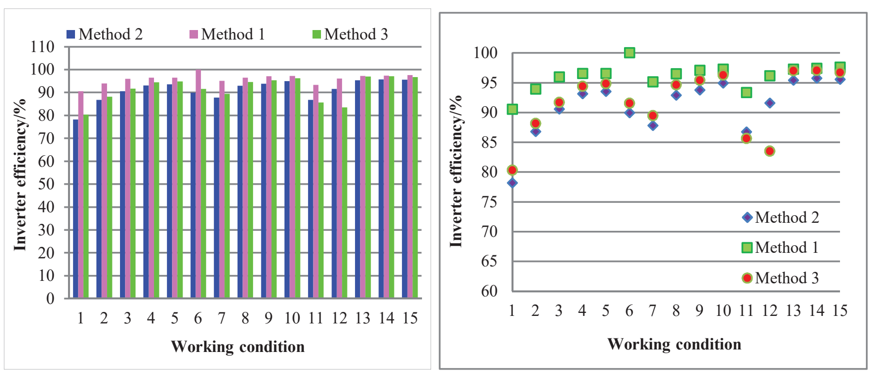


Figure 7 Comparison of inverter efficiency calculation results.

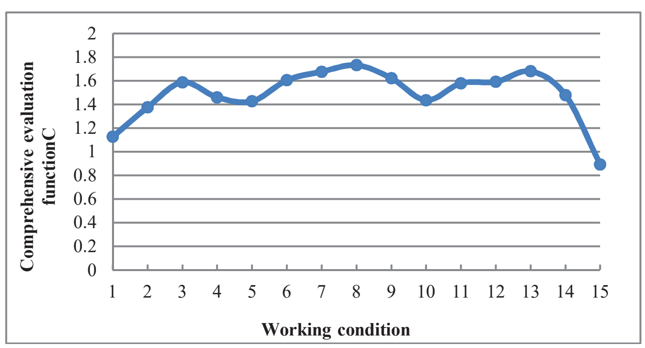


Figure 8 Distribution of comprehensive evaluation results of harmonic influence.

comprehensive performance and energy saving effect under this working condition.

6 Conclusions

In view of the current situation of inconsistent energy-saving test and evaluation methods for frequency conversion systems, according to the relevant current standards, theoretical research and application effects of frequency conversion technology in petroleum companies, the energy-saving evaluation index system and calculation method of the frequency conversion system based on the based on the total harmonic components are proposed in this paper. A set of harmonic evaluation index system has also been established, including a total of 9 indicators on the input and output sides of the inverter. On this basis, the six core harmonic indicators of total voltage distortion rate, total current distortion rate, and three-phase voltage unbalance degree are selected, and a comprehensive evaluation method for the energy-saving effect of the frequency conversion system is proposed based on the total harmonic components and the weighted matrix model. Subsequently, the energy-saving test and evaluation experiment platform for the frequency conversion system based on the LabVIEW virtual test instrument is established, and the experiments under 15 different working conditions have been carried out.

The experimental results show that compared with the existing energy efficiency analysis methods of frequency conversion systems and equipment, the method researched in this article can not only meet the requirements of on-site operation and analysis, but also reflect the efficiency level of frequency conversion system and its equipment more truly. At the same time, the power factor on the input side and output side of the inverter is clearly distinguished. In addition, the comprehensive evaluation method of energy-saving effect proposed in this paper can comprehensively and reasonably analyze the harmonic effects on the performance of variable frequency systems and equipment. The method is mainly to analyze, calculate and sort the comprehensive evaluation function, which can quickly and reasonably determine the best operating conditions of the system and equipment. The method studied in this paper is not only simple and easy to implement, but also conforms to the actual situation. It can be used as a unified regulation and guidance for the testing and evaluation of frequency conversion systems and equipment in petroleum companies and related fields.

Funding Information

This research was supported by China National Energy Board Standard Project (No. 20160237); & Youth Science Foundation Project of NEPU (No. 2018QN-47).

Conflict of Interest

We all declare that we have no conflict of interest in this paper.

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