Research on Interactive Harmonic Impedance Measurement and Control Technology for Traction Network Based on Embedded System

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Abstract. The railway traction power supply system has the problem of harmonic resonance in a wide frequency band. The resonance will not only affect the power quality of the power supply system, but also cause serious harmonic resonance accidents. The impedance frequency characteristic of traction network is the key factor of harmonic resonance phenomenon, which has certain research value, but it is difficult to obtain it accurately through simulation calculation. Therefore, it is particularly important to obtain the impedance-frequency characteristics of traction network in broadband by testing, which is of great significance to the treatment of harmonic resonance problems of existing lines and the prediction and evaluation of harmonic resonance problems of new lines. Based on the existing harmonic impedance testing device, this paper studies a measurement and control technology of traction network harmonic impedance based on embedded system interaction, introduces its interface principle, software and hardware architecture, main functions of supporting software, etc., and proposes a harmonic impedance testing algorithm based on inter-harmonic interpolation and improved fluctuation method.

Keywords: Traction Net · Harmonic impedance test · Resonance · Observation and Control Technology

1 Introduction

With the rapid development of electrified railways in China, power electronic devices and AC-DC-AC electric locomotives and EMUs have been widely used in traction power supply system, and the harmonic resonance phenomenon in traction power supply system also occurs frequently. At present, the resonance mechanism of traction network has been studied deeply [1]. When the frequency of the harmonic current injected by locomotive into the traction network is equal to or close to the inherent resonance frequency of the traction network, and the harmonic current is larger than a certain value, the traction

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network will resonate, which will amplify the harmonic current and generate overvoltage. Overcurrent and overvoltage generated by harmonic resonance of traction network have many consequences. In serious cases, it may damage related equipment, even cause locomotive outage, which threatens the safe and stable operation of traction power supply system [2]. After a large number of new AC-DC-AC locomotives were put into operation, harmonic resonance accidents of traction network occurred in Zurich, Switzerland [3]. Overvoltage caused by resonance caused a large number of locomotives to fail to start normally, and there are similar cases in China [4]. In addition, the high-order harmonics in the traction network may even penetrate into the three-phase system, seriously affecting the power supply quality of the three-phase system [5].

The main idea to solve the high-order harmonic problems of traction power supply system is to optimize from the side of vehicle or network. The main method of side optimization is to optimize the PWM modulation algorithm and control strategy of the Four-quadrant Converter to change the frequency and amplitude distribution of the harmonic current injected into the side of the network [6]. Network side optimization is mainly to set up filters in traction substations or zones [7]. The tuning of relevant parameters for these optimization ideas is based on the accurate harmonic impedance characteristics of power supply system. Therefore, in order to ensure the reliable operation of power supply system, it is necessary to study its harmonic impedance characteristics.

At present, most of the studies on harmonic impedance characteristics of power supply systems are based on modeling methods. It is difficult to model the traction power supply system because of the complex structure of the traction network itself, large parameter changes and the inability to accurately calculate the frequency characteristics of external power impedance. Therefore, it is more direct and effective to obtain the impedance frequency characteristics of the traction power supply system through the test method using a dedicated harmonic impedance test device.

This paper mainly introduces the research on the test technology of impedance frequency characteristics of traction network. Based on the theory of interharmonic interpolation improved wave volume method, a broadband harmonic impedance measurement algorithm for traction power supply system is presented. In practice, using the real-time test data at the access point of the harmonic impedance test device, this algorithm can calculate the harmonic impedance by loading in the impedance characteristic measurement and control software of the test device. The method presented in this paper has the advantages of fast, intuitive, accurate results and strong applicability.

2 Principle of Traction Network Impedance Frequency Characteristic Test Device

The power quality problem of traction power supply system represented by high-order harmonic resonance is essentially caused by the unstable electrical matching of the power supply system. This is closely related to the impedance frequency characteristics of the traction network. Therefore, it is important to study and master the impedance frequency characteristics of traction network for improving the power quality of power supply system. Due to the difficulties of traditional simulation calculation and impedance modeling method, it is difficult to obtain accurate results [8]. Therefore, it is more direct and effective to obtain the impedance frequency characteristics of traction network by the test method using the harmonic impedance test device dedicated to traction network. A harmonic impedance test device [9] has been developed by Beijing Jiaotong University. The way it connects to the traction network is shown in Fig. 1a.

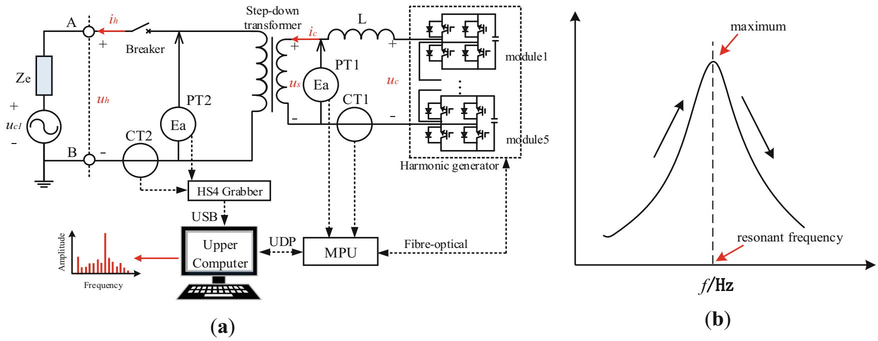

Fig. 1. **a** Schematic diagram of broadband harmonic impedance measurement device for traction network; **b** impedance frequency characteristic curve of traction power supply system.

The key to the harmonic impedance measurement of single-phase power supply system is to replace the harmonic source (e.g. train in traction power supply system) with a special harmonic generator to actively inject specific sequential harmonics in a specific frequency band for impedance measurement. Consider the railways to be tested as black boxes. When looking at the black box from AB port, the measured railways can be represented by the base voltage source U_{e1} and the internal impedance Z_e by Thevenin's theorem [10]. Assuming that the voltage of AB port is U_h stimulated by I_h, the (interharmonic) impedance at a specific frequency f can be obtained as follows:

$$Z_e(f) = \Delta U_h(f)/\Delta I_h(f) \tag{1}$$

where ΔU_h and ΔI_h are the changes of U_h and I_h at the measured frequency f, respectively. This conclusion ignores background noise based on the simplified interpretation of wave method, because there are many measures that can be taken to reduce the impact of background noise in practical application, such as improving the test accuracy by injecting interharmonics into the measured power supply system through the control device's harmonic generator.

Different traction networks have different impedance frequency characteristics and different resonance frequencies. Therefore, the harmonic impedance measurement system needs to meet the requirements of measuring the impedance frequency characteristics of traction networks in broadband. By means of frequency scanning, the control device injects harmonic currents of different frequencies in a broadband into the traction network and conducts harmonic impedance measurements at the same time. By plotting the calculated frequency and impedance, the impedance frequency characteristic curve at the test point under the broad band of the traction network can be obtained, as shown in Fig. 1b.

3 Principle of Harmonic Impedance Measurement and Control Technology for Traction Network

3.1 Architecture and Principles

The hardware and software architecture of the traction harmonic impedance measurement and control technology is shown in Fig. 2. The measurement and control technology is divided into two parts from the functional point of view: control and test. From the composition point of view, it is composed of the hardware of the embedded system and the supporting software.The hardware and software architecture and principles of the measurement and control system are detailed in Sects. 3.2 and 3.3.

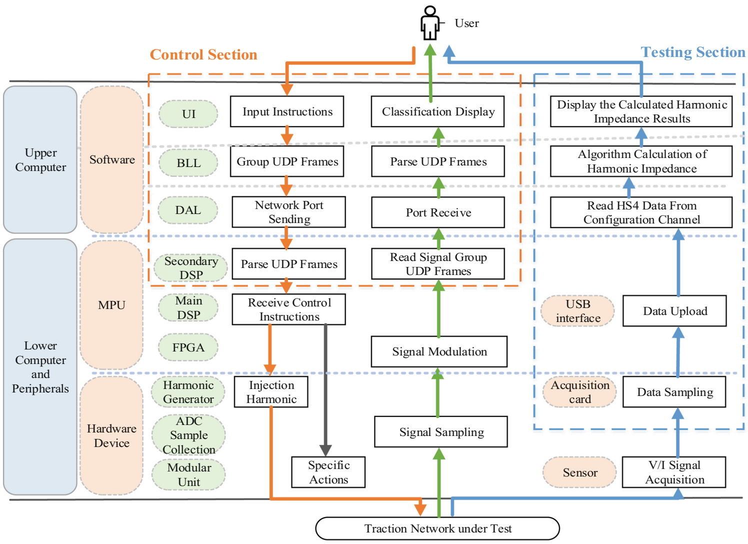

Fig. 2. Software and hardware architecture of harmonic impedance measurement and control technology for traction network.

The principle is that in the process of frequency scan, the control part and the test part cooperate with each other to help users complete the closed-loop operation of input command, issue command, instruction execution, data collection, data upload, impedance calculation, result feedback. The control part receives the user's instructions to the upper computer software and transmits them through the network ports of the embedded system, the auxiliary DSP and the main DSP layers. Finally, the harmonic generator in the control hardware injects specific frequency, amplitude and phase sequence harmonics into the access point of the power supply system. At the same time, the test part uses the voltage and current collected by the sensor, uses the HS4 card to sample and convert the collected signal, and transmits it to the upper computer through the USB interface. Loaded traction network harmonic impedance test algorithm is invoked by the upper computer software of the test section to complete the impedance calculation, and the (interharmonic) impedance of a frequency is obtained immediately and visually fed back to the user. The test part of the hardware principle is shown in Fig. 3. Then, add on the test frequency Δf, repeat injection of harmonic current for testing until the upper computer software calculates and analyzes the harmonic impedance-frequency characteristic curve of the entire required frequency band.

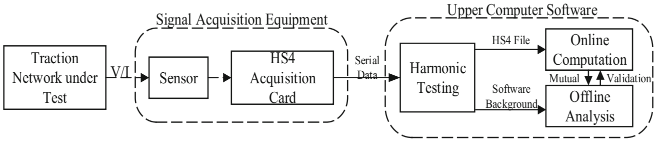

Fig. 3. Hardware principle of testing section.

3.2 Hardware Architecture and Principle of Embedded System

The hardware of the device control section mainly consists of four parts: the main control board used to control each part of the device, the collection board used to collect relevant electrical information in real-time, the fiber optic board used for signal modulation, and the bottom board used to provide power and communication bus to the board. The hardware architecture of each board is shown in Fig. 4.

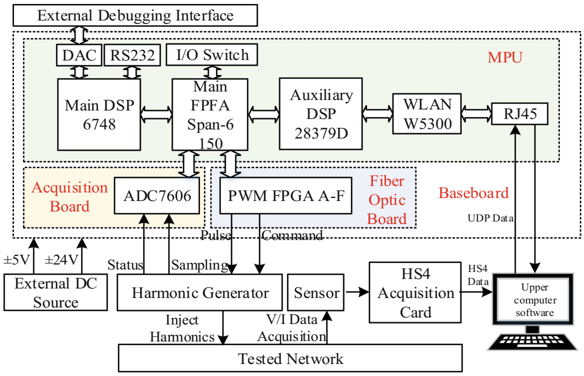

Fig. 4. Diagram of board connection relationship of switching harmonic impedance test device.

The collection board is equipped with three ADC 7606 chips, which serially input the sampled data to the main FPGA and transmit it to the main DSP through the bus for algorithm control; The fiber optic board is equipped with one FPGA chip, which can generate multiple PWM pulse signals and control the H-bridge converter module unit of the harmonic generator through the fiber optic; The base plate is connected to ±5 V and ±24 VDC power supplies to supply power to each board and provide communication bus; The main control board is the control core of the entire harmonic impedance testing device. Due to the limited volume of the device, the layout of the main control board needs to be reasonably planned. Therefore, a single FPGA dual DSP architecture is designed to leverage the excellent multithreading performance of FPGA and the powerful digital signal computing power of DPS [11]. Three chips communicate through an on board bus, with FPGA model XC6SLX45 used to process sampling signals, generate and output interrupt reference signals to other chips, and interact with the outside world through I/O switch signals; The main DSP model is TMS320C674, which is responsible for executing algorithms for hierarchical control calculations. By calling rich library functions, high-performance algorithm processing capabilities are achieved; The auxiliary DSP model is TMS320F28379D, responsible for Ethernet data communication with the upper computer through the user datagram protocol, framing and uploading the collected voltage, current, and other information to the upper computer, and receiving control instructions issued by the upper computer.

3.3 Architecture and Principle of Supporting Software for Measurement and Control Technology

The harmonic impedance measurement and control technology of the traction network is matched with the upper computer software, providing users with a window to interact with the embedded system. The development environment is Microsoft's product Visual Studio 2015, and the programming language is C#. The C/S three-layer architecture was adopted during the design, as shown in Fig. 5.

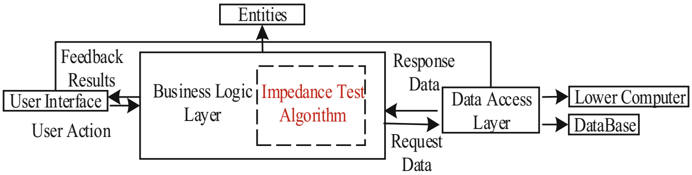

Fig. 5. Upper Computer Software Architecture of User Operating Harmonic Impedance Measurement and Control System.

The software functions include data filtering, Fast Fourier Transform (FFT) calculation, harmonic impedance calculation algorithm for traction power supply system, mapping results, and status monitoring. In the design of the measurement and control system, all functional points are assigned to two parts according to requirements. The following will introduce the functions of the control part and the testing part respectively.

(1) Control part function.

The software control function is mainly divided into three parts: online monitoring, system control, and harmonic control. The following will be introduced in sequence.

The software online monitoring function analyzes and displays the data uploaded by the embedded system in real-time, and presents the results of online monitoring in various forms such as graphs, tables, and network topology, as shown in Fig. 6.

Fig. 6. Software on-line monitoring function.

(2) Test Part Function

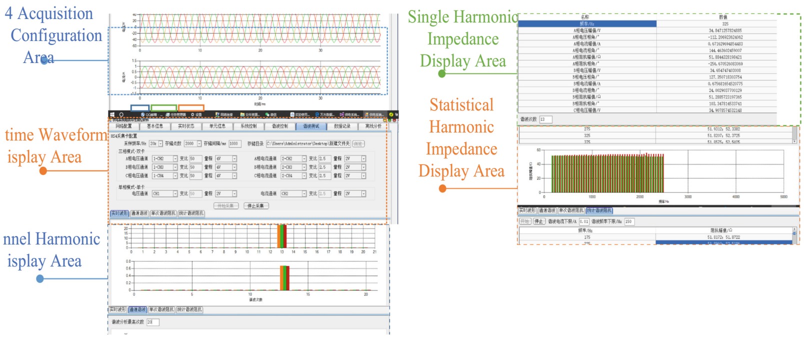

Fig. 7. Software harmonic testing function.

The test part implements two important functions: harmonic measurement and impedance calculation. The function of impedance calculation is divided into online calculation and offline analysis. The test part collects the voltage and current data of the traction network measured by the collection device, uploads it to the software through the serial port, calculates the impedance frequency characteristic by the harmonic impedance test algorithm, and displays the results on the UI interface of the software.

The interface of the harmonic test tab is composed of five parts, as shown in Fig. 7, which are HS4 acquisition card configuration area, real-time waveform monitoring area, channel harmonic monitoring area, single harmonic impedance monitoring area, and statistical harmonic impedance display area.

Real time waveform monitoring area: After completing the configuration of the acquisition card in the HS4 acquisition card configuration area, click the "Start Collection" button to real-time calculate the amplitude of each harmonic impedance. The displayed result is the weighted average of the impedance amplitude at each moment after clicking the "Start" button. The simplified flow chart is shown in Fig. 8, and the impedance testing algorithm is detailed in Sect. 4.

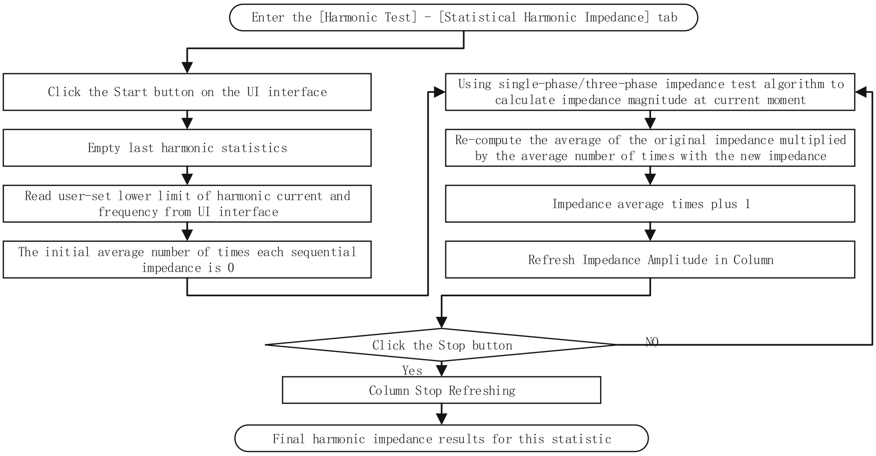

Fig. 8. Schematic flowchart of statistical harmonic impedance function.

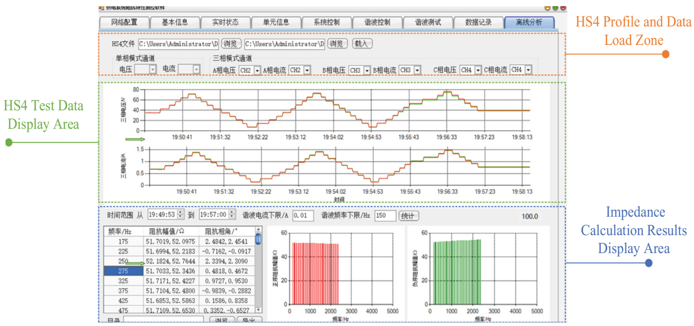

Fig. 9. Software Offline Analysis Function.

The software interface of offline analysis function is divided into three parts: HS4 profile and data loading area, test data display area, and impedance calculation result display area. Its interface partition is shown in Fig. 9.

The HS4 profile and data loading area provide an interface for reading the data of the HS4 file. The test data display area is responsible for displaying the valid values of the voltage and current of each channel collected by the HS4 data file within a specified period of time. The results of impedance calculation show that the table on the left of the display area is the impedance amplitude and phase angle at each frequency, with detailed data. The right icon is a histogram of the frequency-impedance magnitude, making the data more intuitive. The user clicks the "Statistics" button after manually entering the time range, the lower limit of harmonic current and the lower limit of harmonic frequency of impedance calculation on the software interface. After calculating by the software loaded harmonic impedance test algorithm, the impedance calculation results are obtained.

The process of using the software offline analysis function is as follows: (1) In the control part of the system, the user sets the control device in the software foreground interface to issue specific harmonic instructions according to the method of frequency scanning; (2) Instructions are issued in the software background to control the harmonic generator of the control device to inject interharmonic current with controllable amplitude and frequency into the access point of the measured traction network; (3) The test part of the system collects and uploads real-time piezoelectric current response data measured at the access point through the HS4 card; (4) The software obtains the uploaded data and calculates the harmonic impedance of the measured traction network in the background through the loaded algorithm; (5) The software displays the results of impedance calculation in the foreground interface and feeds them back to the user.

4 Algorithms for Harmonic Impedance Testing System

The harmonic impedance test device injects frequency, amplitude-controlled harmonics and interharmonics into the power supply network through a harmonic generator. The harmonic impedance between traction networks is measured, and then the harmonic impedance is calculated by the interpolation algorithm [12].

The h-th harmonic impedance of the traction network can be measured by injecting the interharmonic current with frequency $f_{\mathrm{h+}} = (50\mathrm{h} + \Delta \mathrm{f})$ Hz and $f_{\mathrm{h-}} = (50\mathrm{h} - \Delta f)$ Hz into the traction network with the cascade H-bridge harmonic generator, where $0 < \Delta f < 50$ Hz. The number of adjacent harmonics is counted as h+ and $h-$, and the harmonic impedance parameter is considered approximately constant in the range of $f_{h-} \sim f_{h+}$. The formula is as follows:

$$Z_{\mathrm{h+}} = R_{\mathrm{h}} + \mathrm{j}\omega_{\mathrm{h+}} L_{\mathrm{h}},\ Z_{\mathrm{h-}} = R_{\mathrm{h}} + \mathrm{j}\omega_{\mathrm{h-}} L_{\mathrm{h}} \tag{2}$$

Z_{h} in the formula is the impedance of the h-th harmonic, the real part is the resistance component, and the imaginary part is the reactance component.

$$|Z_{\mathrm{h+}}|^2 = R_h^2 + \mathrm{j}\omega_{h+}^2 L_h^2, \quad |Z_{\mathrm{h-}}|^2 = R_h^2 + \mathrm{j}\omega_{h-}^2 L_h^2 \tag{3}$$

The h-th harmonic impedance is: $Z_h = R_h + \mathrm{j}\omega_h L_h$ $Z_h = R_h + \mathrm{j}\omega_h L_h$.

Substituting into the equation can obtain:

$$Z_{\mathrm{h}} = \sqrt{\frac{|Z_{h+}|^2\omega_{h-}^2 - |Z_{h-}|^2\omega_{h+}^2}{\omega_{h+}^2 - \omega_{h-}^2}} + \mathrm{j}\omega_h\sqrt{\frac{|Z_{h+}|^2 - |Z_{h-}|^2}{\omega_{h+}^2 - \omega_{h-}^2}} \tag{4}$$

When the real part of impedance accounts for a very small proportion, $|Z_{h+}|^2/|Z_{h-}|^2 \approx \omega_{h+}^2/\omega_{h-}^2$, and the impedance interpolation formula can be simplified to:

$$Z_h = \frac{R_{h+} + R_{h-}}{2} + \mathrm{j}\omega_h \sqrt{\frac{|Z_{h+}|^2 - |Z_{h-}|^2}{\omega_{h+}^2 - \omega_{h-}^2}} \tag{5}$$

In wide-band harmonic impedance measurement, the measured frequency is widely distributed and dense. It is necessary to use a small-step frequency scanning method to improve the test accuracy. The specific method of broadband frequency scan is to continuously increase the frequency of the harmonic current injected into the traction contact network according to the small step method, at the same time, the system measures the voltage and current response at the access point in real time, and calculates the resonance frequency and the phase angle of the impedance amplitude through the harmonic impedance test algorithm.

5 Conclusion

The harmonic impedance measurement and control technology of traction network based on embedded system interaction for harmonic impedance measurement device is introduced in this paper. The architecture of hardware and software, the interface with embedded system, the principle of impedance measurement and the main functions of the supporting software are introduced. An improved harmonic impedance measurement algorithm based on interharmonic interpolation is presented.

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