An Application of Embedded Intelligence in the Automatic Tuning System for VLF Transmitter

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Abstract. The research focuses on the automatic tuning system for VLF (Very low frequency) transmitter using embedded intelligence, which constructs a modular architecture control system with flexibility and low cost. In this paper, the main problems of the VLF transmitting system are first analysed to determine the target of the automatic tuning system is mainly to match the output impedance of transmitter with the load impedance of antenna quickly and stably at any time. Then the matching network characteristics of the automatic tuning system are studied based on the conjugate matching principle. Besides, the implementation of the embedded control system is also given which composed of concrete design of hardware and realization of software algorithm. Finally, the embedded control system is successfully applied to the automatic tuning prototype for VLF transmitter and the experimental results verify the effectiveness of the embedded control system.

1. Introduction

Very low frequency (VLF) communication is an important part of the field of radio, the frequency of which is generally between 3 kHz to 30 kHz[1]. Due to its advantages of strong penetration, long propagation distance and small attenuation coefficient, VLF communication is widely used in military training and field operations such as mining and oil drilling[2-3]. In VLF transmitting system, one of the key research affecting the quality of transmitting signal can be described as the output impedance of transmitter can be matched with the load impedance of antenna quickly and reliably at any time and transmitter can radiate electromagnetic waves at full power[4]. Compared with bandwidth matching network, antenna tuning is a more effective solution. For VLF communication system with high octave working frequency, it is difficult for the former to fully match the antennas of different types and sizes under different working conditions and transmitting power.

With the continuous development of electronic technology and integrated circuits in recent years, embedded intelligence has been successfully applied in a large number of industrial automation equipment[5]. Obviously, embedded intelligence is more flexible, convenient, compact and stable with hardware tailoring and software adaptability in comparison with the tradition control method, especially in the VLF communication equipment which has particularly high requirements for reducing the size of device and working stability. On the basis of above, the target of the automatic tuning system for VLF transmitter can be summarized as follows:

- 1)The system can automatically perform tuning work based on real-time analysis of the detected data and state.
- 2)The time of automatic tuning should be kept within 120 seconds.
• 3) The system should be able to achieve reliable tuning under all conditions of demand at any time.

Section 2 gives the analysis of the automatic tuning principle, including composition of the VLF transmitting system, impedance matching principle and matching network characteristics. In section 3, hardware design of the control system, and function of each module are introduced. Software design of the control system, which shows the process of automatic tuning, is given in section 4. The test of the control system on the VLF automatic tuning prototype and the analysis of experimental data are described in section 5. Finally, the conclusion of this paper is given in section 6.

2. Analysis of automatic tuning principle

2.1. Composition of VLF transmitting system

A relatively complete VLF transmitting system as shown in figure 1 mainly consists of five parts: information editing, signal incentive, power amplifier, tuning device and antenna. VLF transmitting system can only transmit message at low rate, but cannot transmit complex signal such as images, due to the low frequency of the electromagnetic wave. Information editing is the process of digitizing and encrypting messages to be sent. Then the messages are modulated in the information incentive device. Finally, the signal is amplified by power amplifier and sent to antenna. The tuning device is responsible for the matching between transmitter and antenna, which is the research focus of this paper.

![Figure 1. Composition of VLF transmitting system.](image)

As shown in figure 2, the tuning device is composed of parameter detection, tuning controller and matching network. The parameter detection device processes the electrical parameters of transmitter and antenna into analog signals acceptable to the tuning controller. The matching network can be adjusted by the tuning controller according to the preset data and the electrical parameters after AD conversion, which is the circuit network consisting of controllable elements between the transmitter and antenna.

![Figure 2. Automatic tuning control network.](image)

2.2. Principle of impedance matching

The equivalent circuit diagram of the VLF transmitting system without matching network can be shown in figure 3, in order to study the radiation power of antenna. The transmitter is equivalent to AC signal source $U_S$ and complex impedance $Z_S$, and the antenna load is equivalent to the complex impedance $Z_L$. For the convenience research, the power of transmitter and the radiated power of antenna load can be defined as $P_{in}$ and $P_{out}$, respectively.
The input power of transmitter as the signal source is:

\[ P_{\text{in}} = U_s^2 \ast (Z_s)^{-1} \]  

(1)

The output power of antenna load is:

\[ P_{\text{out}} = U_s^2 \ast Z_L \ast ((Z_L + Z_s)^2)^{-1} \]  

(2)

The ratio between the load impedance of antenna and the output impedance of transmitter is defined as:

\[ \Gamma = Z_L \ast (Z_s)^{-1} = |\Gamma|e^{j\phi} \]  

(3)

Then the relationship between input and output can be shown as:

\[ P_{\text{out}} = \Gamma \ast ((1 + \Gamma)^2)^{-1} \ast P_{\text{in}} \]  

(4)

When the circuit is in resonance state, the antenna can radiate electromagnetic wave at full power, that is, the reactance part of the circuit should be zero. Since the impedance of transmitter is in pure resistance state, it is necessary to make the reactance of antenna is zero. The relationship between the radiation power of antenna and the proportional coefficient when the circuit is in resonance state can be obtained from the above equation. The antenna load power reaches its maximum value when the impedance proportional coefficient \( \Gamma = 1 \), and the maximum value point is unique. At this point, the antenna load impedance \( Z_L \) is equal to the transmitter output source impedance \( Z_s \).

**2.3. Analysis of matching network**

The matching network is necessary to be added between transmitter and antenna to match the output impedance of transmitter with the total load impedance of the system, due to the parameters of antenna will change with frequency[6]. After the analysis in previous section, only when the load reactance is zero and the load resistance is equal to the transmitter source resistance, can the two parts be matched. As shown in figure 4, two adjustable inductors in the system’s equivalent circuit constitute T-type matching network, in which L1 regulates the reactance part of the load and L2 regulates the resistance part of the load.

When the operating frequency of the system is \( \omega \), the impedance of antenna can be expressed as:
\[ Z = R + j\omega L - (j\omega C)^{-1} \] (5)

The load impedance part in figure 4 can be further equivalent to figure 5:

![Equivalent Circuit Diagram](image)

Figure 5. The equivalent circuit diagram of the total load impedance.

All the reactance of the load can be obtained from figure 5:

\[ X^{-1} = X_{L1}^{-1} + X_p^{-1} = X_{L1}^{-1} + \left( \frac{x_t^2 + R^2}{x_t} \right)^{-1} = X_{L1}^{-1} + \left( \frac{(x_{L2} + x_{L1} + x_C)^2 + R^2}{x_{L2} + x_{L1} + x_C} \right)^{-1} \] (6)

In order to make the circuit reach resonance state, \( L_1 \) can be adjusted to make \( X_{L1} = -X_p \), and then the load impedance only has the pure resistance \( R_p = \frac{x_t^2 + R^2}{R} \). Only when \( L_2 \) is adjusted to \( R_p = Z_s \), the radiated power of antenna can reach the maximum value. Since the regulation of \( L_2 \) also changes \( X_{L1} \), so the regulation of \( L_1 \) and \( L_2 \) is a process of dynamic and successive approximation.

3. Design of the embedded control system

3.1. Hardware implementation

Illustrated in figure 6, the hardware architecture of the automatic tuning system for VLF transmitter based on embedded intelligence could be shown clearly. In the architecture, as the core of the whole embedded control system, MCU plays an important role in multi-module integration and active control. The communication module realizes the information interaction between MCU and client, angle sensor and impedance display instrument through RS485 bus. The client is the main tool to provide man-machine coordination, which is used for the control of antenna tuning, the setting of electrical parameters and the display of system state. The angle sensor is used to detect the rotation angle of the adjustable inductance coils \( L_1 \) and \( L_2 \) in real time, and the load impedance can be accurately displayed on the impedance display instrument after being adjusted by the matching network. The signal display module is used to display the positive inversion of the coil and system alarm in the form of indicator light on the automatic tuning equipment for the convenience of timely monitoring and troubleshooting. The button...
detection module makes it possible to manually operate the rotation and emergency stop of the coil. In order to avoid the coil to the limit position, photoelectric limit sensor can make the coil stop in time.

It’s obvious that motor drive module and data collection module play a direct role in this system. The data collection module based on AD conversion is responsible for collecting the electrical parameters of transmitter and antenna, including amplifier voltage, amplifier current, amplifier power, antenna voltage, antenna current and phase discriminator. The core device of the data collection module is a 16-bit ADC (Analog-to-Digital Converters) with built-in digital filter and 6 channels that can simultaneously at 200 KSPS throughput rate. The drum inductor in figure 6 is exactly the adjustable inductance in figure 4, which is mainly composed external coil and internal rotatable coil. The stepper motor drives the internal coil to rotate through the transmission device, changing the magnetic field distribution of the internal coil and thus causing the change of reluctance in the magnetic path of the external coil and realizing the continuous adjustable inductance. Among them, L1 mainly regulates the inductance part of the load and L2 mainly regulates the resistance part.

3.2. Software implementation

![Flow Chart of Phase Tuning](image1)

![Flow Chart of Impedance Tuning](image2)

Embedded software based on uC/OS-III runs on MCU, and the scheduler organizes the execution of tasks including communication, input detection, output refresh, AD conversion, data calculation and motor movement. Automatic tuning is the core program of the system, which mainly includes phase tuning and impedance tuning. This paper presents the execution process of these two parts in the form of flow chart, as shown in figure 7 and figure 8. When the automatic tuning system starts tuning, it first performs phase tuning and then impedance tuning, forming a cyclic process of dynamic and successive approximation until both phase and impedance are reached.

4. Experimental results

The embedded controller designed in this paper is applied to the VLF automatic tuning equipment. The functions of RS485 communication, data acquisition, input and output, and manual positive and negative rotation of motor have been tested successively with relevant instruments, and all of them can work
normally. Finally, the automatic tuning function is verified. Frequency bands of 25 KHz to 30 KHz were selected as test bands, with an interval of 0.5 KHz. For each target frequency point, the longest time from the remaining 10 frequency points to the target frequency point was tested. The experimental data are shown in figure 9. The experimental results show that all detuning states can be frequency hopping to the set target point, and the maximum time is no more than 64 seconds.

![Figure 9. Results of automatic tuning experiment based on embedded intelligence.](image)

5. Conclusion
In this paper, the matching principle and matching network of the automatic tuning system are analysed, and then an embedded control system driven by a motor with adjustable inductor is designed. Now, the system has been applied to the VLF automatic tuning equipment, and the matching of the transmitter output impedance and the antenna load impedance is realized through the successive approximation of phase and impedance, and the electromagnetic wave is radiated with the maximum power. The tuning time basically fluctuates within 60s, within the limit of 120s, achieving the goal of being fast, reliable and stable.

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References
[1] Barr R, Jones D L, Rodger C J. ELF and VLF radio waves[J]. Journal of Atmospheric and Solar-Terrestrial Physics, 2000, 62(17): 1689-1718.
[2] Swanson E R. ELF-VLF Applications in Navigation and Communications[M]// ELF-VLF Radio Wave Propagation. Springer Netherlands, 1974.
[3] Gogoi A K, Raghu Ram R. Analysis of VLF loop antennas on the Earth surface for underground mine communication[C]// Antennas & Propagation Society International Symposium. IEEE, 1996.
[4] Boyle K R, Spits E, De Jongh M, et al. Antenna tuners for mobile applications[C]// European Conference on Antennas & Propagation. IEEE, 2013.
[5] Vassiliev A E, Ivanova T Y, Tapia D F C, et al. Microcontroller-based embedded system equipment development for research and educational support[C]// 2016 International Conference on Information Management and Technology (ICIMTech). IEEE, 2016.
[6] Jeon S, Yoo K, Kim Y, et al. Advanced impedance matching technology to optimize RF circuit design of practical wireless systems[C]// Asia-pacific International Symposium on Electromagnetic Compatibility. IEEE, 2017.