IOP Conf. Series: Earth and Environmental Science **188** (2018) 012005 doi:10.1088/1755-1315/188/1/012005

Development of digital control system for medium frequency induction furnaces

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Abstract. Traditional medium frequency induction furnace usually adopts analog circuit, which use the theory of PLL to synchronize the drive signal with the induced current signal, so that the upper and lower devices of each phase leg could be gated simultaneously Besides, some problems appear subsequently such as matching debugging difficulty and high failure rate. This paper describes the effect of the burden on the resonant electromagnetic field and resonant frequency through theoretical analysis and magnet field simulation. Based on this, a control and monitoring system designed by digital passive trigger architecture is proposed, phase locking of which is performed according to the frequency of the system itself, fully ensuring that the thyristor will not be simultaneous. In order to improve the stability of the system, this paper optimizes the inverter output control process. At the same time, a friendly human-computer interaction platform is designed, which can achieve distributed data mining, and improve the quality of the product and find the common problems in the product. Finally, the reliability of the control system is verified by experiments.

1. Introduction

As an important equipment in the field of thermal engineering, the mid-frequency induction furnace is widely used in smelting non-ferrous metals and ferrous metals. However because of its special application, it has been a small industry in China. At present, the research of this domain mainly focuses on improving the quality of smelting, such as optimization of melting temperature control [1], smelting process [2] and prolonging the life [3], or based on the side of the grid, focusing on the harmonic control and energy saving of the medium frequency induction furnace [4]. However, because of the shortcomings of resource allocation, there are many problems in the development of medium frequency induction furnace, such as the unreasonable control flow, the high failure rate of the thyristor, and the not timely feedback condition [5].

All these problems not only increase the risk of equipment damage, but also reduce production efficiency. Therefore, it is very important to design a set of control and monitoring system that can realize the reliable and stable monitoring of medium frequency induction furnace and realize the friendly human-computer interaction at the same time. Combined with circuit principle analysis and magnetic field simulation, a control and monitoring system is designed, which has digital passive trigger architecture and a powerful human-computer interaction platform.

2. Theoretical analysis and simulation

2.1. The basic principle of the medium frequency induction furnace

The basic principle of the medium frequency induction furnaces is using eddy currents in the metal for heating the metal, which are induced by an alternating magnetic field. The frequency of the alternating magnetic field is, generally, of 200~2000 Hz. The medium frequency induction furnaces are mainly used for metal smelting, roughing of mechanical parts and part-heating treatment processes. The basic circuit of the furnace consists of a med-frequency power supply, an induction coil (L), a compensation capacitor (C) and the metallized burden (R) in the crucible, as shown in figure 1. In figure 1, L1, L2 and L3 are equivalent transformer windings, VT1~VT6 are the thyristors of the rectifier, L_d is a filter, and Q1~ Q4 are the switching tubes of the inverter.

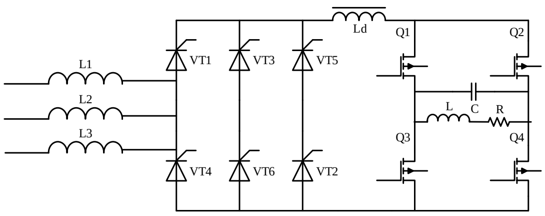

Figure 1. The working principle of the medium frequency induction furnace.

Through the full-controlled rectifier, the filter and the inverter, the 50Hz current is turned into a higher frequency current. The induction coil, compensation capacitor and metallized burden are used as loads, and the working frequency is close to the state of series resonant. High-frequency current in the coil produces high-frequency and high-density magnetic field, and large eddy currents are induced in the metal in order to heat it.

2.2. Electromagnetic field analysis and simulation for the medium frequency induction furnace

The induction furnaces are based on the principle of electromagnetic induction that heats the metallized burden. According to the principle of electromagnetic induction, if the metal (metallized burden) is close to the coil, two phenomena would occur, which are the change of the coil's dielectric condition and the correspondent eddy current effect. As shown in figure 2, the resonant frequency of the coil changes due to changes of the magnetic field strength of the coil.

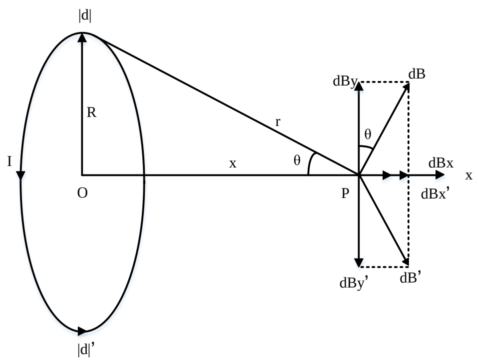

Figure 2. Changes in the coil's media conditions.

When an alternating current, I, passes through an N-turn circular inductor with a radius of R, an alternating magnetic field is generated around the inductor coil. The magnetic induction intensity B for a point on the central axis of the coil can be calculated from the Biot-Savart Law:

$$B = \int dB_x = \int dB \sin\theta = \int_0^{2\pi r} \frac{N\mu I}{4\pi r^2}\frac{R}{r} dl = \frac{N\mu I R^2}{2r^3}$$
$$= \frac{N\mu I R^2}{2(x^2+R^2)^{3/2}} = \frac{N\mu_0\mu_r R^2 I_m}{2(x^2+R^2)^{3/2}}\cos\omega t \quad (1)$$

In equation (1), $\mu=\mu_0*\mu_r$, μ is the permeability of medium, μ_0 is the absolute permeability of the vacuum and μ_r is the relative permeability of the medium. If there is no metal in the effective detection range of the inductor, μ_r =1, and the magnetic induction intensity B at a point on the central axis of the inductor coil will remain unchanged. When the ferromagnetic metal objects appear around the coil, the value of μ_r and the magnetic induction intensity increase. So L will be changed. According to the parallel resonance formula $\omega = \frac{1}{\sqrt{LC}}$, the resonance frequency is $f = \frac{1}{2\pi\sqrt{LC}}$. Therefore, when there are ferromagnetic metal objects around the coil, the resonant frequency will be changed too.

When a large piece of metal appears in the alternating magnetic field, the metal will generate, due to the eddy current effect, an additional electromagnetic field, which shall be opposite to the external magnetic field. The electromagnetic field generated by the eddy current will weaken the external magnetic field. The larger the conductivity σ of the metal is, the greater will the eddy current intensity be, and the stronger will the suppression of the original magnetic field be.

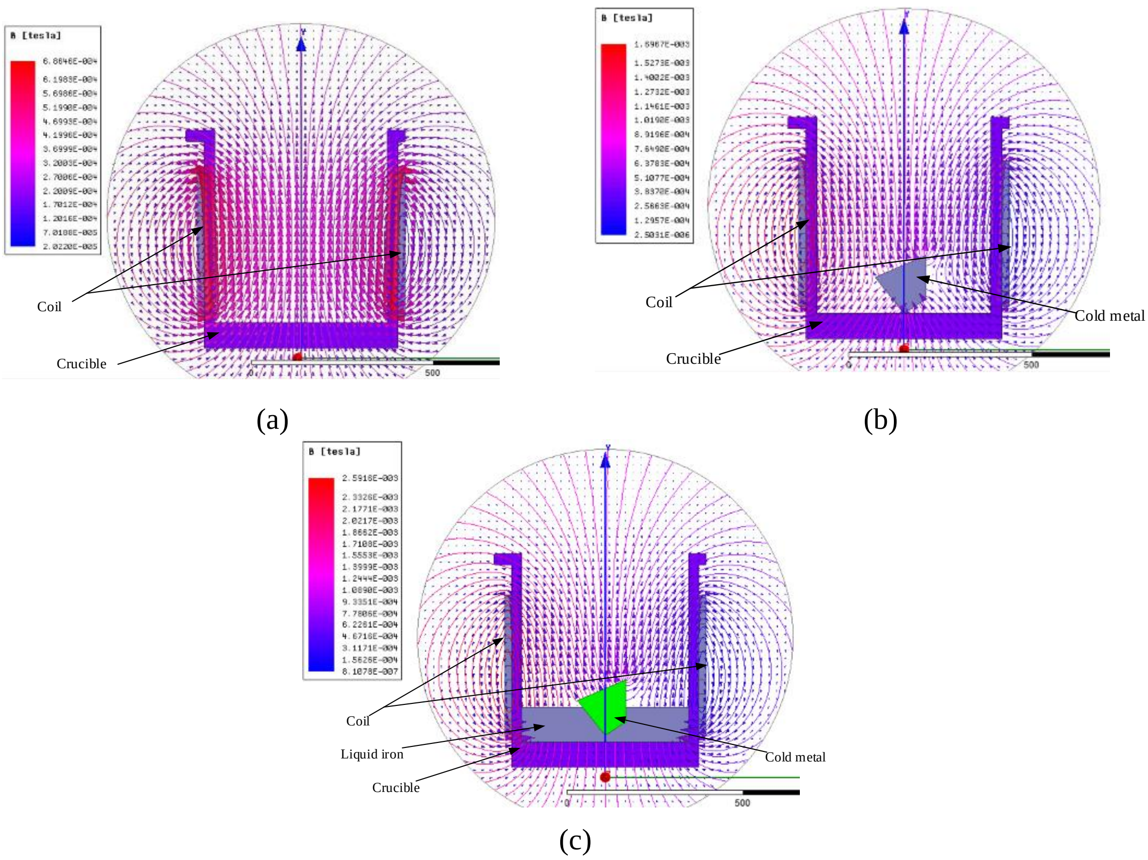

Figure 3. Magnetic field simulation for a medium frequency induction furnace. (a) Magnetic field simulation for the empty furnace, (b) Magnetic field simulation for suddenly adding big metallic material in the empty furnace and (c) Magnetic field simulation of suddenly adding big metallic material in the hot furnace.

The working conditions of the induction furnace are the cold furnace, the hot furnace, the empty furnace and the full furnace while smelting metal. The live operation is more complicated. And in the process of smelting, there are bad working conditions such as suddenly adding big metallic material in the hot furnace. In order to simulate the electromagnetic field distribution of the empty furnace and the full furnace, the induction furnace model is simplified and modeled in the electromagnetic field simulation software ANSYS Maxwell, which is used to simulate the different working conditions of the medium frequency induction furnace. The simulation results are shown in figure 3.

From figures 3(b) and 3(c), it can be seen that the existence of the metallic material weakens the electromagnetic field generated by the resonance of the coil. The change of the magnetic flux will change the inductance of the induction coil, and the frequency of the resonance will also fluctuate.

3. Optimization of software control

At present, a silicon controlled rectifier (SCR) is used as the power tube of the inverter for the high-power medium frequency induction furnaces. The analog circuit is mostly adopted in control system, and a phase-locked loop (PLL) is used to synchronize the driving signal and the induced current signal. Due to the current zero-crossing shutdown characteristics of SCR, the number of melted iron in the furnace and the sudden addition of big metallic material will change the resonant frequency. The traditional PLL technology uses a method of triggering first and testing afterwards, which may lead to a direct connection between the upper and the lower bridge arms of inverter. This means the occurrence of a short circuit. This paper proposes the digital control system, by using a passive trigger program. The zero-crossing of current is detected first, and then the SCR is triggered, after a certain time delay. The phase locking is performed exactly according to the resonant frequency of the system, in order to ensure that the SCRs will not turn on simultaneously and to increase system stability.

3.1. Passive trigger program

The controller of the system detects the inverter current with a frequency of 400 kHz and uses a combination of hardware zero-crossing detection and software zero-crossing detection to obtain a stable and reliable zero-crossing signal. The phase shift control is triggered by the upper edge and the lower edge of the zero-crossing signal, in order to ensure a real-time response to the system frequency and to prevent the SCR from turning on simultaneously.

Software zero-crossing detection means the controller samples sinusoidal signals with a reference voltage of 1.25 V by an A/D converter, and sit samples at least 400 times per period. The sampled values are then compared to the reference voltage of 1.25 V and it is considered that the software sampled values are higher when the sample values are continuously above the number of reference voltage pulse widths, and it is considered to be software low when the sample value are continuously below the reference voltage pulse widths.

Hardware zero-crossing detection means the sinusoidal voltage signal and the zero potential is compared by a comparator with hysteresis, and the hysteresis difference is set to 0.1 V. The positive and the negative pulse signals are obtained and rectified into square wave signals, which are sent to the controller for sampling. The signals are considered to be hardware high when the sample values are continuously above the number of pulse widths, and considered to be hardware low when the sample values are continuously below the number of pulse widths.

The practical zero-crossing signals with high accuracy and strong anti-interference ability are obtained by combining the zero-crossing of the hardware and software. If negative zero-crossing is detected in the positive half-cycle, the program is overturned to the negative half-cycle and the delay register of negative half-cycle starts counting at the same time. When the value of negative half-cycle delay register reaches the power set value and it is above the TOT limit, the pulse controlling the lower arm is set to high level, which is cleared and set to low level after the number of pulse widths, and it is waiting for pulse output of negative half-cycle.

If a positive zero-crossing is detected in the negative half-cycle, the program is overturned to the positive half-cycle and the delay register of the positive half-cycle starts counting at the same time.

When the value of positive half-cycle delay register reaches the power set value and it is above the TOT limit, the pulse controlling the upper arm is set to the high level, which is cleared and set to the low level after the number of pulse widths, and it is waiting for pulse output of negative half-cycle. The flow chart of zero-crossing detection is shown in figure 4.

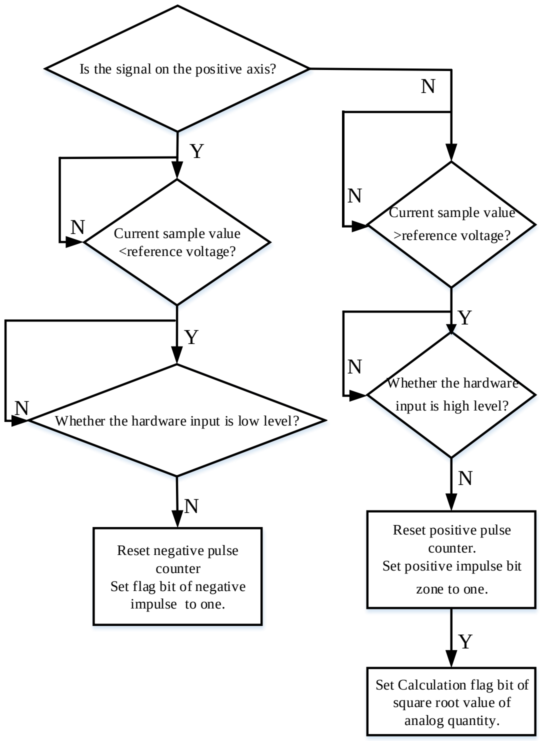

Figure 4. The flowchart of zero-crossing detection.

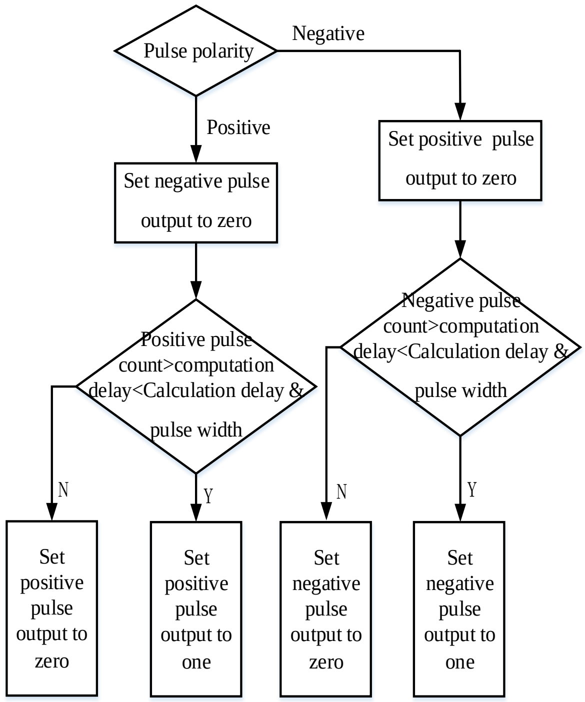

Figure 5. The flowchart of the inverter output.

After the inverter output, an AND gate and an AVR microcontroller circuit called mega8 are added to realize logic interlocking of positive and negative pulse signals. When the positive and negative pulse signals are all zeros, as decided by the AVR microcontroller, the high level is delayed more than half of a resonant period before the output to the AND gate. At this time, if the trigger signals given by STM32F407 are high, the output of AND gate is high, and the SCRs are turned on. But, if the trigger signals given by STM32F407 are mistaken due to the interference, the interval between the two high levels must be less than half of a resonant period. Therefore, the circuit can effectively ensure that the upper and lower bridge arm will not be straight-through by interference. The flowchart of the inverter output is shown in figure 5.

4. Hardware optimization and experimental verification

The control platform of the traditional medium frequency induction furnace is mostly implemented by an analog circuit. However, the analog circuit control system has many disadvantages, such as debugging difficulties, high requirements of on-site debugging personnel, error diagnosing failures, and a high failure rate because of the big number of devices. The system described in this paper uses digital control, which has the advantages of high integration, strong anti-interference capability, fast reaction speed and reliable operation. At the same time, this system can intuitively monitor all the operational data through a HMI (Human Machine Interface, HMI) and it can record the history of the operational data. The system can realize remote transmission of data through an Ethernet communication module, so that the enterprises can remotely monitor the operation of their technological processes. Meanwhile, the enterprises can obtain a lot of on-site operational data, and they can carry out distributed data mining on big data volumes in order to improve the quality of their products and to discover their common problems.

4.1. The passive trigger program

The system's structure is shown in figure 6, and the system is divided into six functional blocks, namely the main controller module, the communication module, the analog-digital conversion module, the digital signal processing module, the inverter signal processing module and the rectifier control unit, respectively. The communication processes among the modules are shown in figure 6.

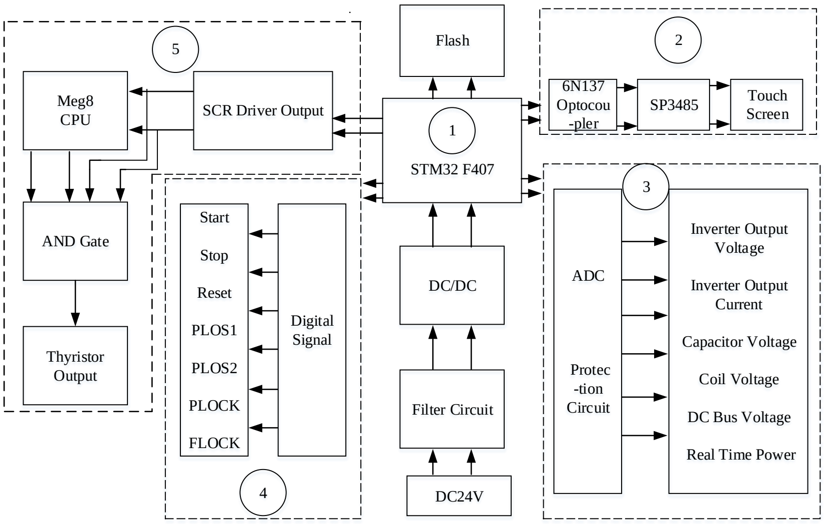

Figure 6. The system structure diagram.

The main controller module is an ARM microcontroller, belonging to the STM32F407 series. The internal clock frequency of the controller is up to 168 MHz, and the sampling speed can reach up to 1 MHz, while the system response time is of only 10 μs. The controller also integrates a 12-bit A/D converter, and the sampling accuracy can reach 0.02%. The main controller is responsible for the A/D sampling, data processing, logic signal judgment, fault alarm, communication with the host computer and other functions, being the core unit of the system.

Module 2 is a communication-processing module. The TTL signal is converted into a 485 signal through the high-speed optical coupler 6N137 and the 485 communication chip SP3485, in order to achieve a long-distance transmission, and the optical isolation is implemented at the same time, so as to prevent the induced high voltage from affecting the system operation or even burning down the main controller. The control system uses 2 serial communication ports to communicate with the touchscreen and with the remote industrial control machine, respectively. The communication protocol is based on the MODBUS-RTU standard protocol, and the controller works as a substation.

As an important part of the communication module, this paper designs a friendly HMI for the touch screen and realizes intuitive and comprehensive monitoring through simple operation. Through the Kunlun pass-through touchscreen it can monitor the key parameters of the entire system, such as voltage, power, frequency, etc. Besides, it can store in real-time the history of the current curves, voltages, while the current limits can also be changed at any time. The HMI designed is shown in figure 7.

The function of module 3 is analog quantity acquisition. The external sampling signals such as inverter voltage, inverter current, capacitor voltage, coil voltage, DC bus voltage and real-time power are modulated into 0~3.3 V through a resistive divider, an inductor-capacitor filter and a diode protection. The 0~3.3 V signals are input to the main controller, which samples them at a sampling frequency of 200 kHz. The obtained sampling results are stored in an array, at the beginning of each period. The RMS values are calculated at the end of each period, and at least 400 samples are taken per resonant period, which ensures the accuracy of sampling and calculation.

Figure 7. The HMI of the monitoring system.

The 4th module is a digital signal processing circuit, which optically isolates external input signals such as START, STOP, RESET, PLOSS1, PLOSS2, PLOCK and FLOCK through the optical coupler. The 74LVC4245 buffer chip modulates the 0~5 V signals to 0~3.3 V, and the 0~3.3 V signals are input to the main controller. The main controller performs anti-shake processing on the signals and then performs the corresponding operation.

Module 5 is an inverter signal generation module. The main controller calculates the trigger delay time according to the zero-crossing signal and the power signal. The inverter signal generation module gives the trigger pulse of the corresponding arm according to the calculation time. In order to prevent the possible errors, the system adds an additional logical protection at the back, in order to ensure correct signal triggering.

The 6th module is a rectifier trigger unit. When the system starts, it sends 42 pulses at the frequency of 5Hz and detects, at the same time, the DC bus voltage. During this period, if the DC bus reaches the normal value, the trigger frequency will be changed to 2.4 kHz and normal operation will be performed. If the DC bus voltage still does not reach the normal level after 42 pulses, the trigger is stopped and the fault is reported.

4.2. Experimental verification

In order to verify the reliability and stability of the system, it has been applied to effective working conditions, the specific experimental environment is as follows.

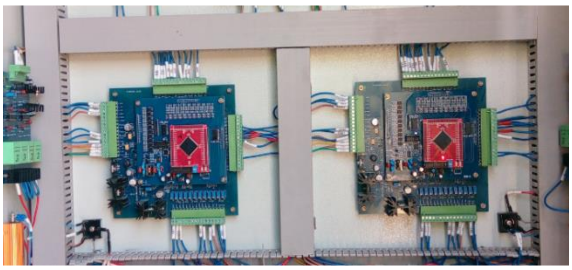

Figure 8. The control system in the „one towing two" model.

Figure 9. The current waveform of the resonant coil and the voltage waveform of the capacitor.

The test uses the "one towing two" model, of which the total power is 1500 kW. The rated power of each medium frequency induction furnace is of 1500 kW, and the capacity is of 2 tons. The natural resonance frequency is set to 330 Hz. The intelligent power distribution is performed through using the controller, so that the sum of the powers of the two furnaces do not exceed the total power limit. The melting time of each furnace is about 41 minutes, the first melting time is about 58 minutes. In the process of testing, there are bad working conditions such as the sudden addition of big metallic materials in the hot furnace, and the running state is, still, stable. Figure 8 shows the application of the control system in the "one towing two" model. Figure 9 shows the current waveform of the resonant coil and the voltage waveform of the capacitor.

The experiment shows that the communication between the hardware modules of the system is good, the response of the software control is fast and reliable, and the anti-interference ability of the system is strong. The waveform obtained by the experiment is relatively stable, and the system can run steadily when suddenly adding big metallic material in the hot furnace and other harsh working conditions. The data acquisition of the host computer is reliable and comprehensive, which can meet the industrial needs.

5. Conclusion

This paper designs the control and monitoring system of medium frequency induction furnaces in order to optimize and to improve the solving of the practical problems in the application, such as short circuit on one arm of the bridge of the inverter and debugging difficulties. After practical testing and experiments, it can be stated that the reliability and the anti-interference performance of the system can meet the needs of on-site applications, and the system can play a protective role for the good operation of the medium frequency induction furnaces and it can have a positive effect on effective production.

Acknowledgments

This research has received funding from "Numerical simulation of solution flow and heat transfer in the growth of DKDP crystal" (2016QN005) & the Basic Research Grant (2015.4-2017.4) of Shandong Academy of Sciences.

References

[1] Bi H H *et al* 2016 Analysis of temperature compensation control system in medium frequency induction furnace *Spec. Casting. Nonferrous Alloys* **36** 700-2
[2] Sun W B 2010 Quality control and research of cast iron smelting by medium frequency induction furnace *Nanjing Univ. Sci. Tech.* **4** 42-55
[3] Dong Z J 2004 Measures to improve the age of IGBT medium frequency induction furnace *Machinist Metal Forming* **2** 48
[4] Kong X P 2015 Electrical energy-saving technology of medium frequency induction furnace *Shandong Ind. Tech.* **15** 152-3
[5] Zhang Y Y *et al* 2004 Structure and working principle of medium frequency induction *Heating Device* **33** 120-1