J. Meas. Sci. Instrum., 2024, 15(2): 224-234.
DOI: 10.62756/jmsi.1674-8042.2024023
http://jmsi.publish.founderss.cn
jmsi@nuc.edu.cn

Design and test of embedded control device for electric heating of heavy oil

HE Lile[1*], YAN Dongyang[1], LIU Peijin[1], XIAO Yong[1], SUN Yu[2]

1.School of Mechanical and Electrical Engineering, Xi'an University of Architecture and Technology, Xi'an 710055, China;
2. School of Science, Xi'an University of Architecture and Technology, Xi'an 710055, China

***Corresponding author:** HE Lile (hllnh2013@163.com)

Received: October 12, 2023 **Revised:** December 5, 2023 **Accepted:** January 15, 2024

Abstract: In order to improve the heating efficiency of the electric heating system for heavy oil wells and solve the current situation that the heating operation control of the medium frequency power supply in the oilfield mainly relies on manual experience settings and low-efficiency automatic control resulting in electric power waste, an embedded control device for heavy oil electric heating was designed. Based on the non-embedded oil well production electrical signal, the electric power of the heavy oil production motor was used as the closed-loop feedback signal to obtain the reference input of the optimal oil temperature. On this basis, through the differential feedback link of the wellhead oil temperature, the temperature hysteresis effect was improved, and the energy-saving optimization control of the medium frequency power supply was realized. Through the design of the embedded hardware core circuit module and the development of the main software functions, not only the dynamic control of the electric heating process of heavy oil wells was realized, but also realized the real-time monitoring of various operating indicators on-site and in the cloud. The heavy oil well field test analysis showed that the designed heavy oil electric heating embedded control device could meet the production requirements of energy saving and safety in the well field, and the energy consumption was saved by 20%.

Key words: heavy oil thermal recovery; medium frequency power supply; double closed loop control; embedded control; energy saving test

0 Introduction

Heavy oil resources occupy a large proportion of the world's oil and gas resources, and its distribution is also very extensive. However, heavy oil has high wax content and high freezing point, and it is easy to stick well during the production process which affects the reliability and safety of normal production[1]. So heavy oil heating technology plays an important role in this case. At present, the main means of heavy oil heating includes steam injection, hot water tracing, dilute oil mixing, and electric heating[2]. The hollow sucker rod electric heating method uses the heat generated by the skin effect to perform nonlinear heating in the whole well depth, reducing the viscosity of crude oil and increasing its fluidity[3]. Compared with other technologies, it has obvious advantages and has been used as the main heating method for heavy oil production way[4].

The electric heating of heavy oil controls the output electric power of the medium frequency power supply and converts the electric energy into heat energy, so as to raise the temperature of the heavy oil, and reduce the viscosity of the heavy oil[5]. At present, the output power and heating time of the medium frequency power supply are manually set based on empirical values, or the wellhead heating temperature is set based on field experience, and the output power of the heating power supply is controlled by the combination of PLC and configuration software[6]. Although this control method can ensure the safe production of oil wells, it causes unnecessary huge energy consumption[7]. In fact, under the premise of satisfying the fluidity of crude oil, there is the best match between the heavy oil electric heating system and the power condition of the oil pumping production system[8,9]. The matching relationship is affected by factors such as ambient temperature, crude oil viscosity, and motor efficiency, etc[10]. The production control based on empirical parameters alone cannot accurately and adaptively respond to the changes of the above factors, resulting in the phenomenon of excessive heating or insufficient heating[11]. So, the current heating control method has a low degree of automation and serious energy consumption[12-14]. Therefore, in the process of heavy oil exploitation, it is very important to study how to realize the self-adaptive adjustment of the medium frequency electric heating power through the learning and optimization of the production parameters, so as to achieve energy saving, carbon reduction, and energy efficiency improvement under the premise of meeting the on-site working conditions, and to increase the level of automation in production.

The heavy oil thermodynamic model and the heavy oil production system model were established in this paper, which could reflect the mapping relationship between the temperature of the viscosity characteristics of the heavy oil and the electric power of the oil pumping motor. On this basis, the heavy oil heating and exploitation control scheme was designed, and the embedded heating control device was developed. At last, in order to verify the performance and energy saving effect of the control device designed and developed in this paper, it was tested in the actual production control of the oil field, and the energy saving effect was analyzed.

1 Analysis of control principle of heating system in heavy oil exploitation

1.1 Heavy oil thermodynamic model

During the process of lifting crude oil from the bottom of the well to the surface, the heat exchange between crude oil and the formation is constantly carried out[15]. According to the principle of heat transfer, the final heat absorbed by the crude oil is equal to the difference between the heat generated by the hollow sucker rod electric heating system and the heat lost by the crude oil to the surrounding formation[16]. Therefore according to the principle of thermodynamics, the heat calculation of the hollow pumping rod is calculated by

$$MC\frac{\mathrm{d}(T_1-T_0)}{\mathrm{d}t}+HA(T_1-T_0)=Q_i, \tag{1}$$

where M is the mass of the hollow sucker rod; C is the specific heat capacity of the hollow sucker rod; H is the heat transfer coefficient; and A is the heat transfer area of the hollow sucker rod.

Since the heating heat Q_i is about proportional to power energy which is the output power by the medium-frequency power supply. And the power has a nonlinear relationship with the voltage U. In actual production control, this relationship can be linearized, then the linear relationship can be obtained as $K_\mu=\frac{\Delta Q_i}{\Delta U}$. Therefore, the incremental differential equation of the heating system can be expressed as

$$T\frac{\mathrm{d}\Delta T}{\mathrm{d}t}+\Delta T=K\Delta U+Q_{i0}. \tag{2}$$

According to Eqs. (1) and (2), the electric heating time constant $\frac{1}{\tau}=\frac{MC}{HA}$ and the system amplification factor $K=\frac{K_\mu}{HA}$ can be obtained. Therefore the transfer function of the heating system can be expressed by

$$G(s)=\frac{\Delta T(s)}{\Delta U}=\frac{K}{1+s\tau^{-1}}. \tag{3}$$

Due to the large hysteresis characteristic of the heavy oil heating system, after the delay link is introduced into the system, the function of the heating system can finally be expressed as

$$T(t)=u(t)K\tau\mathrm{e}^{-\tau t}. \tag{4}$$

Typically, the system temperature lag time is about 10 minutes—40 minutes[17,19].

From analysis above, it can be known that the oil temperature $T(t)$ is the final control goal. According to the demand of the temperature, $u(t)$ can be determined, and the output power of medium-frequency supply can be gotten equivalently. However, this power also consumes electric energy. In fact, different T needs different power of oil pumping motor too. If T is low, the power of heating process is low, but the power of oil pumping motor is high. In other words, if T is high, the power of heating process is high, but the power of oil pumping motor is low. Therefore, there is a balance point which can afford the minimum total power of the whole system.

1.2 Power flow analysis of whole system

As to Fig. 1, the power flow model established in this paper shows the relationship of powers among every unit of the system.

The process of pumping crude oil from the formation to the ground is a process of continuous energy transfer and transformation. As the energy source for crude oil extraction, the power grid mainly converts electrical energy into mechanical energy, and with the loss of electrical energy to heat energy. The process of lifting crude oil from the formation to the ground is the transfer of mechanical energy, that is, the mechanical energy of the oil production mechanism is transferred to the crude oil in the formation, so that it is lifted to the ground.

In the process of heavy oil extraction, the energy loss along the way accounts for a large proportion of the transmission loss, which is reflected in the increase of the power required by the pumping unit motor[20]. The size of the energy loss along the way is closely related to the viscosity of the crude oil. By changing the power of the medium frequency heating power supply to adjust the temperature, the viscosity of the crude oil can be changed to reduce the loss along the way, so that the power required for the operation of the pumping unit motor is reduced accordingly.

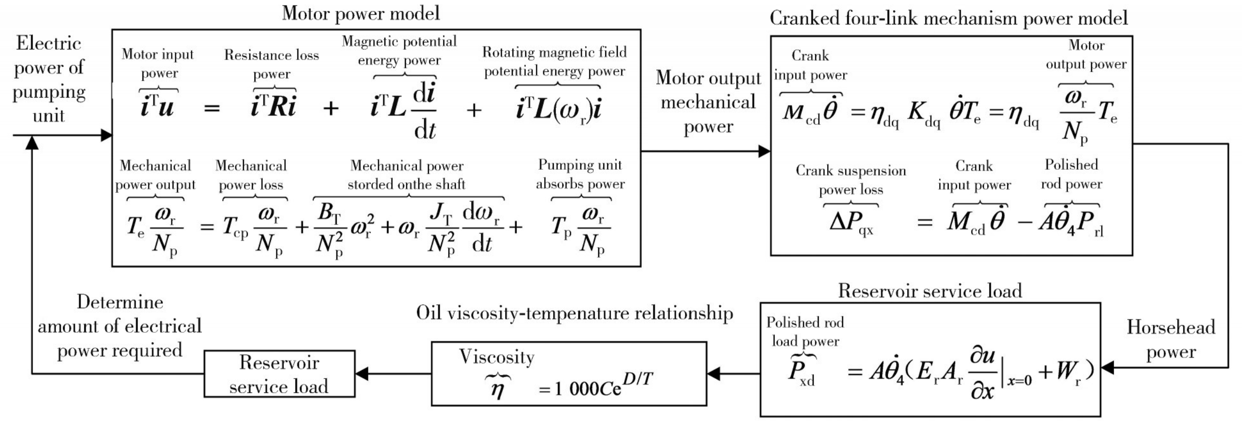


Fig. 1 Energy flow diagram of medium frequency heating system

When the system operates at the balance point, there is always an optimal pumping motor power corresponding to it. Therefore, the optimal power of the oil pumping motor can also be used as the input parameter of the controller to achieve the control goal of the lowest overall energy consumption of the heavy oil production system.

1.3 Structure of heavy oil production control system

The heavy oil thermal exploitation technology mainly uses the skin effect of the conductor to pass medium frequency alternating current to the hollow pumping pipe, and the skin effect is generated during the current flow on the outer wall of the conductor to realize the conversion of electric energy into heat energy. And through the form of heat conduction, the heat energy is transferred to the heavy oil around the conductor to increase the temperature of the heavy oil, increase the fluidity of the heavy oil, and avoid the occurrence of the phenomenon of pump sticking caused by heavy oil waxing on the inner wall of the oil pipe. The structure of heavy oil exploitation system is shown in Fig.2.

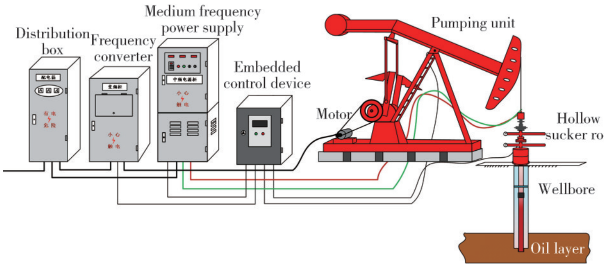


Fig. 2 Schematic diagram of heavy oil exploitation system

Compared with the power frequency electric heating technology, the control of the medium frequency electric heating control system needs to ensure the superiority of its control performance and the high efficiency of heating, the stability of its output power, the dynamic adjustment speed, and the anti-interference ability of the system. And its output power needs to be adjusted automatically with the change of the load to ensure the high efficiency of the heating system. Secondly, because the power frequency heating load is a single-phase load, the closed loop connected by the cable and the sucker rod is a single-phase load, and its power supply can only be heated by a single-phase, which will easily lead to an unbalanced three-phase load in the power grid, the medium frequency electric heating technology forms single-phase output AC power to heat the load through rectification, filtering, inversion and other links, which can greatly ensure the three-phase load balance of the power grid and reduce the harmonic pollution to the power grid.

1.4 Control scheme design

According to the energy flow of the heating system in heavy oil exploitation, the output power of the intermediate frequency heating power supply has the following qualitative relationship with the electric power of the pumping motor under the condition of safe exploitation of the oil well.

$$P_f\uparrow\rightarrow T\uparrow\rightarrow P\downarrow\rightarrow P_m\downarrow, \tag{5}$$

where P_f is the medium frequency power output power; T is the oil temperature; P is the oil load; and P_m is the motor power.

Obviously, the higher the output power of the medium frequency power supply, the higher the oil heating temperature, and the lower the electric power of the pumping motor. However, when the oil temperature is obviously higher than the inflection point temperature, the oil load decreases slowly with the increase of temperature, and the power of the pump generator decreases. At this time, the total energy consumption of the system increases instead. Therefore, the minimum power (minimum total energy consumption) was used to optimize the objective function to determine the optimal power of the pumping motor.

The control task of the system is to take the optimal power of the pumping motor obtained by the optimization as the reference input, and by controlling the output power of the medium frequency power supply, the oil is heated to a suitable temperature, and finally the electric power of the pumping motor of the heavy oil exploitation system is tracked the optimal power, so as to achieve the effect of energy saving. At the same time, in the oil well production site, the non-embedded acquisition method of the electric signal of the pumping motor makes its reliability and accuracy higher than that of the beam smooth rod load signal. Based on the above factors, the control scheme designed in this paper mainly took the electric power signal of the heavy oil exploitation pumping motor as the feedback signal, and took the optimal power as the reference input for the heating control of the system.

Considering the hysteresis effect of heavy oil heating temperature changing with heating power and the feasibility of field signal acquisition, the control scheme in this paper added the wellhead oil temperature signal, and adopted differential priority control in the feedback link of temperature signal to form dual control with the power signal of the pumping motor. The control principle of closed-loop control is shown in Fig.3.

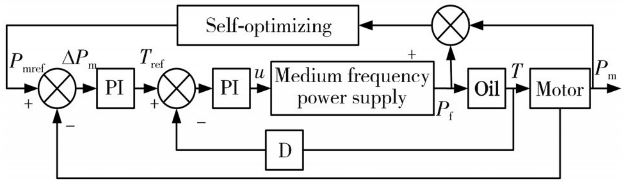


Fig. 3 Device control principle diagram

Among them, P_{mref} is the motor reference power, ΔP_{m} is the difference between the motor reference power and the actual power, T_{ref} is the oil temperature reference value, u is the medium frequency power supply voltage, P_{f} is the medium frequency power output power, T is the oil temperature, and P_{m} is the motor power.

2 Structure design of embedded control device for heavy oil electric heating

Based on the control scheme and on-site user communication and monitoring requirements, the system function structure of the embedded control device is designed as shown in Fig.4.

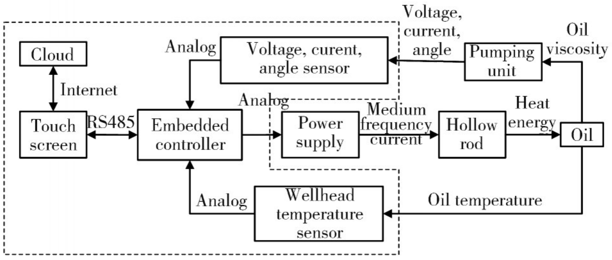


Fig. 4 Functional structure diagram of embedded control device for heavy oil electric heating

The system includes embedded controller, wellhead oil temperature sensor, pumping unit voltage and current angular displacement sensor, touch screen and cloud platform, etc. Among them, the wellhead temperature sensor and the pumping unit voltage, current and angular displacement sensor are the basis of the system. They collected voltage, current, angular displacement, and temperature data as the input of the embedded controller. As a human-computer interaction device, the touch screen can monitor the wellhead temperature, heating rod current and pumping unit power and other information for the operator to observe. At the same time, the operator can use the touch screen buttons to set the power coefficient, the maximum and minimum wellhead temperature and the maximum heating time, etc. The embedded controller module is the core of the whole system. It can analyze and process various data and execute corresponding control calculations, and then output the control voltage through the D/A output module, and transmit it to the medium frequency power supply to control the output power of the medium frequency power supply. At the same time, the changing load, wellhead temperature, heating rod current and pumping unit current are fed back to the embedded controller to automatically and continuously control the output power of the medium frequency power supply.

3 Hardware design of embedded control device

3.1 Selection of main control chip

According to the control scheme of this paper and the use environment and requirements of the heavy oil production site, STM32F103RDT6 was selected as the main control chip of this controller. The chip is a high-performance ARM 32-bit Cortex$^{\mathrm{TM}}$-M3 CPU in the STM32 series produced by STMicroelectronics, which uses a 64-pin chip as the core. The chip has the advantages of low cost, low power consumption, high performance, and rich on-chip resources. The chip has built-in high-speed memory, including 384 kB of flash memory and 64 kB of SRAM for storing programs and data. Abundant enhanced I/O ports and peripherals connect to two APB buses, three 12-bit ADCs, four universal 16-bit timers and two PWM timers, two watchdog timers, 12-channel DMA Controller, and so on. In addition, it also contains a variety of standard and advanced communication interfaces: 5 USART, 3 SPI, 2 I^2C, 2 I^2S, 1 SDIO, 1 USB, 1 CAN. The working frequency of the control chip was 72 MHz, and the operating temperature range was −40 ℃ to 85 ℃[8].

3.2 Signal acquisition circuit design

In the heavy oil electric heating embedded control device, the pumping motor power was used as an important indicator for controlling the power output of the medium frequency power supply, so the HLW8032 chip was used to measure the pumping motor power. HLW8032 is a high-precision energy metering chip. It adopts CMOS manufacturing process and can measure line voltage and current, and can calculate active power, apparent power, and power factor. HLW8032 has the advantages of high accuracy, low power consumption, high reliability, and strong ability to adapt to the environment. UART was used for data communication. The TX pin was used for data communication with the main control chip. In order to prevent the interference between the field low-voltage control circuit and the peripheral high-voltage circuit, an optocoupler isolation chip was connected between the HLW8032 and the main control chip to prevent interference.

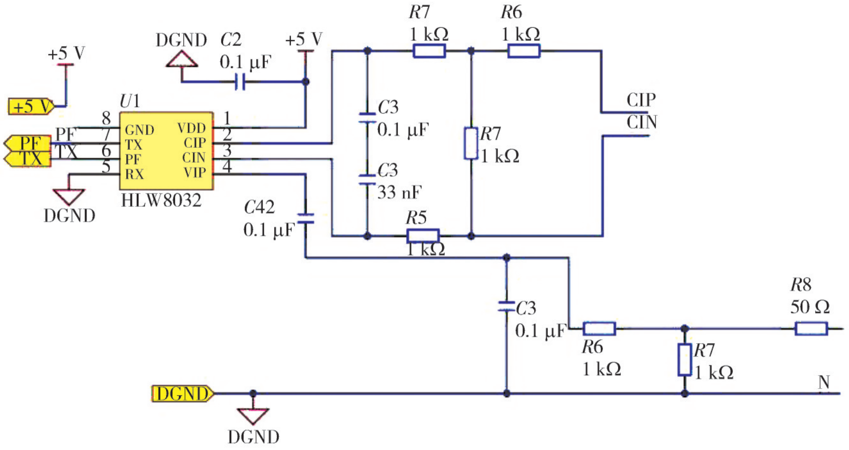


Fig. 5 HLW8032 circuit

In the heavy oil electric heating embedded control device, the wellhead oil temperature was used as an important feedback signal of the control algorithm. In this paper, the PT100 temperature transmitter and ADC0831 conversion chip were used to realize the acquisition of the wellhead oil temperature signal. This measuring circuit can amplify and output the current signal output by the PT100 sensor through the bridge measurement, and then sample the amplified sensor signal through the 8-bit A/D conversion chip ADC8031, and calculate the current temperature value through the program. The TTL serial port on the chip can output the converted digital signal of the current temperature value to the main control MCU. The measurement resolution was 1 ℃, and the absolute error in the full temperature range was ±0.5 ℃. The temperature measurement circuit is shown in the Fig.6.

In the heavy oil electric heating embedded control device, in order to perceive the operating state of the pumping unit, the angular displacement data of the pumping unit was also one of the important reference signals. UZZ9000 chip with magnetoresistive angle sensor KMZ41 was selected to achieve accurate non-contact angle measurement. The UZZ9000 chip included 2 channels of A/D converters and 1 channel of D/A converters, as well as filters, digital oscillators, and logic controls.

The UZZ9000 chip can convert the two sinusoidal signals with phase difference output by the magnetoresistive angle sensor KMZ41 into a linear voltage signal output. The output voltage of the UZZ9000 had a linear relationship with the measured angle α, and its linear output range was $0° - 180°$. Its voltage output signal was transmitted to the main control chip through the internal A/D converter of the chip through the SPI communication interface. The angle detection circuit composed of UZZ9000 chip and magnetoresistive angle sensor KMZ41 is shown in Fig.7.

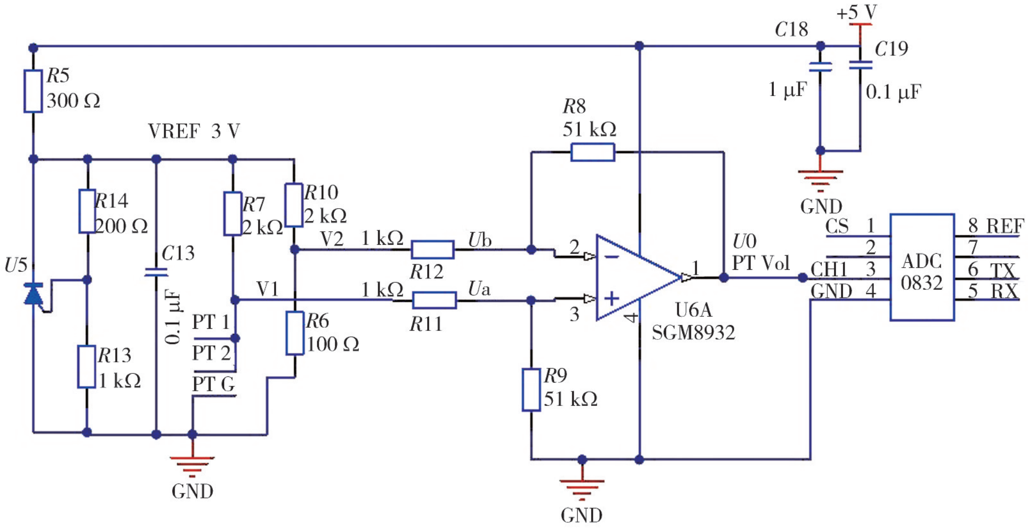


Fig. 6 Temperature measurement circuit

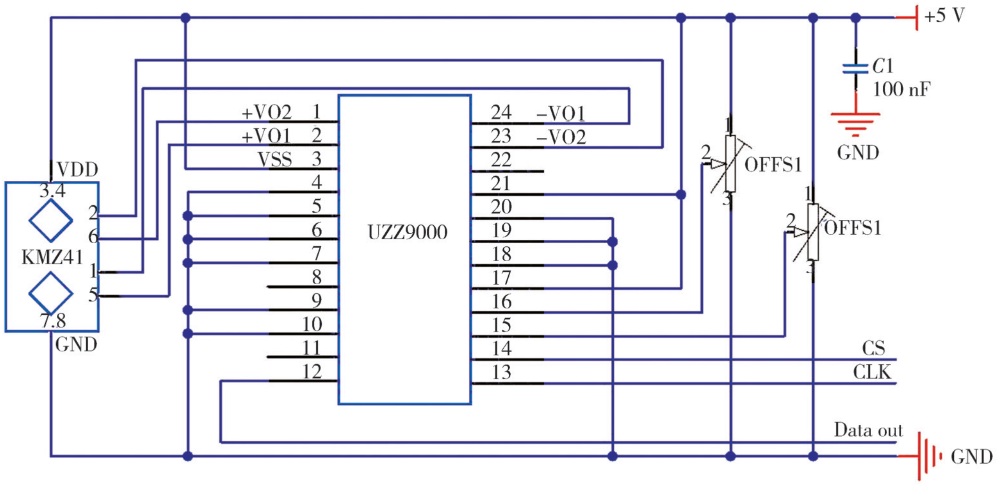


Fig. 7 Angular displacement measurement circuit

3.3 Signal filtering circuit design

Due to the complexity of the oilfield site, various electrical equipment will generate more electromagnetic interference, which may easily lead to signal distortion during transmission. In order to filter out high-frequency resonance and related noise caused by interference, a band-pass filter circuit was added to the control device to ensure the reliability and stability of the collected signal. The band-pass filter circuit designed in this paper adopted an active band-pass filter circuit based on LM324 series devices. The circuit only allowed the signal within a specific passband range to pass through, and attenuated or inhibited the signal below the lower frequency of the passband or above the upper frequency.

According to the signal frequency requirements of the control device, the center frequency of the passband circuit was $f_0=2$ kHz, the bandwidth $B=50$ Hz, and the quality factor $Q=40$. Its specific circuit is shown in Fig.8.

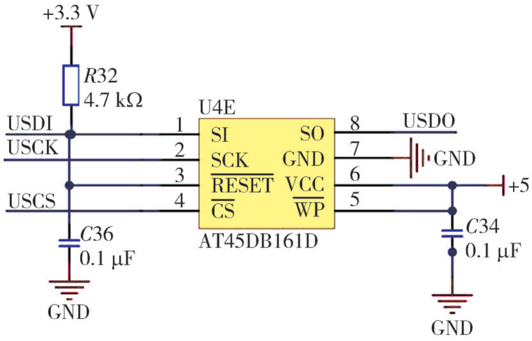


Fig. 8 Signal filter circuit design

3.4 Communication circuit design

In order to be able to monitor various indicators of the pumping unit more intuitively during operation, the embedded controller needs to transmit the collected data to the touch screen. Due to the complexity of the oilfield site, various electrical equipment will produce more electromagnetic interference, which will lead to signal transmission errors. Therefore, the RS485 bus communication based on Modbus protocol commonly used in industry was adopted. Using SP3485 chip as transceiver, the chip conformed to the electrical specifications of RS485 serial protocol, the data transmission rate could be up to 1.25 MB/s, the drive and differential reception were balanced, the ability to resist common mode interference was strong, and the long-distance multi-station communication could be realized[9]. The RS485 communication module is shown in Fig.9.

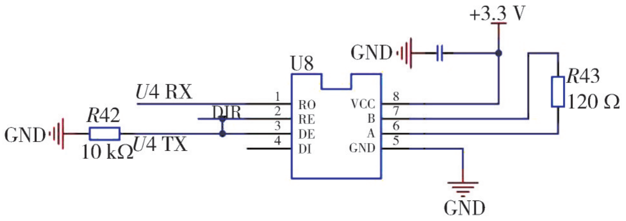


Fig. 9 RS485 interface circuit

At the same time, in order to facilitate the programming and improve the efficiency of optimization and debugging of the control program, a serial communication circuit was designed. The serial port communication was RS232 communication. The MAX3232 level conversion chip was used between the control chip and the PC to realize the conversion between TTL level and RS232 level. Among them, the control chip was TTL level +5 V, which was represented as 1, 0 V was represented as 0, RS232 was a negative logic level, −3 V−−15 V was represented as 1, and 3 V−15 V was represented as 0. As shown in Fig.10, J4 used the RS232 interface on the PC side and adopted the DB9 package. When connecting to the PC, the serial port adapter cable was used to switch to the serial port.

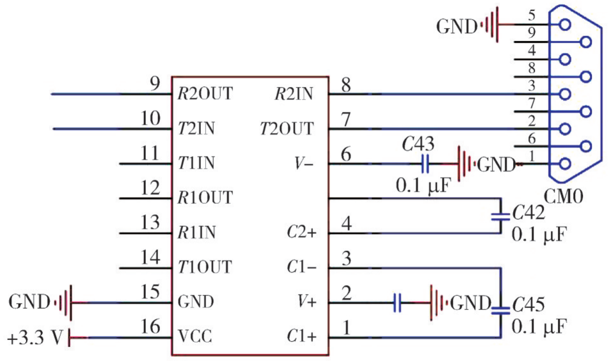


Fig. 10 RS232 serial port circuit

4 Embedded control device software design

4.1 Embedded controller software

The software part of the embedded controller adopted a modular design method. It used C language for programming in the Keil uVision5 software compiling environment, J-Link simulator debugging, and ST-Link burning program. Combined with system functions and corresponding indicators, the software of the controller should have functions such as data acquisition, data storage, data processing, parameter setting, algorithm operation, system upgrade and communication. When the device works, the system was powered on to complete the initialization of the operating system and hardware equipment, the touch screen parameter configuration was checked, and then the EEPROM, Micro SD card module, and A/D sampling module were self-checked to complete the initialization[11,12]. The software flowchart of the embedded controller is shown as in Fig.11.

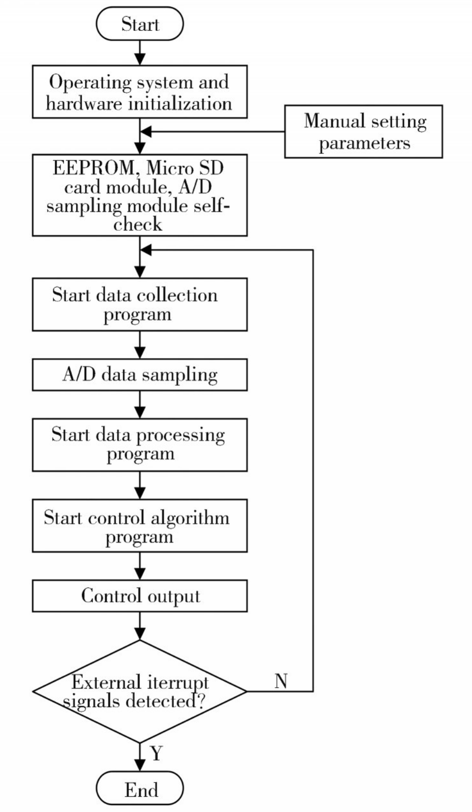


Fig. 11 Embedded controller software flow chart

After the above steps were completed, the system entered data acquisition, and the output data of each sensor was sampled through the data acquisition module. The collected data entered the control chip and was saved in the Micro SD card at first according to the storage protocol, and then entered the data processing subroutine. The processed data was applied to the embedded control algorithm, and the voltage value for controlling the output power of the medium frequency power supply was obtained according to the calculation result. The system then proceeded to the next cycle. According to the collected data changes, the output power of the intermediate frequency power supply was continuously controlled, and the cycle control was continued. The system did not end the process, and the program could only be ended by an external manual and automatic switch.

4.2 Data processing program

The power data of the pumping motor was collected by sensors. There were some singularities in the original data obtained because of influence of sand in the oil, and the data processing method was used to remove these singularities. The data collected by the data acquisition module was transferred to the embedded control algorithm after data processing, so that the control algorithm can obtain external data feedback in real time. The flowchart is shown in Fig.12.

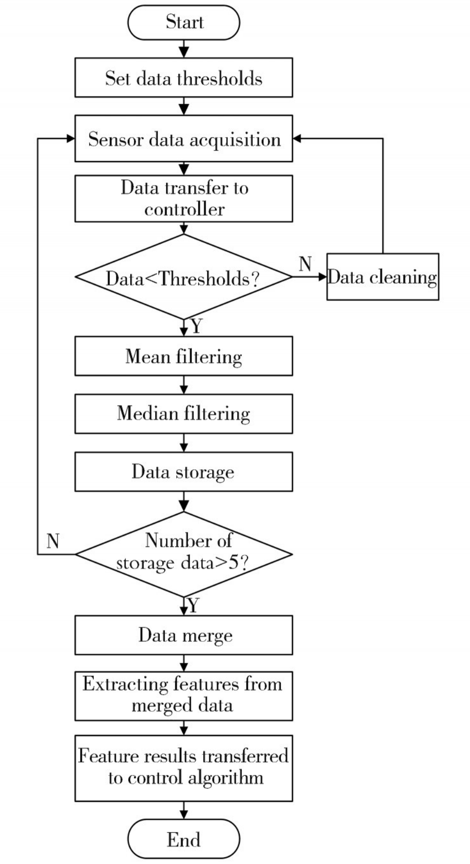


Fig. 12 Data processing flow chart

4.3 Control program

The optimal power of the pumping motor is determined by taking the sum of the energy consumption of the system pumping motor and the medium frequency power supply as the optimization objective function. Taking the obtained optimal power of the pumping motor as the reference input, by controlling the output power of the medium frequency power supply, the oil was heated to a suitable temperature, so that the electrical power of the pumping motor of the system could track the optimal power. Differential control was used in the feedback link of the temperature signal to form a double closed-loop control with the electric power signal of the pumping motor. The control flow chart is shown in Fig.13.

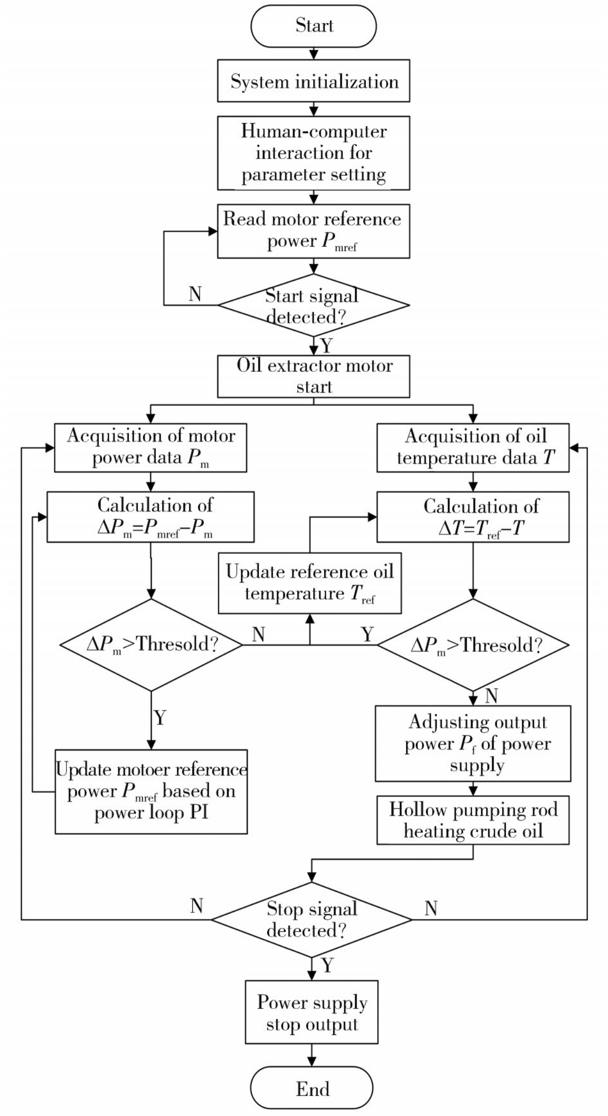


Fig. 13 Control structure diagram

5 Performance and energy saving test and analysis of embedded control device

In order to verify the data acquisition and processing effect and energy-saving effect of the device designed, the device was applied to oil well production site. When the pumping unit is waiting for the stable operation of the oil exploitation system, after powering on the heavy oil electric heating embedded control device, acquisition signals are verified in manual mode at first. After comparing with on-site electric meters and hand-held meters, the error of the measured value of the sensor was all less than 1.3%, which met the requirements of on-site production.

5.1 Data acquisition accuracy analysis

At the oil well production site, the raw data including wellhead temperature, load, motor power, and other signals were obtained by sampling the signals of each sensor installed on the site. The raw data are shown in Tables 1 and 2.

Table 1 Data analysis of temperature sampling circuit

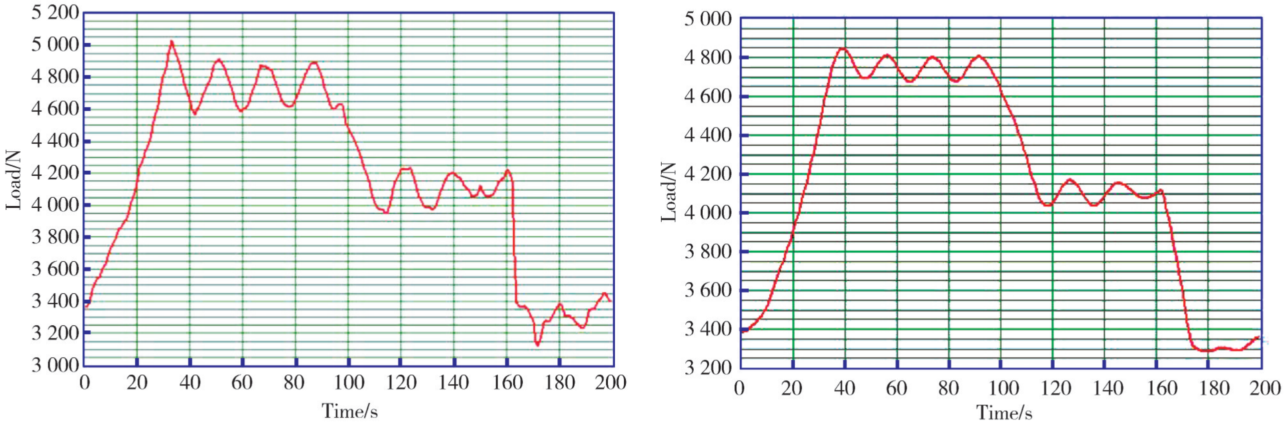
No.	Time	Sampling value/℃	Actual value/℃	Error/℃
1	09:00AM	20.2	20.1	0.1
2	10:00AM	23.6	23.2	0.4
3	11:00AM	26.2	26.4	0.2
4	12:00PM	30.3	30.6	0.3
5	01:00PM	34.5	34.2	0.3
6	02:00PM	38.6	38.2	0.4
7	03:00PM	40.3	39.9	0.4
8	04:00PM	43.7	43.5	0.2
9	05:00PM	48.3	48.0	0.3
10	06:00PM	51.4	51.9	0.5
11	07:00PM	53.2	53.1	0.1
12	08:00PM	59.1	58.8	0.3

Table 2 Data analysis of angular displacement sampling circuit

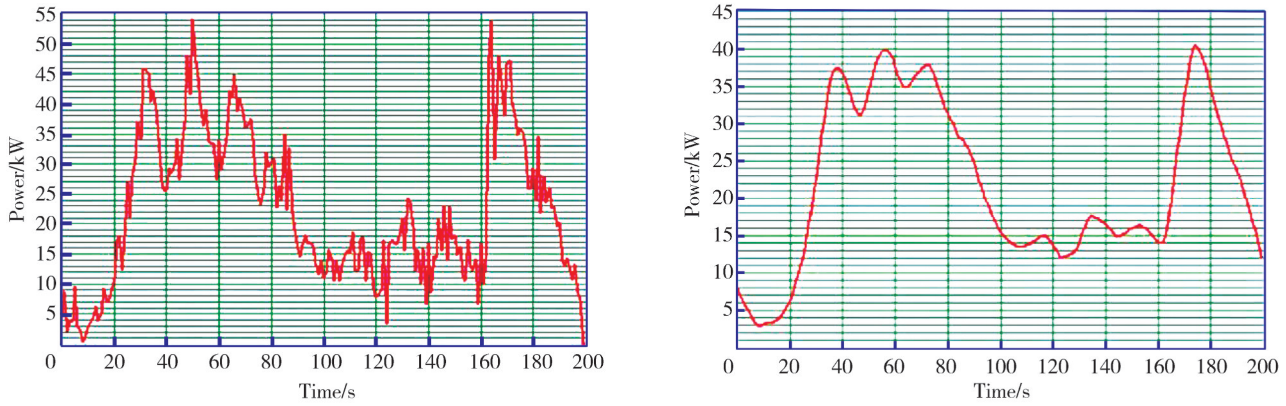
No.	Sampling value/(°)	Actual value/(°)	Error/(°)
1	−26	−25	1
2	−20	−20	0
3	−15	−15	0
4	−9	−10	1
5	1	0	1
6	9	10	1
7	15	15	0
8	21	20	1
9	25	25	0
10	27	26	1

5.2 Data processing effect analysis

The original data was processed through the data processing program in the embedded controller. It can be seen from Fig. 14 that the signal noise of the processed data is greatly reduced, the data authenticity is restored, and the data features are more obvious, which provides a good data support for the precise implementation of the control algorithm.



(a) Raw load (b) Processed load



(c) Raw power (d) Processed power

Fig. 14 Comparison diagram of data processing

5.3 Energy saving effect analysis

In the manual mode of the original control mode of the wellsite, the intermediate frequency power supply used constant power heating and the heating current was 50 A. Through the monitoring of the electric energy meter at the input end of the on-site medium frequency power supply, the main data is shown in Table 3. During constant power heating, the average hourly power consumption of the medium frequency power supply was 41 kW·h.

Table 3 Energy consumption data of medium frequency power supply controlled by experience value of the oil field

No.	Sampling time	Energy meter reading/(kW•h)	Energy consumption/(kW•h)
1	9:00AM	3 821.1	0
2	10:00AM	3 863.0	41.9
3	11:00AM	3 903.6	40.6
4	12:00PM	3 944.1	40.5
5	01:00PM	3 985.2	41.1
6	02:00PM	4 025.7	40.5
7	03:00PM	4 066.5	40.8
8	04:00PM	4 107.7	41.2
9	05:00PM	4 148.6	40.9
10	06:00PM	4 190.1	41.5

After the manual mode test was completed, the automatic control function test of the device was carried out. The parameters of the L-88 oil well pumping motor were set through the touch screen and then adjusted to the automatic mode. Through the analysis of the data in Table 4, it can be concluded that the average hourly power consumption of the medium frequency power supply in the automatic mode is 32.8 kW·h, which is significantly lower than the current power consumption on site.

Table 4 Energy consumption data of medium frequency power supply with embedded control

No.	Sampling time	Energy meter reading/(kW•h)	Energy consumption/(kW•h)
1	00:00AM	6 071.0	0
2	01:00AM	6 105.0	34.0
3	02:00AM	6 138.3	33.3
4	03:00AM	6 172.0	33.7
5	04:00AM	6 202.6	30.6
6	05:00AM	6 237.3	34.7
7	06:00AM	6 269.1	31.8
8	07:00AM	6 301.9	32.8
9	08:00AM	6 335.5	33.6
10	09:00AM	6 370.8	35.3
11	10:00AM	6 404.3	33.5
12	11:00AM	6 436.3	32.0
13	12:00PM	6 469.8	33.5
14	01:00PM	6 503.0	33.2
15	02:00PM	6 533.6	30.6
16	03:00PM	6 567.4	33.8
17	04:00PM	6 598.8	31.4
18	05:00PM	6 633.8	35.0
19	06:00PM	6 666.9	33.1

The results showed that by using the heavy oil electric heating embedded control device, the medium frequency power supply could save 20% of the original power consumption, and the average annual medium frequency power supply could save 71 832 kW·h. The rules of peak-valley flat electricity price in Liaoning province are 8 hours during peak hours, 7 hours during valley hours, and 9 hours during normal hours. The peak-hour electricity price is 1.5 times of the normal electricity price, and the valley-hour electricity price is 0.5 times of the normal electricity price. The peak-valley-level electricity prices are 0.76 yuan/(kW·h), 0.30 yuan/(kW·h) and 0.531 yuan/(kW·h) [13], respectively. In order to facilitate the calculation, the peak and valley flat electricity price is converted to 0.54 yuan/(kW·h), and the heavy oil electric heating embedded control device can save 38 789 yuan per well per year.

6 Conclusions

An embedded control device for heavy oil electric heating based on the double closed loop of the electric power of the pumping motor and the temperature of the heavy oil at the wellhead was designed to effectively improve the heating efficiency of medium frequency electric heating in heavy oil production and reduce the power consumption of heavy oil production. The device was equipped with two working modes, i. e., manual and automatic, which can be switched by operators according to site conditions. In the automatic mode, the sensor collected real-time data on the spot, and used the embedded controller to adaptive control the output power of the on-site medium frequency power supply. Good robustness of embedded controls was obtained in the face of external disturbances and human intervention. The device was also designed with a cloud platform, which could be remotely monitored through the network. The actual test results showed that after the application of the heavy oil electric heating embedded control device, the medium frequency power supply could save 20% of the original energy consumption, and the medium frequency power supply could save 71 832 kW·h and 38 789 yuan per well per year. The energy-saving and power-saving effect is remarkable.

Acknowledgement

This work was supported by National Natural Science Foundation of China (No.61903291); Shaanxi Province Key R&D Program (No.2022GY-134).

Declaration of conflicting interests

The authors have no conflict of interests related to this publication.

References

[1] HE J Q, LI X Y, LI Z L. Combustion characteristics of heavy oil infiltrated in aluminum oxide porous media. Speciality Petrochemicals, 2023, 40(2): 62-66.

[2] SUN H Q, LIU H Q, WANG H T, et al. Development technology and development direction of China's thick oil thermal recovery. Journal of Petroleum, 2022, 43(11):

1664-1674.

[3] FANG T, LIU Y G, BAI J H, et al. Research on electric heating technology for hollow rod of offshore electric submersible pump well. China Offshore Oil and Gas, 2023, 35(2): 163-167.

[4] MENG X. Research progress of viscosity reduction technology in heavy oil production. Clean World, 2020, 36(3): 33-34.

[5] ZHANG L. Progress and direction of recovery enhancement technology in Sinopec's old oilfields in eastern China. Oil and Gas Geology, 2022, 43(3): 717-723.

[6] LI W K. Application research of wellbore electric heating technology in heavy oil production. Chemical Management, 2019(6): 180-181.

[7] SUN B J, SU L, ZHANG C. The application of the amorphous metal transformers in heavy oil electric heating system. Applied Mechanics and Materials, 2014, 532: 191-195.

[8] LIU H L. The application of electric heating temperature control system for high pour-point oil to Shenyang oilfield. Technology Supervision in Petroleum Industry, 2012, 28(4): 51-52.

[9] ZOU J T. Research and design of heavy oil recovery dynamic temperature compensation self-optimizing control system. Shenyang: Shenyang University of Technology, 2009.

[10] YU H G. Optimal PID parameters self-adjusting control methods on heavy oil well electrical heating system. Journal of Binzhou University, 2010, 26(6): 104-107.

[11] WU H Y, GU L C, GENG B L, et al. Multi-model adaptive PID control of variable speed pump-controlled hydraulic cylinder system. Journal of Measurement Science and Instrumentation, 2023, 14(2): 209-217.

[12] WANG X Y. Principle and hardware circuit design of STM32 single chip microcomputer principle and hardware circuit design. Southern Agricultural Machinery, 2020, 51(14): 163-164.

[13] TAO Y J, YU S R, WU M L, et al. Design of boiler combustion control system based on STM32 microcontroller. Electronic Measurement, 2018, 41(24): 134-138.

[14] CHEN X, LIN J H, WANG J P, et al. Design of axle end acceleration detection device for electrical multiple units based on STM32. Instrument Technology and Transceiver, 2021(2): 36-40.

[15] DAO G, LIU Y Y, PAN T W. Design and development of fire alarm system software for pellet production. Enterprise Technology and Development, 2020(8): 50-52.

[16] LIU J, CHENG K, ZHAO P G, et al. Design and implementation of data collector based on STM32 microcontrollers and CH438Q. Instrument Technology and Sensor, 2021(1): 30-32.

[17] XIA B Y, GAO Q C, SUN L W, et al. Heat-fluid coupling Pattern in the whole interval of heavy-oil thermal recovery wells. Specialty Oil and Gas Reservoirs, 2022, 29(4): 142-148.

[18] WANG C J, ZHANG F, ZHANG H W, et al. Research on the integration of anti-corrosion patching equipment for oil and gas pipelines. Petroleum Machinery, 2022, 50(5):142-149.

[19] CAI S Y. Analysis of the increase and decrease of the peak-valley-level electricity tariff in the Liaohe Oilfield. Petrochemical Technology, 2017, 24(1): 191.

[20] GUAN W L, JIANG Y W, GUO E P, et al. Heavy Oil Development strategy under the "Carbon peaking and carbon neutrality" target. Acta Petrolei sinica, 2023, 44(5): 826-840.

稠油电加热嵌入式控制装置设计及其试验

贺利乐[1*], 晏东阳[1], 刘沛津[1], 肖勇[1], 孙昱[2]

1. 西安建筑科技大学 机电工程学院, 陕西 西安 710055;
2. 西安建筑科技大学 理学院, 陕西 西安 710055

摘　要：为提高稠油井电加热系统的加热效率，解决油田中频电源加热运行控制主要依靠人工经验设置和低效的自动控制造成电能浪费的现状，本文设计了稠油电加热嵌入式控制装置。基于非嵌入式获取的油井生产电信号，以稠油开采电机的电功率为闭环反馈信号，获取油液最优温度的参考输入。在此基础之上，通过井口油液温度的微分反馈环节，改善温度迟滞效应，实现中频电源的节能优化控制。通过对嵌入式硬件核心电路模块的设计和主要软件功能的开发，不仅实现了稠油井电加热过程的动态控制，还实现了各项运行指标的现场及云端的实时监测。稠油井场试验分析表明，所设计的稠油电加热嵌入式控制装置符合井场节能安全的生产需求，节约能耗可达20%。

关键词：稠油热采；中频电源；双闭环控制；嵌入式控制；节能测试

引用格式：HE Lile, YAN Dongyang, LIU Peijin, et al. Design and test of embedded control device for electric heating of heavy oil. Journal of Measurement Science and Instrumentation, 2024, 15(2): 224-234.