Design and Experiment of Embedded Control System for Low Pressure Steam Generating Equipment

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ABSTRACT: In view of the problem of large amount, low temperature, wide distribution, low recovery efficiency and difficult recovery of present low-temperature waste heat. This paper studied the mechanical structure and working mechanism of the new type of low pressure steam power generation device with blower as the core. And developed the embedded control system of the power generation device composed of a substrate board and functional boards using modular design method. The system with the C8051F040 MCU at its core was composed of speed encoder, temperature sensor and other sensors, signals of which were real-time input into the MCU. The MCU received real-time human-machine interface through RS232 bus to supervise and control the control system. The PID power regulator with encoder as the feedback signal is designed, which eliminated the disturbance of waste heat, and regulated the power quality of the generator steadily and reliably .The experimental results show that the control system has good openness, flexibility and stability, and can adjust the power quality, realize that the low-temperature waste heat power generation device efficiently recycle the low-temperature waste heat and conversion of electrical energy.

KEYWORDS: Low pressure steam; Waste heat power generation; Embedded system; Modular design control.

INTRODUCTION

There are plenty of low temperature waste heat resources generated in industrial production. For this part of resources recycling can largely relieve the energy crisis. For waste heat recovery technology, electric energy conversion is the most reasonable way for the overall utilization of waste heat resources, and the economic and environmental benefits are the highest. It is an effective method for increasing energy efficiency and reducing environmental pollution to convert waste heat energy into electric energy [1].

Current low temperature waste heat power generation devices are obtained by optimizing or modifying relatively mature screw expanding power generator to make it adapt to the low quality of energy. Screw expansion of power systems, power generation systems and organic Rankine's spiral cycle power generation system, which research and development by foreign meet the needs of the part of low temperature waste heat [2, 3]. Some domestic enterprises have realized the grid generation of low pressure saturated steam in a certain temperature and pressure range, so the problem of efficient utilization of saturated steam in low grade medium and small flow is solved. However, due to the limitation of steam quality, flow rate and design cost, led to the capacity of current low temperature waste heat power generation equipment in 200 kw and above, and failed to achieve widespread application. Small or sub-miniature low temperature waste heat power generation equipment is still a blank in the domestic. So this paper took a unique way of thinking: using the blower of reverse operation as a heat engine, then designed a simpler structure, lower manufacturing costs and easier to maintain power generation equipment to take advantage of poor quality waste heat steam.

In ordinary steam power generation process, motor output power is constantly changing, and the output power quality is difficult to ensure due to the factors of steam flow, temperature and other parameters as well as the operation of the load device [4]. To solve the above problems, this paper developed a kind of embedded control system with automatically adjust the power, conveniently operate and maintain, strong portability and high universality using modular design method.

THE OVERALL SCHEME DESIGN

Roots-steam Generator Structure and Working Principle

Roots blower is a positive displacement blower, and the air conveying capacity and speed in a certain proportion. As shown in Figure 1, the impeller of the three types of impeller 3 times per rotation by the 2 air suction, exhaust. Three-leaves type impeller per rotation, the 2 impeller for 3 times to inhale, exhaust [5, 6]. It has a small gas pulsation, little vibration and low noise characteristics. Between the impeller of the 2 axis of the fan and the inner hole surface of the elliptical shell, between the end cover of the impeller and the front cover of the fan, as well as between the fan impeller, always keep a small gap. Driven by synchronous gears, the wind from the fan into the air outlet along the shell side of the wall to the outlet.
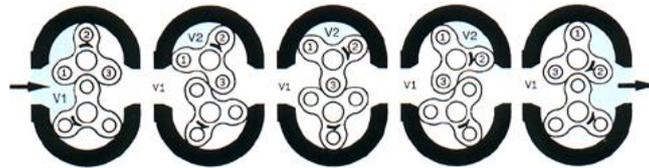

Figure 1. The working principle of three leaves roots blowers.

According to the principle of roots blower is shown in Figure 1, assuming that a certain pressure of liquid or gas is passed through the air outlet of the roots blower, or both mixed media, and the roots blower exhaust outlet pressure is less than the air inlet. The medium will in the shell expansion to drive the impeller along the clockwise rotation and acting. At this time of roots blower is regarded as a kind of engine.
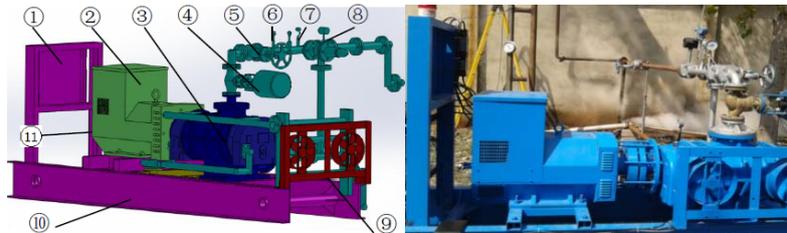

Figure 2. Roots - steam generator 3D model and real photos.

According to the above assumptions, design the power generation device with blower as the steam engine [7, 8]: to reform the generator and a blower, roots - steam generator was designed, the design power of 100 kw. The model is shown in Figure 2. It includes: (1) Control system, (2) Generator, (3) roots-type engine, (4) Electric proportional control valve, (5) Manual control valve, (6) Pressure gauge, (7) Thermometer, (8) Electromagnetic Flowmeter, (9) Cooling fan, (10) Damping base, (11) Encoder.

Roots-steam Generator Control System Design

Roots-steam generator control system with high speed mixed signals SoC MCU - C8051F040 as the core. In accordance with the principle of modular design, the system is divided into power module, I/O interface module, communication module and analog module. As shown in Figure 3.
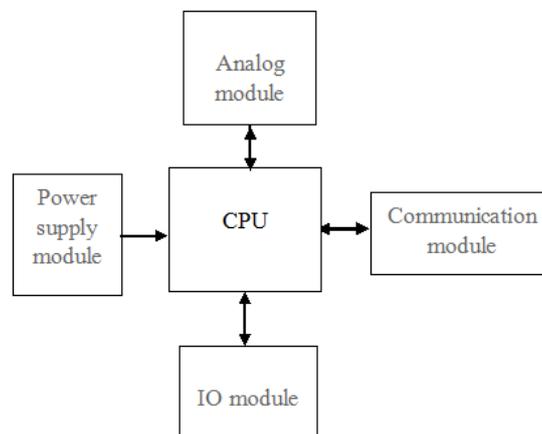

Figure 3. The principle diagram of the control system.

The power supply module provides energy for each module, and provides a working power supply for the speed encoder, temperature sensor, humidity sensor and flow control valve, electric energy meter, etc. The IO interface includes inputs interface for transmitting information with a speed encoder, a temperature sensor, a humidity sensor and other sensors. And the outputs interface of the device sends command to the flow control valve, the electric energy meter, and the generator. Communication module through the RS232 bus to achieve real-time communication between host computer (human-machine interface) and MCU to supervise and control the control system. The output voltage, current, and power of the output voltage, current, and power of the electric energy meter are acquired by the RS485 bus, and the above parameters are coupled to a multi-parameter electric energy regulator. And the power regulator can adjust the power quality of the generator stably and reliably. CPU receive temperature sensor temperature information, humidity sensor humidity information, flow control valve flow information, electric energy meter voltage, current information and steam source pressure, flow and other analog information. Through the PID power adjustment algorithm to achieve the output power quality adjustment.

THE HARDWARE CIRCUIT DESIGN

The CPU Resource Configuration

According to the principle that use of simple, easy extension, and satisfying the functional requirements and performance requirements of the generator system , the final choice of C8051F040 single chip as CPU. The single chip processing speed of up to 25MIPS, with a very rich system resources, built-in 8/12bitA/D conversion controller, 64 I/O pin can be designed to be flexible programming configuration. After the analysis of power generation system control requirements, the C8051F040 system resource planning configuration, as shown in Figure 4 for the modular design of the system hardware circuit.
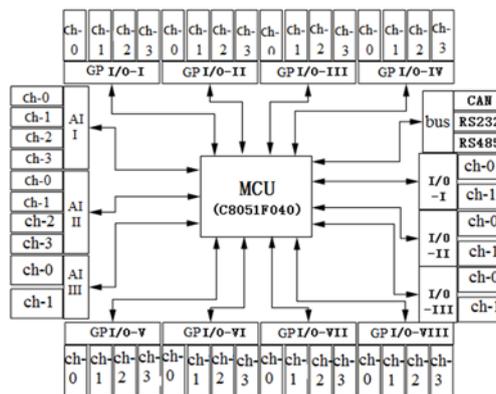

Figure 4. CPU resource allocation plan block diagram.

The Power Supply Circuit Design

C8051F040 total of 3 pairs (DGND, VDD) system digital power input pins and 3 pairs (AGND, AV+) system analog power input pins, the 6 pairs of pins must be connected to the +2.7V~+3.6V. The schematic diagram is shown in Figure 5 below.
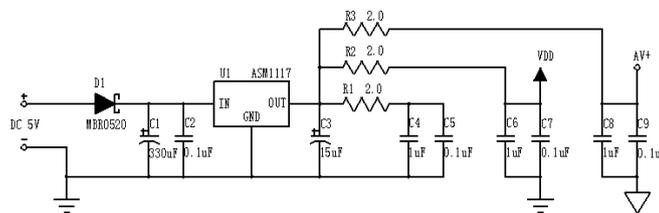

Figure 5. Power supply principle diagram of digital power supply.

DC5 V power supply through the Schottky diode (MBR0520) output as a power source. MBR0520 is suitable for low voltage, high current, and high response frequency, very suitable for the power input polarity protection. Input voltage through the ASM1117 regulator chip output 3.3 V.

Analog power and digital power should power supply respectively, and the voltage difference between the two power supplies is less than 0.3 V. But the actual design takes into account the cost and space and other issues often use the same power supply, but the need to filter between two power supplies. The decoupling capacitor and bypass capacitor are used to stabilize the supply voltage, as shown in Figure 6 C11~C16.The analog ground is connected with the system ground through a 0 ohm winding resistance (R11) to generate enough parasitic inductance, enhance filtering effect.
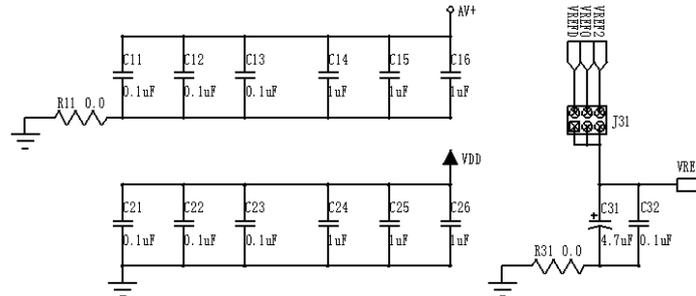

Figure 6. Filter power supply schematic diagram.

Due to digital power and analog power supply use the same power supply, therefore ensure the digital power supply output voltage meets the requirements of precision, also ensure the precision of the analog voltage. Testing system power supply circuit, the effects are shown in Figure 7 below.
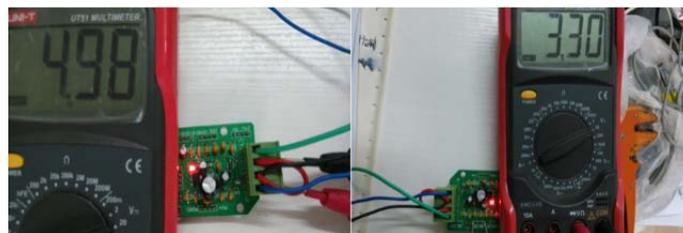

Figure 7. Test effect diagram of system power supply module.

Test using a commercially available DC power supply (5 V/24 V), the actual measured voltage at the input side of the 5 V power is 4.98 V. And 5 V through the ASM1117 chip as well as the external device of the regulator and the filtered output voltage is 3.30 V. The measured voltage is equal to the designed voltage, and the analog power supply is not only obtained by the digital power supply voltage regulator and filter, but also meets the accuracy requirements.

Analog Interface Circuit

Analog interface circuit is divided into analog acquisition input AD converter and digital conversion output DA converter. Shown in the Figure 8, left for the input interface and right for the output interface. Due to the analog input reference voltage uses the internal 2.4 V band gap reference voltage, the analog input voltage signal in the system is between 0 V~2.4 V.

According to the formula: Vout=Iin * R103, the value of R203 and R201 are calculated and selection of high precision resistance with 0.1% error. In addition, the analog input port by another 0.1 uF filter capacitor. To protect the input channel is not damaged due to the polarity reverse, diodes are added at the entrance and the by-pass of filter capacitor as protection.
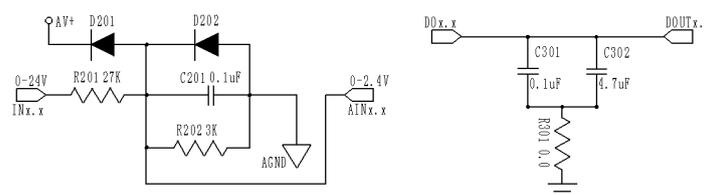

Figure 8. Analog interface circuit.

The DAC module is connected to the external 5 V reference voltage via the VREFD pin as its reference voltage. And access 0.1 uF and 4.7 uF bypass filter capacitor between VREFD pin and AGND pin, as shown in above Fig.8.

Test set DAC conversion module, make the channel DAC0 output voltage 2.00 V, the multimeter measurement results are shown in Figure 9 below. Connect the output voltage and ADC0 channel, programming measure ADC0 channel value, each 500ms collects a measurement value. Measurement method for tracking and maintaining measurement, and the measured value is sent to the receiving end of the computer serial port by the RS232 module for display.

Figure 9. DAC0 analog output measurement figure.

Figure 10 for the simulation of measurement test, serial data sent to the computer display as "23 46 00 32 0D 30 30 2E" (shown in red square).According to the designed frame format, "23" for frame head and "0D" for frame head tail, the "46" for the command type "F" to set float type, "00" is the channel number 0.Converted "32, 2E, 30, 30" into decimal is "2.00". It is equal to the design value, the conversion results are shown in figure.
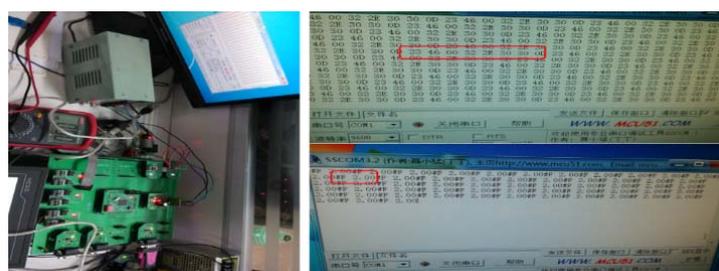

Figure 10. ADC0 analog test pattern.

According to the experimental results can determine that the design of analog input/output module meets the requirement.

Based on the method of modular embedded system design, the whole control system is composed of basic and functional modules. The substrate is the carrier of each functional block, its electrical interface should be consistent with each function block. In order to ensure the consistency, the way of first modular design and then mapping interface position was adopted the first module design, mapping interface position after the way to make the electrical interface of the whole system is consistent. The main function of the substrate is to provide a functional block in the fixed position, and the electrical interface base. Due to the substrate area is large, so the power supply can be designed on it, and according to the design principle of EMC to routing.

Figure 11. Embedded system overall structure physical figure.

Function block connected to the substrate by row of needles, and substrates by cable. Besides the electrical connection，Each functional modules are tightened by the bolt column. As shown in above Figure 11.

THE SOFTWARE SYSTEM DESIGN

Control System Software Process

Software of the system uses the modular design method, and software process as shown in Figure 12.The main program is completed the initialization, self-check and program calls, etc., to be prepared for the system to work. Subroutine modules mainly include: waste heat recovery module, Steam power generation module, Grid generation module, Condensate recovery module and cooling lubrication module. The working process of the system is: after power up, the system transfer the state of sensors and regulators to make sure they are in the initial state. Self-check is completed, then beginning to waste heat recovery, after a period of time to calculate heat inlet temperature and outlet temperature of the waste heat temperature. In normal operation, the system uses steam to generate electricity at this time, or else the fault diagnosis program is executed. The principle of the steam generator is: heat energy of the steam driven rotary steam engine by expansion work, so as to drive the generator to work, and then complete the steam generation and grid connected. Throughout the entire power generation process, condensing recovery process is mainly recycling of substance of steam. Steam engine cooling and lubrication process to provide a safe and good working environment for steam power machine to prevent reduce system working efficiency, service life, and even accidents, which caused by thermal fatigue and mechanical wear.
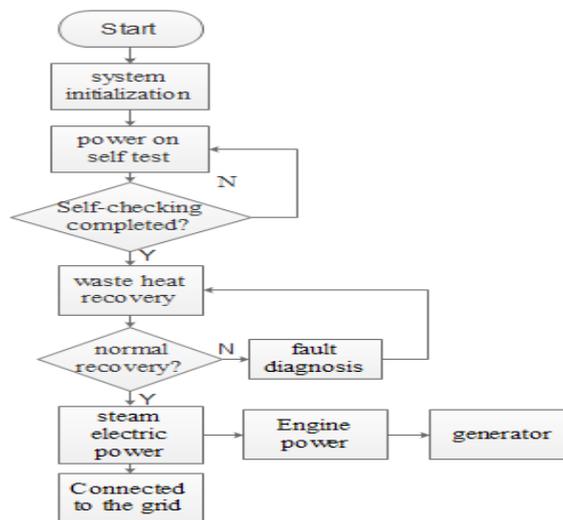

Figure 12. Program flow chart.

Electricity Regulator Design

Work process is divided into steam generator inlet, expanding power, power transmission and feedback to adjust four stages, from the level of power quality is the key to feedback adjustment phase, so need to study power adjustment control law to improve the efficiency of power quality and power generation, its control principle are shown in Figure 13 below.
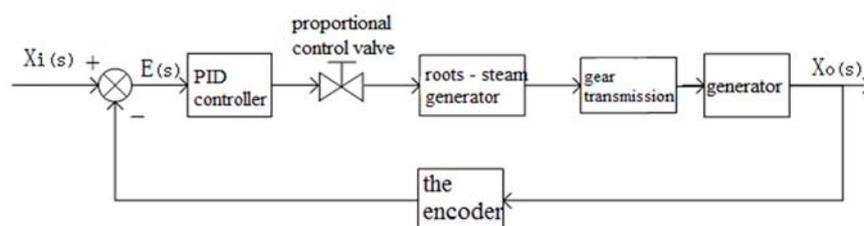

Figure 13. Power regulating principle block diagram.

To gear transmission principle is shown in Figure 13 and generator characteristic analysis shows that The linear relationship between the gear mechanism and the front and rear of the transmission power and the speed of the speed is characterized by the mathematical sense, the transfer function as a constant gain link; The mathematical

characteristics of the generator itself is very complex, but since it has automatic voltage regulation (AVR) controller, can adjust the voltage automatic tracking, so the power quality can be thought of as the efficiency of power transmission problems.

To simplify the controller model, and based on Matlab8.0 / Simulink6.0 (speed) of low-pressure steam engine load control system simulation model, as shown in Figure 14.
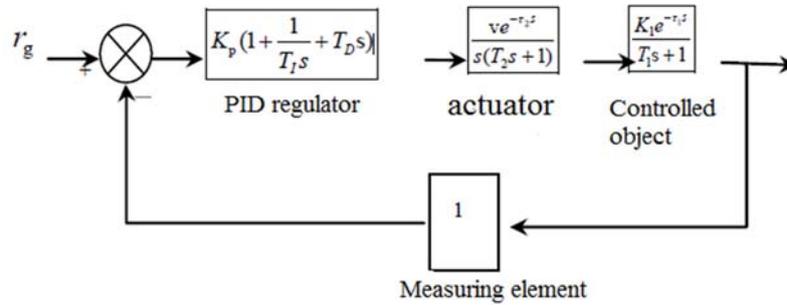

Figure 14. Electricity regulation PID control model diagram.

In the process of electricity PID control system, to achieve the good control quality, need to set PID control three undetermined parameters Kp, Ki and Kd , other parameters according to the actual operation situation and related resources values: T1 = 1 s, T2 = 0.6 s, T3 = 0.4 s, v = 0.016 Mpa/s, = 0.44 s, = 0.4 s, K1 = 0.2. In MATLAB based on Ziegler Nichols the critical ratio coefficient method using root locus function rlocus and rlocfind command to determine the Kp, Ki, Kd, Ziegler Nichols PID parameter setting table as shown in table 1, Kk for cross gain, Tk for the system critical period of oscillation, specific as shown in Table 1.

Table 1. Ziegler-Nichols PID parameter setting table.

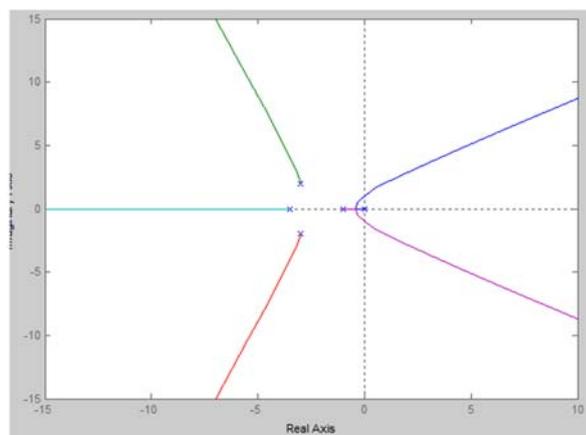| Regulator	KP	TI	TD
P	0.5 Kk	NOP	NOP
PI	0.45 Kk	0.85 Tk	NOP
PID	0.6 Kk	0.5 Tk	0.125 Tk

By calculate the root locus diagram is shown in Figure 15:

Figure 15. Root locus of power controller PID.

The results show:

>> wm = imag (pole(7))% The critical stable angular frequency

wm = 0.0460

>> kp = 0.6*km

kp = 3.0086

>> ki = 0.5*kp*wm/(2*pi)

ki = 4.8847e-005

>> kd = 0.125*kp*wm/(2*pi)

kd = 7.7118e-006

THE TEST AND THE RESULT ANALYSIS

System No-load and Load Test

The System no-load and load test are carried out in order to study the system performance and the characteristic. The manual valve opened a small angle (about the open degree of 1/5), and observe the operation of the equipment. To be stable, generator speed, line voltage as well as flow and pressure, which before the steam into the roots-steam engine were recorded, then gradually increase the manual valve opening, and the relevant data were recorded, as shown in Table 2.

Table 2. Roots-steam generator no-load-low pressure data.

Generator speed(r/min)	Line voltage			Steam flow [t/h]	Steam pressure MPa
	AB V	**BC V**	**CA V**		
210	10	3	7	0.51	0.07
265	32	40	38	0.65	0.09
732	46	42	49	2.46	0.25
986	138	143	150	2.87	0.32
1200	202	200	200	4.32	0.45
1270	290	289	284	5.03	0.59
1400	343	349	336	5.74	0.67
1430	363	369	355	5.83	0.68
1490	378	380	379	6.45	0.69
1700	383	385	383	7.56	0.77
1930	389	389	389	8.72	0.81

Table 3. Roots - steam generator load - low pressure data.

Generator speed [r/min]	Line voltage			Steam flow [t/h]	Steam pressure [MPa]	Load
	AB V	BC V	CA V			
1487	382	379	380	5.84	0.68	No
1200	202	200	200	6.34	0.74	35 kw
1283	263	266	273	7.01	0.74	35 kw
1403	321	315	329	7.57	0.78	35 kw
1500	382	389	386	8.78	0.81	35 kw

When the pressure increases from 0.07 MPa to 0.32 MPa, the flow rate increases from 0.51 t/h to 2.46 t/h, the generator speed increased gradually and the variation is larger, but a little voltage change of power by Table 2 shown. When the speed is increased from 986 r/min to 732 r/min, the output voltage of power in jump, the pressure reaches 0.32 MPa, the flow rate is 2.87 t/h. When the speed increased from 1200 r/min to 1270 r/min, and the average voltage increased by 87 V, the flow and pressure increased by 0.14 MPa and 0.71 t/h respectively. the average voltage value reaches 333 V, the

generator speed of 1400 r/min, the steam flow rate can be measured is 5.74 t/h, and the pressure value is 0.67 MPa. During the process of the voltage value to achieve the rating value, the generator speed, steam flow and pressure compared to the last stage changes smaller. Generator power output voltage value is essentially remaining unchanged after the generator speed is over 1490 r/min.

Now add 35 kw load to the system. Similarly, the electric control valve is fully played, then manually adjust Inlet valves to simulate the change of the gas source. Data were recorded as shown in Table 3.

Analysis data can be found in Table 3.In the process of gradually increasing the manual valve opening, the steam flow and pressure increase. Compared with no load, the steam flow is increased by 23%, the pressure is increased by 19%, which indicates that the flow and pressure are two parameters that are directly related to the working efficiency of the generator.

Steam and Load Dynamic Balancing Adjustment Test

In order to study the adaptability of the power generation system to the fluctuation of steam and changing load, the following experiments were designed.

The Adjustment Test of Fluctuating Steam Source

Manual control valve fully open, after the system is in stability, the valve opening gradually reduced. So repeated to exert artificial interference, the whole process is under the condition of system with 35 kw load. And the PID adjustment process is shown in Figure 16 (left); After steam power system stability, the manual valve to implement a large range of interference until completely closed, at this time PID regulation has become severe, as shown in Figure16 (right).
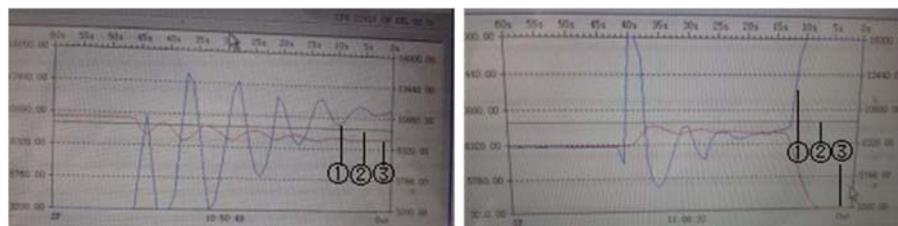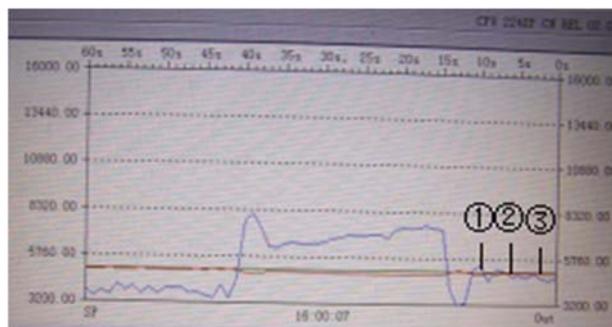

Note: (1) The output value, (2) The set value, (3) The feedback value.

Figure 16. The effect figure of valve opening and reducing regulation.

The effect of the PID regulation in Figure 16 showed that the power generation system has an obvious effect of regulation on the low quality steam source.

The Adjustment Test of the Variable Load

In the experiment of the fluctuation of steam source, it is proved that the power system has a more obvious effect of regulation on the fluctuation of the steam source. When the power generation device is stable under 35kw load, the load of 15kw is rapidly connected. The system of the impact of the load response curve is shown in Figure 17.

Note: (1) The output value, (2) The set value, (3) The feedback value.

Figure 17. The variable load regulation effect diagram.

It can be seen from Figure 17 that the adjustment time of the system is about 5 s at the time of sudden loading, and 4 s sudden to unloading, which is slightly worse than steam source fluctuation adjustment.

The Test Result Analysis

Roots-steam generator no-load - low pressure test showed that the steam pressure is less than 0.32 MPa, flow under the condition of less than 2.87 t/h, the device can generate electricity. About 0.77 MPa steam pressure and about 7.56 t/h flow the device can produce rated voltage 380 V. It is proved that roots-steam generator with low pressure saturated steam power generation technical scheme is feasible.

Roots - steam generator load - low pressure test showed that the steam pressure is 0.81 MPa, flow under the condition of 8.87 t/h device can generate electricity to drive 35 kw load, illustrating roots - steam generator can recovery low pressure saturated steam and mechanical work.

Fluctuations in the steam source adjustment experiment showed that roots - steam generator has a certain ability to adapt to the waste heat of steam pressure is greater than 0.4 MPa and flow rate is greater than 2.8 t/h.

The adjustment experiment of the variable load showed that showed the roots - steam generator has a certain ability to adapt to pressure is greater than 0.45 MPa, and flow rate is greater than 2.8 t/h range under the condition of 50 kw and below the load.

System no-load and load experiments can be explained that reverse roots blower used for steam engine and the use of low-pressure saturated steam generation technology scheme is feasible.

Steam and load dynamic balancing adjustment test is a functional test of the embedded system, and the experimental results confirm that the embedded system can complete the function of the voltage quality regulation.

CONCLUSIONS

According to the technical requirements of low temperature waste heat recovery and utilization, this paper analyzed and studied the mechanical structure and working principle of the new low pressure steam generating device with the roots blower as the core, and put forward the power generation device embedded control system scheme, developed the embedded control system using modular design method. Based on the modular design methods, the function is divided into various modules. Eventually, form a platform and modular hardware system, which combine with substrate and the functional board, and developed the software system using modular programming development according to the technological process. Finally, the control system was tested, and the experimental results show that the control system can adjust the power quality, realize that the low-temperature waste heat power generation device efficiently recycle the low-temperature waste heat and conversion of electrical energy. In this paper, the embedded control system designed by adopting the method of modular meet the control demand of the new power generation device control system, and has a very high openness, flexibility and general. The modular design method also has a very good reference for other embedded control system design.

CONFLICT OF INTEREST

This article content has no conflict of interest.

ACKNOWLEDGEMENT

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