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Energy efficient multi-circuit cogeneration plant

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Abstract. The paper reviews an energy efficient multi-circuit power plant with three independent power generation circuits and a generator control system. The proposed three-circuit autonomous power plant was constructed in accordance with a modular design. The structural scheme, design, operating modes, and simulation model in the Matlab+Simulink environment is presented. The increase in electrical efficiency at this cogeneration plant is due to the use of low-temperature boiling point heat-transfer fluids. This article proposes the method of increasing the efficiency of an existing installation from 60 kW to 100 kW by equipping it with additional equipment. This equipment provides deeper utilization of flue gas heat. If the base power plant is 60 kW, the heat input is about 200 kWh (an efficiency of the station is 30%), then the total electricity generation will be 100 kW. In this case, an additional 40 kW of power is without increasing fuel consumption.
Keywords. Multi-circuit power plant, low-temperature boiling point heat-transfer fluid, organic Rankine cycle, modeling and simulation in MATLAB

1. Introduction

The object of our study was an autonomous electric equipment complex comprising of a three-circuit gas turbine power plant using the technology based on low-temperature boiling point heat-transfer fluids. The complex had an automatic control system distributing electrical loads among the circuits in a given proportion. The proposed three-circuit autonomous power plant was constructed in accordance with a modular design. Each circuit of the power plant could operate as an independent electric generator. The second and the third modules had similar sets of their elements.

To simulate the various modes of operation in a three-circuit power plant, a simulation model was developed in the Matlab Simulink system.

The advantage of the developed autonomous gas turbine power plant with a multi-circuit thermal power plant was the possibility of a fuller utilization of the thermal energy from the gases generated in the gas turbine.

The proposed circuit solution allowed increasing the electrical efficiency of the device up to 50-55%, which affected the effectiveness of a fuel gas usage. An increase of electrical efficiency by 1% results in 3% fuel savings.

It is assumed that the first circuit of the cogeneration plant operates on the basis of existing microturbines (for example, of Capstone brand) and has an electrical power of 60 kW. The second and third circuits operate on the Rankine cycle. They differ from each other in the following details: the turbine on the second circuit operates on the Rankine gas-steam cycle, while purified water is used as the coolant. The third circuit has the lowest temperature, although it operates on the Rankine cycle as well.

The transformation of low-potential thermal energy can be carried out in various thermodynamic cycles. However, attention of the specialists is attracted by organic Rankine cycle. This cycle differs from conventional Rankine vapor-gas cycle in various organic substances (such as freons) rather than water used as a working medium.

The technology using the Rankine organic cycle can work on any heat source with a minimum temperature difference of 65 °C between the heat source and the heat sink.

Calculations conducted by the specialists have shown that radial-axial centripetal turbines can be used as expansion machines and drives of electric generators in the low-power Rankine cycle. This type of turbine provides a fairly high energy conversion efficiency at low cost and relatively high degree of working fluid expansion.

Use of water as a working medium in power plants operating in the Rankine cycle with a single-stage radial-axial turbine at low output power necessitates an increase in the operating frequency of the turbo generator shaft to extremely high values and, as a result, unreasonable complication of the electric parts of the power plants.

The use of the Rankine organic cycle allows for lower operating temperatures and relatively high operating pressures in the cycle.This leads to decrease in geometric dimensions of the turbine.

This results in technologically acceptable dimensions of the impellers, relatively high values of the thermal efficiency of the cycle and isentropic efficiency of the turbine [1].

As an example, table 1 provides the parameters of single-stage radial-axial turbines operating on organic Rankine cycle on R114 freon in the power range from 1 to 60 kW.

Table 1. Physical parameters of organic Rankine cycle.

Condensation temperature (°C)			30		
Boiling point (°C)			120		
Temperature in front of turbine (°C)			130		
Turbine inlet pressure (bar)			20.8		
Turbine outlet pressure (bar)			2.5		
Turbine shaft power (kW)	**1**	**15**	**30**	**45**	**60**
Mass flow through the turbine (kg/s)	0.04	0.59	1.16	1.70	2.22
Impeller outer diameter, mm	16	62	86	105	120
Turbine rotor speed, thousand rpm	200	52	38	31	28
Isentropic efficiency of turbines, %	79	81	82	84	85
Thermal efficiency of the cycle, %	15.7	16.0	16.1	16.5	16.8

Acceptable values of thermodynamic conversion efficiency in low-power power plants are provided at a relatively high frequency of the turbine rotor rotation. This implies the implementation of a gearless design of microturbine cogeneration plant. A high-frequency generator is used as an electromechanical energy converter. The heat energy of the flue gases in the Capstone C65 microturbine is 559 BTU/h [2]. This value corresponds to heat output of 164 kW. Let us take this indicator as the basis for our calculations.

In the second circuit, generation of 30 kW of electrical power is expected from such heat energy of flue gases.In the third circuit, the heat energy of flue gases of the second stage is expected to produce 10 kW of electrical power. Ethanol (ethyl alcohol) is used as a low boiling point working substance.

The choice of ethanol as a working substance is largely determined by its low capability to serve as a solvent for various materials, such as gaskets, sealing rings, glands and various insulating materials.

The calculation of the Rankine cycle on ethanol for the third generation loop is performed using the information resource [3] based on MathCad software. Such calculation is required to identify the the efficiency of converting thermal energy of flue gases into electricity.

When calculating a microturbine of the second circuit with a temperature drop from 350ºC to 100ºC using the steam cycle, the theoretical efficiency of cogeneration plant is 40%. To achieve this, it is necessary to expend 75 kW of thermal power to generate electricity.

When calculating a microturbine of the third circuit with a temperature drop from 100° C to 30 °C using an ethanol cycle , cogeneration plant efficiency is 15% [4-6]. Here, it is necessary to expend heat power equal to 67 kW to generate electricity.As a result, total thermal power output from the first circuit for additional power generation should be at least 142 kW.

As mentioned earlier, the heat output from the gas turbine unit of the first circuit is 164 kW. Thus, it can be stated that with such output of thermal power, it is possible to provide deeper heat utilization with an increase in cogeneration plant efficiency up to 50% by adding two additional circuits.

2. Materials and Methods

Based on the analysis of existing microturbine technologies and the developed projects of autonomous power plants, the following concept of increased efficiency multi-circuit gas turbine power plants is proposed [7-13]:

Three independent power generation circuits:

- in each circuit on the same shaft with the turbine a high-speed electric generator with gas-dynamic bearings is installed;
- to obtain electric power of industrial frequency, a frequency converter is installed;
- a rectifier is connected to each electric generator to rectify the generated voltage and current;
- in order to summarize the power of electric generators generated in each circuit, stabilize the voltage and obtain voltage of a given quality, an inverter is installed.

The scheme of the proposed multi-circuit gas turbine power plant is shown in figure 1.

The positions in the drawing indicate the following: 1 - compressor intake; 2 - compressor; 3 - the first turbine; 4 - second gas turbine; 5 - the first electric generator; 6 - second electric generator; 7 - recuperator; 8 - the first evaporator; 9 - smoke exhaust; 10 - the first pump; 11 - the first shell-and-tube heat exchanger-condenser; 12 - supply pipeline fuel; 13 - combustion chamber; 14 - third turbine; 15 - the third electric generator; 16 - the first rectifier; 17 - the second rectifier; 18 - the third rectifier; 19 - second evaporator; 20 - second shell-and-tube heat exchanger-condenser; 21 - the second pump; 22 - inverter; 23 - microprocessor control unit, 24 - current sensor after the first rectifier, 25 - current sensor after the second rectifier, 26 - current sensor after the third rectifier, 27 - voltage sensor after the first generator, 28 - voltage sensor after the second generator, 29 - voltage sensor after the third generator.

It is assumed that the first circuit of the installation is a microturbine of a finished industrial production (for example, Capstone brand) with an output electric power of 60-65 kW.

Gases exhausted in the primary circuit are used as a heating medium, including a circuit with a low-boiling medium, which are used as freons, aqueous ammonia, pentane, isopentane, isobutane, etc.

The second and third circuits operate on organic Rankine cycle, but depending on the choice of the heating medium and the output heat parameters, the second circuit can operate onRankine steam-gas cycle (in which purified water is assumed to be the heat transfer medium) or on organic Rankine cycle, and the third, low temperature, circuit - on organic Rankine cycle with a deeper heat recovery.

Each circuit has its own high-speed electric generator installed on the same shaft as the turbine.

It is assumed that the first circuit of the installation is a microturbine of a finished industrial production (for example, Capstone brand) with an output electric power of 60-65 kW [14].

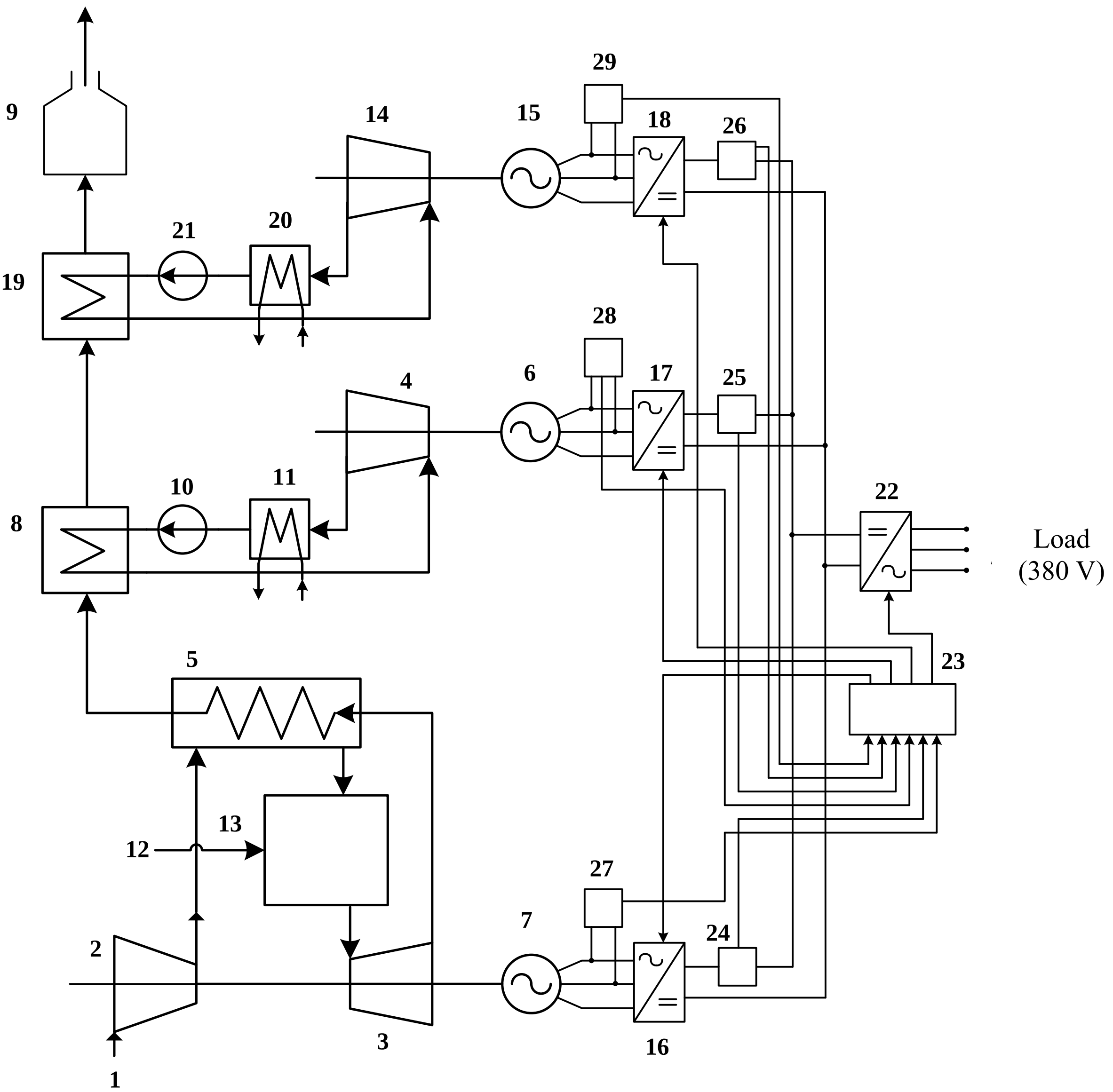

Figure 1. The scheme of the proposed multi-circuit gas turbine power plant.

Gases exhausted in the primary circuit are used as a heating medium, including a circuit with a low-boiling medium, which are used as freons, aqueous ammonia, pentane, isopentane, isobutane, etc.

The second and third circuits operate on the Rankine cycle, but depending on the choice of the heating medium and the output heat parameters, the second circuit can operate on Rankine steam-gas cycle (in which purified water is assumed to be the heat transfer medium) or on the organic Rankine cycle, and the third, low temperature, circuit - on organic Rankine cycle with a deeper heat recovery.

Each circuit has its own high-speed electric generator installed on the same shaft as the turbine.

For the proposed circuit, the following values of the output electric power were set: the first circuit - 60 kW, the second circuit - 30 kW, the third circuit - 10 kW.

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3. Results

As mentioned above, on the first circuit, the electrical efficiency of an existing microturbine is on average 30% (for various manufacturers). In this case, with the given electrical installation parameters, the power of the consumed thermal energy of the primary source is 60 / 0.3 = 200 kW, on the second circuit with the consumed thermal power of 200 kW, the efficiency can be increased to (60 + 30)/200 = 45%, on the third accordingly, up to (60 + 30 + 10)/200 = 50%.

Thus, when constructing a system using a three-circuit scheme with a total power of 100 kW, it is possible to increase the electrical efficiency by 1.5 times compared to a conventional single-circuit microturbine system, without additional emission of harmful substances into the atmosphere.

The thermal output of the Capstone C65 microturbine is 591 000 kJ/h. This indicator corresponds to a thermal power of 164 kW (591000 kJ/h = 591000/3600 kJ/s = 16 kJ/s = 164 kW).

This indicator was taken as the basis of theoretical calculations. When calculating a microturbine of 2 circuits with a temperature difference from 350 °C to 100 °C when using a cycle on water vapor, the theoretical efficiency of the installation was 40%. Here, it is necessary to expend heat power equal to 30 kW/0.40 = 75 kW to generate electricity. When calculating microturbines of 3 circuits at a temperature difference from 100ºC to 30ºC when using a cycle on ethanol, the plant efficiency was 15%.

Here, it is necessary to expend heat power equal to 10 kW / 0.15 = 67 kW to generate electricity.

As a result, the total heat output at the output from the primary circuit to obtain additional power generation should be at least 142 kW. As mentioned earlier, the output thermal power from the gas turbine installation of the first circuit is 164 kW.

Thus, it can be stated that with such heat output, it is possible to provide a deeper heat recovery with bringing the efficiency of the installation by adding two additional circuits to 50%.

In order to be able to supply power to the final consumer of the proposed power plant, a number of tasks need to be solved, such as providing the required parameters of power quality in terms of voltage and frequency.

Acceptable values of the thermodynamic conversion efficiency in low-power power plants are provided at a sufficiently high frequency of rotation of the turbine rotor. This circumstance involves the use of high-frequency generators as an electromechanical energy converter.

Assessing the advantages and disadvantages of various types of synchronous and asynchronous generators, as well as drawing on the experience gained by domestic and foreign experts in studying the operation of high-speed electric turbomachines with powers not exceeding 200-250 kW, synchronous machines with excitation from permanent magnets are offered as electric generators, which eliminates the problems arising from the parallel operation of generators. In this case, the inability to control the output voltage is compensated by the use of semiconductor power converters.

Thus, the consumer is connected to the power generating installation through a frequency converter with a DC-link (D_1) the generated alternating current is first rectified, and then transmitted through the inverter I1, which provides the required frequency, to the consumer (figure 2). In the concept of a three-circuit power plant, for each generating circuit (generators G_1, G_2, G_3), a rectifier device R_1, R_2, R_3 with an individual control unit (ICU) is used, operating on a common DC bus, by which the power of individual generating circuits is summed.

In this case, it is necessary to ensure:

- the same value of the rectified voltage for each circuit;
- synchronous control of rectifiers in a complex of three parallel-running generators of different power.

Rectifiers R_2 and R_3 are controlled by feedback on the load current determined by the current sensor CS_n.

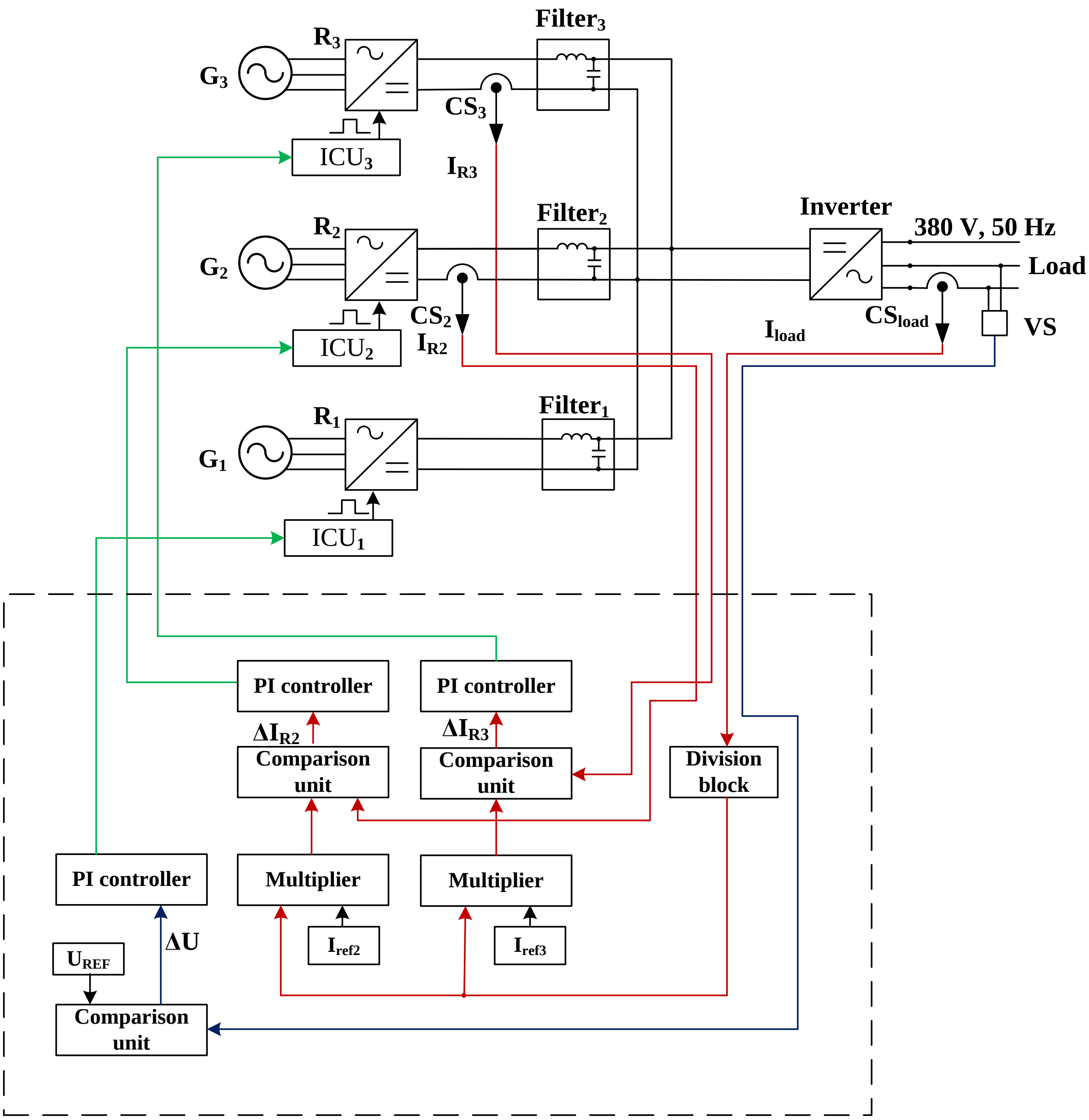

Figure 2. Block diagram of the formation of control rectifiers for work on the total load.

The signal from the CSn is transmitted to the division unit, in which the load current value is compared with the set value of the rated current generated by the electrical installation. To obtain information on the values of the generated current IR_2, IR_3, the current sensors CS_2, CS_3 are connected to the output circuits of the rectifiers. In the comparison blocks, the deviation of the value of the generated current of the generators from the load required by the conditions is determined and a control signal is set, which is transmitted to the controlled thyristor electrode of the rectifier unit and unlocks it. Since the initial feedback signal according to the magnitude of the load current is supplied simultaneously to all rectifier control units RCU and the process of generating the control signal is the same, the percentage distribution of the generated power by each generator is stored at any load value.

Thus, the load of the generators is the same and varies synchronously in proportion to its rated power.

The rectifier R1 is controlled by feedback on the voltage determined by the voltage sensor VS at the terminals of the inverter. Information about the voltage value from the voltage sensor VS is compared in the comparison unit with the value of the specified reference voltage U_R. The signal from the comparison unit enters through the regulator to the control unit of the rectifier RCU_1, which forms the control signal necessary to maintain the voltage at the required level, regardless of the load. Thus, a voltage stabilization system has been formed, which allows providing the required voltage value at the rectifier terminals, including in the idle mode.

The use of a two-bridge autonomous inverter (current or voltage) with a thyristor-reactor compensation circuit allows you to get the output voltage at the consumer's terminals with the required quality in magnitude and harmonic composition.

4. Discussion

The ideas embodied in the presented power plant can find implementation in the design of autonomous power supply systems for remote consumers, for example, the far north, where the issue of energy supply is quite acute and the efficiency of their use is the most relevant.

5. Conclusion

The paper proves the technical feasibility of constructing multi-module power generation systems on low-boiling coolants in combination with gas turbine power plants, which allows increasing electrical efficiency up to 50%.

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