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## MODELING OF BLOCK OF ELECTRICITY GENERATION OF COGENERATION SYSTEM FOR HEAT GENERATOR

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## МОДЕЛЮВАННЯ ЕЛЕКТРОГЕНЕРУЮЧОГО БЛОКУ КОГЕНЕРАЦІЙНОЇ СИСТЕМИ ТЕПЛОГЕНЕРАТОРА

**Purpose.** Selection and substantiation of the method for maintaining the maximum power of a thermoelectric generator unit to provide its energy-efficient modes of functioning in various modes of operation of the cogeneration system.

**Methodology.** Theoretical studies were based on the theory of thermoelectric conversion law of thermodynamics, heat transfer theory using the methods of mathematical and physical modeling according to the theory of identification and theory of experiment. Designing computer models was implemented according to the simulations methods using Simulink tools. The check of theoretical research on the experimental sample the cogeneration system in a production environment was realized.

**Findings.** Based on the established mathematical relations, an algorithm was designed to maintain the maximum power of the thermoelectric module taking into account the temperature coefficient of its internal resistance changes. A simulation model of a cogeneration unit was designed, which includes, in particular, the heat generator subsystem and power generating unit. It was proved possible to increase the efficiency and the maximum capacity of power generating unit by calculating and setting the input current required for it.

**Originality.** The algorithm for determining the maximum power of thermoelectric generator in cogeneration systems is defined. This can improve their energy efficiency under different temperature conditions.

**Practical value.** Application of the developed models can adequately reproduce the dynamics of the operation of a thermoelectric module of a cogeneration system and to identify the parameters of the system under various load conditions. The proposed algorithm for determining maximum capacity is implemented in the power generating unit control system module. This makes it possible to ensure improved energy efficiency of the cogeneration system.

**Keywords:** *power generating unit, thermoelectric modules, autonomous cogeneration system, heat generator, energy efficiency, modeling*

**Introduction.** Heat is a byproduct of literally any technology. Heating and electricity generation are not exceptions, there is always some amount of heat emitted from the surfaces or exhausted into the air. The very physics of the Carnot Cycle restricts the amount of energy that can be transformed into mechanical (and later to electrical) form by the ratio of temperatures [1]. Roughly from 50 to 70 % of primary energy thus can be just wasted, if only mechanical or electrical energy is considered to be 'useful'.

That is why the so-called co-generation or combined heat and power generation technologies are a far more thrifty way of energy utilization. There are various types of such systems. Those including renewables and the so-called micro cogeneration systems [2] are becoming more and more popular because the advance in these

technologies has made them more efficient and affordable.

The Peltier elements or thermoelectric generators, being known for many years, have recently got their wider application. They may be used for cooling by supplying electricity to them, or, vice versa, consuming thermal energy and generating electricity. Application of cogeneration plants based on the use of renewable sources, including biofuels, is a promising area of small power engineering. This is because the heat and electricity is used directly in the place of their generation, which is cheaper than construction and operation of multikilometer heating mains and power grids.

Autonomous energy sources with combined electricity and heat generation can provide power reserve for centralized utilities [3]. In addition, the reduction of heat emissions into the atmosphere at a larger scale would mitigate environmental problems.

Therefore, the use of heat wastes in the recuperative production process as a source of electrical energy is a viable solution. One of effective ways to solve the above-mentioned problem is the use of thermoelectric generators (TEG) that perform direct conversion of heat into electric power [3].

The power of modern thermoelectric generators (TEG) varies from several watts to tens of kilowatts. Despite low efficiency in this mode, they have obvious advantages. They do not have moving parts, are easy to install and, most importantly, do not require high temperature differences. Due to their high reliability and durability, simplicity of operation, absence of noise TEGs can be used to supply facilities that are distant from power lines as well as when they are the only possible source of electric energy [4].

Power generating modules based on thermoelectric elements can work even at minimum temperature differences, including those on the surfaces of industrial equipment. This is especially important considering that in industry 90 % of the heat energy is emitted from the surfaces at temperatures up to 300 °C [4]. Thus, the use of thermoelectric modules in cogeneration systems as the source of accumulation of electric power from thermal emission of heat generators, including the application of heat obtained from flue gases, is a promising area of power saving [2].

To do that, it is necessary to solve many problems. Among them is the problem of optimal operation of the generation unit. These comprise heat generator, electricity generator and cooling system. The loads or consumers – of both heat and electrical energy, should also be taken into account. All the components are interconnected; their performances affect each other and overall efficiency. Heat transfer, cooling processes and electricity generation are described by non-linear functions; therefore, it is not easy to provide an optimal combination of component parameters [4]. Moreover, under a varying load, a point of optimal operation should be set up and sustained.

Therefore, the research on thermoelectric generators under different operation conditions to determine the energy efficient parameters of system operation is very important. To do that, we first need a complex model of heat and electric power generation module.

**Objective.** Research on the thermoelectric generator module performances via its modeling to determine its energy efficient modes of operation for different modes of cogeneration facility is the objective of this paper.

**Presentation of the main research and methods of.** Solving the task of improving the quality of cogeneration system control should begin with development of the effective systems of smooth adjustment of operating parameters depending on preset values and environmental conditions. Optimal control under these requirements needs identification of the object state and appropriate adaptation of the control system parameters with regard to the requirements concerning stability of parametric and power disturbances.

In order to make an adequate model of the electric

cogeneration system it is necessary to examine the operation of the entire installation.

The technological process of cogeneration, implemented on the basis of solid fuel heat generator is performed according to the following sequence. The process of burning of technological biomass in the cell occurs simultaneously with forcing of air in the heat exchanger by the fan. When the heat generator is at rated power, the power generating unit generates the energy that is used to charge the battery and supplied to the inverter producing voltage for power supply of the fan and to the consumer. On the wall of the smoke bonnet and in the area of installation of the power generation unit the thermal sensors are embedded, which, together with the automatic control system, control the temperature of the cold side, and do not allow the hot side temperatures to exceed 150 °C. The process of adjustment is carried out by changing the throttle position [1].

The studies show that the effective operation of thermoelectric generator requires achieving the maximum allowable temperature difference between the surfaces of the module. The temperature difference on the surfaces of the module installed in the heat generator that works on solid fuel depends on several factors, including the relationship of thermal power characteristics of biofuels and technical parameters of the heat generator [1]. Moreover, the value of the electrical resistance of the load must approach the value of the internal resistance of the generator module in operating conditions [2].

In this regard it is necessary to control the temperature modes of generator module operation ensuring their limits, which is expedient to implement using the method for determination of the hot surface module temperature by its electrical parameters – output voltage and the load current [4].

$$T_1 = T_2 + \frac{U + I \left( R_0 + \alpha_0 \left( \frac{T_1 + T_2}{2} - T_0 \right) \right)}{k}, \quad (1)$$

where  $U$  is output voltage;  $I$  is load current;  $R_0$  is the internal resistance of the module at temperature  $T_0$ ;  $\alpha$  is the temperature coefficient of resistance change;  $T_1$ ,  $T_2$ , are temperature values of hot and cold surfaces of TEG respectively;  $k$  is the Seebeck coefficient.

According to dependence (1) for maximum output power of TEG in the allowable temperature range  $\Delta T$  (50–110 °C), the current consumed by thermocouple should be

$$I = \frac{k\Delta T}{2(R_0 + \alpha(T_c - T_0))}, \quad (2)$$

where  $T_0$  is the temperature of thermoelectric module under normal conditions (20 °C);  $R_0$  is electrical resistance of thermoelectric module under normal conditions (20 °C);  $T_c$  is the average temperatures of the cold and hot side of TEG;  $\alpha(T_c - T_0)$  is the component that takes into account the dependence of resistance on the temperature.

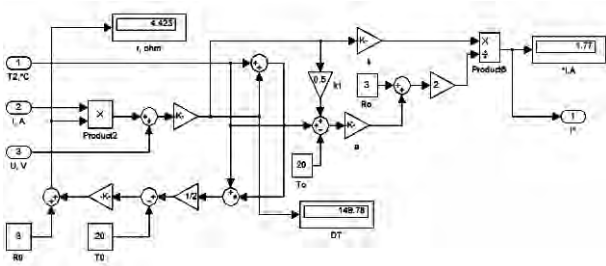


Fig. 1. Imitating model of the algorithm of maintaining the maximum power of TEG taking into account the change of its internal resistance

The indicated relation (2) is the basis for developed calculation algorithm of load current that provides maximum power output based on TEG load characteristics. The algorithm is implemented as a separate module of the control system of battery charger voltage converter (Fig. 1).

The imitating model of cogeneration installation is developed for the estimation of impact of external factors and identification of system parameters at different loading modes in general and for operation analysis of power generating module (Fig. 2).

The model of power generating panel  $28 \times$  TEG Module comprises subsystem of elements taking into account their total mass, heat capacity, space and wall thickness, their thermal conductivity and other physical characteristics. The input parameters of the block in a power generating mode, defined in the settings, are thermal characteristics of the selected number of TEG elements; output parameters are electric ones.

The developed model is universal because it allows the user to form power generating module with any

number of TEG elements taking into account their thermal and electric power parameters.

This model is reversible: electrical characteristics can serve as input parameters while the output will show the thermal performance of the model.

*Teplogenerator* subsystem reproduces operation of solid fuel boilers considering thermal parameters (weight, specific heat, thermal conductivity, heat transfer area, etc.) and its structural elements. The input parameters of the block are (in per units) a required amount of air and biofuel that are designed respectively as *Vent* fan and as *Dozator* screw feeder. Output parameters of the subsystem are thermal power and the temperature of the “hot” side of thermoelements subsystem as well as oxygen concentration in the flue gases, which indicates the efficiency of combustion. Residual heat is taken from the “cold” side of TEG module by *Cooler* subsystem.

The *Control System* control module regulates the operation modes depending on the magnitude of the voltage, output temperature and oxygen concentration: with increasing the voltage, fan speed of *Cooler* cooling system decreases, and, therefore, the temperature difference between “cold” and “hot” TEG surfaces decreases.

The input of the *DC-AC* subsystem inverter is fed by the voltage from the battery, which is initially used for the start of the installation, and then charged by generated power.

The input of *DC-DC* converter subsystem, which is used to charge the battery, is supplied by voltages of the thermoelectric elements subsystem. This process occurs automatically, and the output current of thermoelectric module is maintained at efficient level dur-

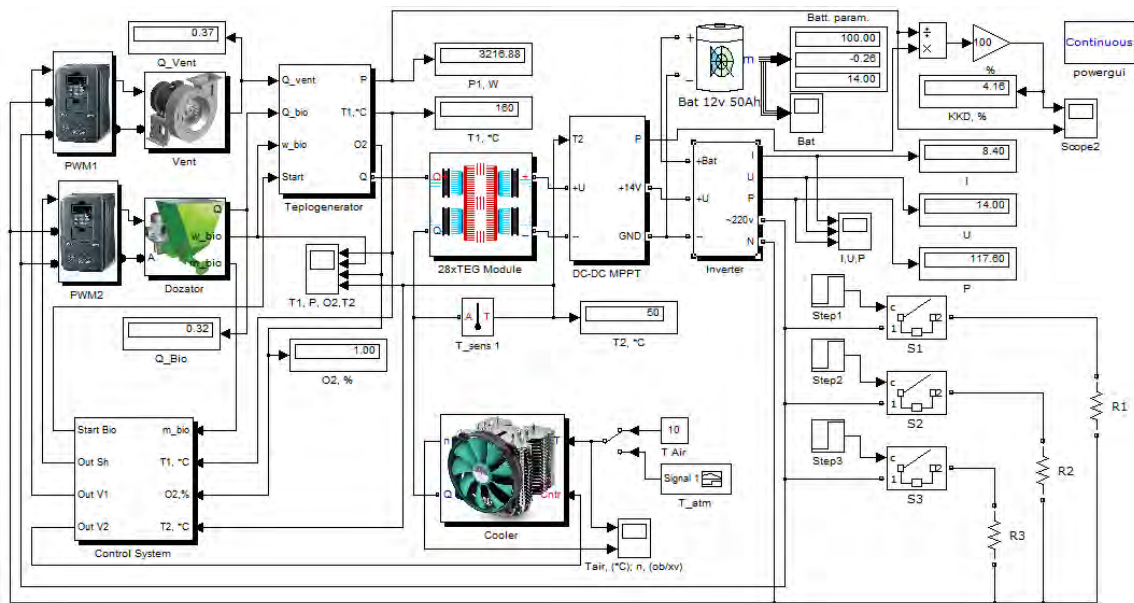


Fig. 2. The structure of the imitating model of a cogeneration facility:

- 1 – power generating block ( $28 \times$  TEG Module);
- 2 – heat generator (*Teplogenerator*);
- 3 – cooling subsystem with a fan (*Cooler*);
- 4 – subsystems of the feeder and of the fan for ensuring the combustion process (*Dozator*, *Vent*);
- 5 – frequency converters (*PWM1*, *PWM2*);
- 6 – control subsystem (*Control System*);
- inverter (*Inverter*);
- 7 – power battery (*Bat*);
- measurement devices of input and output parameters (*Scope*, *Display*);
- 8 – load elements with switching devices (*R1*, *R2*, *R3*, *S1*, *S2*, *S3*)

ing the battery charging. Comparison of simulation results suggests the feasibility of the algorithm developed, which will help to increase the output power by 25–50 %, depending on the lower end of input voltage range.

Fig. 3, *a* and Fig. 3, *b* show the results of imitation modeling of functioning of the power generating module with the enabled and disabled algorithm of maximum power adjusting. Transients of the voltage, current and power consumption for battery charging interval 10–100 % indicate that application of the algorithm allows maintaining the energy efficiency at the maximal level.

The electric circuit connection diagram of the voltage converter module with developed algorithm of maximum power adjusting is shown in Fig. 4. Conversion scheme is implemented by standard schematics using DC-DC controller with appropriate algorithms and performs functions of raising or lowering the voltage depending on the value of the input voltage that comes from TEG.

Based on the experimental results, imitation simulation results (Fig. 5), and developed functional diagram of the cogeneration power generating module of experimental setup, the physical model of the module of electric power accumulation and voltage conversion is implemented.

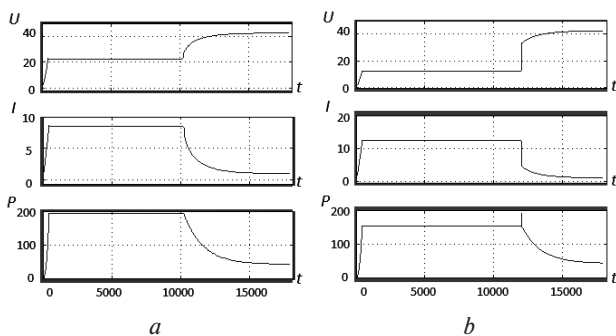


Fig. 3. Transients of power parameters of the output of TEG (*U*, *I*, *R*) with enabled (*a*) and disabled (*b*) algorithm of maximum power regulation

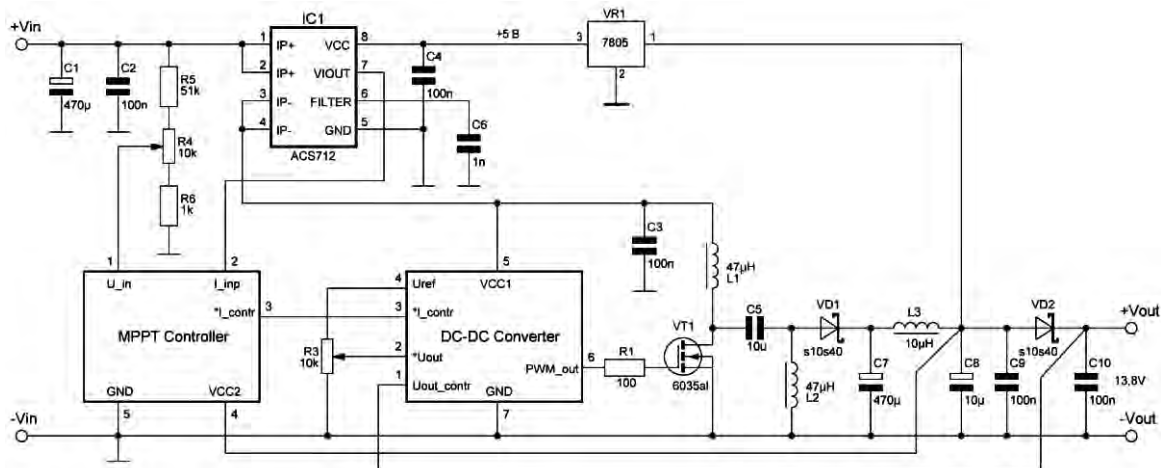


Fig. 4. The electrical circuit of the voltage converter module with developed algorithm of maximum power adjusting

The examined model with the power generating module provided the following results during the tests: TEG output voltage in idling is 45 V, in load conditions (with voltage converter): input is 22.5 V, output is less than 14 V (at full battery charge).

The cogeneration installation (Fig. 6) was made using a 20 kW heat generator with a block of 28 TEG elements, inverter and control module with the embedded developed algorithm of maximum power regulation.

The installation passed production tests at the regional enterprise “Ukrainian Technological Systems” (the City of Ternopil); maximum electric power obtained is 200 watts.

In the future, the development of adaptive control system is planned that operates on the basis of the developed algorithm for cogeneration facilities based on heat generators of various capacities with the automated fuel supply.

**Conclusions.**

1. On the basis of the established regularities, the algorithm of maintaining the maximum power of the thermoelectric generator considering the temperature change coefficient of its internal resistance is developed. The implementation of the algorithm allows providing an increase in output power of TEG by 25–50 %, depending on the lower limit of the operating range of converter input voltage.

2. The imitation model of a cogeneration installation is developed that includes, in particular, heat generator and power generating block subsystems, that allows examining operation of the system under different loads.

3. According to the results of mathematical and physical modeling it is determined that the load voltage of TEG is equal to voltage drop on its internal resistance and is invariable over time for interval of 10–100 % battery charging that indicates the efficiency of the proposed algorithm.

4. Experimental tests of the developed autonomous cogeneration system based on a 20 kW bio-thermal generator are performed. Installation produced maximum electric power output of 200 watts.

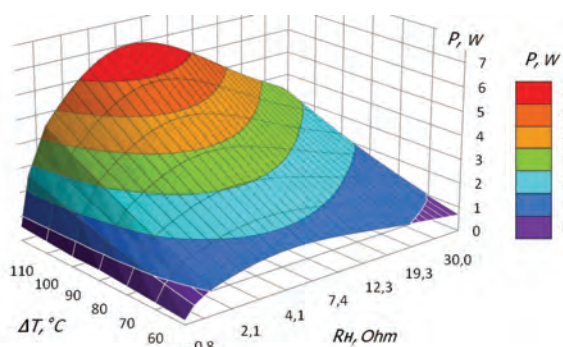


Fig. 5. Dependence of output power of a single TEG element on the temperature difference between its surfaces and from load impedance



Fig. 6. Cogeneration installation that is based on a 20 kW heat generator with TEG block and modules of electric energy conversion and accumulation

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**Мета.** Вибір та обґрунтування методу підтримання максимальної потужності термоелектричного генераторного блоку для забезпечення його енергоефективних режимів функціонування при різних режимах роботи когенераційної установки.

**Методика.** Теоретичні дослідження базувалися на теорії термоелектричного перетворення, законах термодинаміки, теорії теплопередачі з використанням методів математичного й фізичного моделювання згідно з теорією ідентифікації та теорією експерименту. Конструювання комп'ютерних моделей реалізовано за допомогою імітаційного моделювання з використанням інструментарію Simulink. Проведена перевірка теоретичних досліджень на експериментальному зразку когенераційної системи у виробничих умовах.

**Результати.** Керуючись встановленими математичними залежностями, був розроблений алгоритм підтримання максимальної потужності термоелектричного модуля з урахуванням температурного коефіцієнта зміни його внутрішнього опору. Розроблена імітаційна модель когенераційної установки, до складу якої входять, зокрема, підсистеми теплогенератора та електрогенеруючого блоку. Доведена можливість підвищення коефіцієнта корисної дії та максимального значення потужності електрогенеруючого модуля шляхом розрахунку й задання необхідного для нього вхідного струму.

**Наукова новизна.** Встановлені закономірності, на основі яких визначено алгоритм відбору максимальної потужності термоелектричного генератора в когенераційних системах, що дає змогу підвищити їх енергоефективність при різних температурних режимах.

**Практична значимість.** Застосування розроблених моделей дозволяє адекватно відтворювати динаміку роботи термоелектричного модуля у складі когенераційної системи теплогенератора та ідентифікувати параметри системи при різних режимах навантаження. Запропонований алгоритм відбору максимальної потужності імплементовано в модуль системи керування електрогенеруючим блоком. Це дозволило забезпечити підвищення енергоефективності когенераційної системи.

**Ключові слова:** електрогенеруючий блок, термоелектричні модулі, автономні когенераційні системи, біотеплогенератор, енергоефективність, моделювання

**Цель.** Выбор и обоснование метода поддержания максимальной мощности термоэлектрического генераторного блока для обеспечения его энергоэффективных режимов функционирования при различных режимах работы когенерационной установки.

**Методика.** Теоретические исследования базировались на теории термоэлектрического преобразования, законах термодинамики и теории теплопередачи с использованием методов физического и математического моделирования согласно теории идентификации и теории эксперимента. Конструирование компьютерных моделей реализовано с помощью имитационного моделирования с использованием инструментария Simulink. Проведена проверка теоретических исследований на экспериментальном образце когенерационной системы в производственных условиях.

**Результаты.** Руководствуясь установленными математическими зависимостями, был разработан алгоритм поддержания максимальной мощности термоэлектрического модуля с учетом температурного коэффициента изменения его внутреннего сопротивления. Разработана имитационная модель когенерационной установки, в состав которой входят, в частности, подсистемы теплогенератора и электрогенерирующего блока. Доказана возможность повышения коэффициента полезного действия и максимального значения мощности электрогенерирующего модуля путем расчета и задания необходимого для него входного тока.

**Научная новизна.** Установлены закономерности, на основе которых определен алгоритм отбора максимальной мощности термоэлектрического генератора в когенерационных системах, что позволяет повысить их энергоэффективность при различных температурных режимах.

**Практическая значимость.** Применение разработанных моделей позволяет адекватно воспроизводить динамику работы термоэлектрического модуля в составе когенерационной системы теплогенератора и идентифицировать параметры системы при различных режимах нагрузки. Предложенный алгоритм отбора максимальной мощности имплементирован в модуль системы управления электрогенерирующих блоком. Это позволило обеспечить повышение энергоэффективности когенерационной системы.

**Ключевые слова:** *электрогенерирующий блок, термоэлектрические модули, автономные когенерационные системы, теплогенератор, энергоэффективность, моделирование*

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