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# The Use of SOFC-based Mini-CHP for Remote Consumers Power Supply

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**Abstract**

The article deals with the problem how to supply remote consumer's offline by employing SOFC-based mini-CHPs, which run on biogas. The paper determines the most promising types of mini-CHPs and fuel cells. It also provides the method of selection SOFC-based mini-CHPs, which can be further used to power supply low-capacity agricultural enterprises. Issues concerning the integration of SOFC-based mini-CHPs into agricultural enterprises power supply system are also considered here. The authors have developed the algorithm and Simulink-model of SOFC-based mini-CHP power supply system (PSS) which makes it possible to investigate PSS energy characteristics.

**Keywords:** SOFC-based mini-CHP, power supply system, remote consumer, biogas, agricultural enterprise of dairy farming, Simulink model

## INTRODUCTION

Stable performance of electricity consumers is achieved through reliable and uninterrupted power supply. Supplying Russian remote consumers with electric power of desired quality has become an up-to-date challenge.

The effective solution to this problem can be the wide use of offline renewable energy sources [1,2] which include biogas-based power plants.

Mini-CHP is a power plant capable of efficiently converting products of biowaste fermentation into electricity and heat. The most promising power plants are mini-CHPs on fuel cells (FCs), which directly convert biogas into electricity. Having no fuel combustion makes them environmentally friendly.

According to research [3], the efficiency of cogeneration power plant is determined by the efficiency of the primary engine and heat utilization system as well as fuel utilization factor. Table 1 shows comparative characteristics of efficiency of different types of cogeneration power plants [4]. FC-based mini-CHPs boast the best efficiency.

**Table 1**: The efficiency of cogeneration power plants

| Characteristics of power plants efficiency | Gas-turbine-based mini-CHPs | Gas-piston-based mini-CHPs | FC-based mini-CHPs |
|---|---|---|---|
| Electrical efficiency of primary engine, % | 25-35 | 40-45 | 50-55 |
| The fuel utilization factor, % | up to 90 | 70-92 | up to 95 |
| Specific consumption of equivalent fuel for electricity generation without heat recovery, g.t./kWh | 300-615 | 360-610 | 210-340 |

Solid oxide fuel cells (SOFCs) attract the greatest attention of researchers and developers around the world. SOFCs have the highest efficiency, low cost of ceramic materials and can use conventional hydrocarbon fuel [5,6].

In the article the problem of power supply of energy remote consumers is considered and the solution of using SOFC-based mini-CHP is proposed. Swiss company «Hesis» actively conducts R&D of SOFC-based mini-CHP [7].

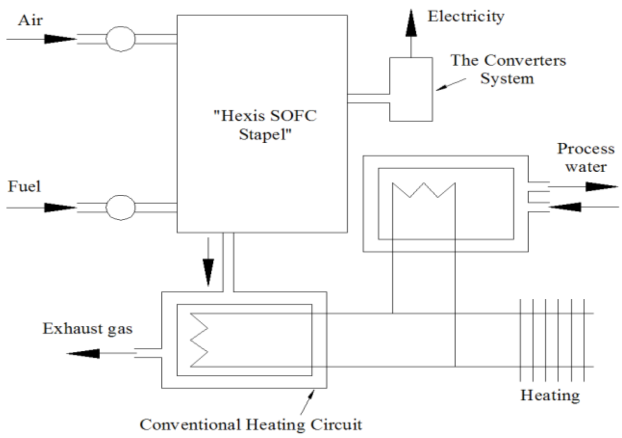


**Figure 1**: Schematic diagram of «Hesis» SOFC-based mini-CHP

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Despite the advantages of SOFC-based mini-CHP, they aren't used in electrical power supply systems of consumers. Application of such power plants is restricted by their low maneuverability, lack of engineering solutions for consumers integration into power supply system, lack of SOFC-based mini-CHPs regulatory design documents, and by a range of other problems [8,9].

Scientific and technical solutions proposed by the authors address the issues related to SOFC-based mini-CHP running/working on biogas. The solutions are considered by the example of electricity supply agricultural enterprise of dairy farming.

## THE METHOD OF SELECTION SOFC-BASED MINI-CHPS

The authors have developed the method of SOFC-based mini-CHP choosing for small factories, which have ability to generate biogas, rated up to 1MW and their nominal voltage is 380V. The algorithm of power rate choosing for mini-CHP on SOFC is consists of four stages.

On the first stage, calculated electrical load of a factory is determined. It should be mentioned, that calculated electrical load is a basis of electrical power rate selection on mini-CHP. For designed factories the calculated electrical load is determined by well-known analitic methods [10]. While modernization of PSS – by factory's load curves.

The second stage calculates the daily volume of biomethane production ($V_M$) and theoretically possible mini-CHP power ($P_{CHP.TH}$). The input data includes cattle number ($N_C$) and the mass of biowaste from every animal ($M_i$). The calculation is done according to [11]:

$$V_M = N_C \cdot M_i \cdot K_{IM} \cdot K_{U.} \cdot N_B \left(1 - \frac{V}{100}\right) \cdot \left(\frac{R_O \cdot F \cdot \mathrm{G}}{100}\right), \quad (1)$$

where $K_{IM}$ – factor taking into account the impurities in the biomass; $K_U$ – biomass utilization factor; $N_B$ – the specific yield of biogas per 1 kg dry matter, m$^3$; $V$ – moisture of biomass, %; $R_O$ – the organic matter content in dry biomass, %; $F$ – the extent of biomass fermentation, %; $\mathrm{G}$ – the methane content in the biogas, % [12].

The third stage calculates SOFC-based mini CHP own electrical needs ($P_{OWN.E}$).

The fourth stage determines the appropriate power of SOFC-based mini-CHP considering electrical losses in power supply system components ($\Delta P$).

The nominal electric power of mini-CHP ($P_{CHP.E}$):

$$P_{CHP.E} \geq P_{O.C} = P_C + P_{OWN.E} + \Delta P, \quad (2)$$

where $P_{O.C}$ – overall calculated power of agricultural enterprise, kW; $P_C$ – calculated power of agricultural enterprise, kW.

This should satisfy the condition (3):

$$P_{CHP.E} \leq P_{CHP.TH} = \frac{V_M}{F_f}, \quad (3)$$

where $P_{CHP.TH}$ – theoretically possible electrical power of mini-CHP which depends on biomethane daily production volume and specific SOFC-based power plant fuel consumption ($F_f$).

Thermal power of mini-CHP ($P_{CHP.T}$) is determined on $P_{CHP.E}$ which is provided by SOFC-based power plant producer.

The developed methodology was used to select the SOFC-based mini-CHP to power supply existing agricultural enterprise of dairy farming. Overall power of agricultural enterprise is kW, cattle number is 550 animals. The enterprise can daily generate 906 biomethane which enables the continuous use of mini with its nominal electric power 140 kW within a year.

## THE SOFC-BASED MINI-CHP INTEGRATION INTO AGRICULTURAL ENTERPRISES POWER SUPPLY SYSTEM.

The power supply system, which employs SOFC-based mini-CHP, is made up of four subsystems:

1. Main generation (SOFC-based mini-CHP);
2. Energy accumulation;
3. Energy conversion and distribution;
4. Back-up generation.

The accumulation system, which operates on stationary batteries, solves the problem of SOFC-based mini-CHP low maneuverability by providing enough power for peak consumptions in daytime as well as to charge batteries at night. Fig.2 shows the daily load schedule of the agricultural enterprise with the highest daytime peaks (typical winter day). The low dotted line shows the level of mini-CHP power. When the mini-CHP has the minimal load (min1, min2 и min3), the power is used to charge batteries. At maximum loads (max1, max2) the battery spends accumulated energy, when it runs flats, it activates the alternative back-up power source, i.e. gas-powered generator.

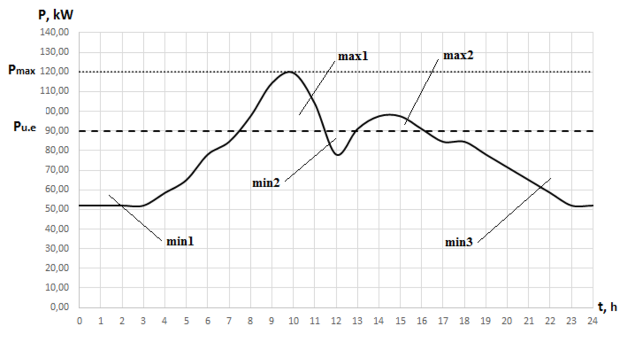


**Figure 2**: The agricultural enterprises daily load schedule of SOFC-based mini-CHPs power supply system

The integration of mini-CHP and accumulation system into the enterprise power supply system is done with conversion subsystem on DC/AC invertors (Fig. 3).

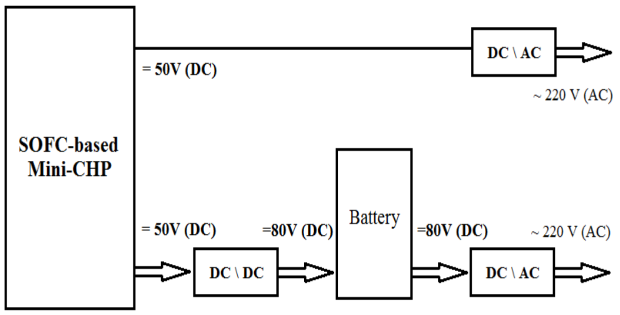


**Figure 3**: Block diagram of conversion subsystem

The subsystem of back-up generation is designed to be used when two key conditions occur at the same time: when consumed power exceeds generated power from mini-CHP and when the battery goes totally flat. Gas-powered generator 10 kW power «ФАС-10-1\ВП» is used as source of energy [13].

Single-line diagram of SOFC-based mini-CHP power supply system of remote agricultural enterprise is shown in Fig. 4.

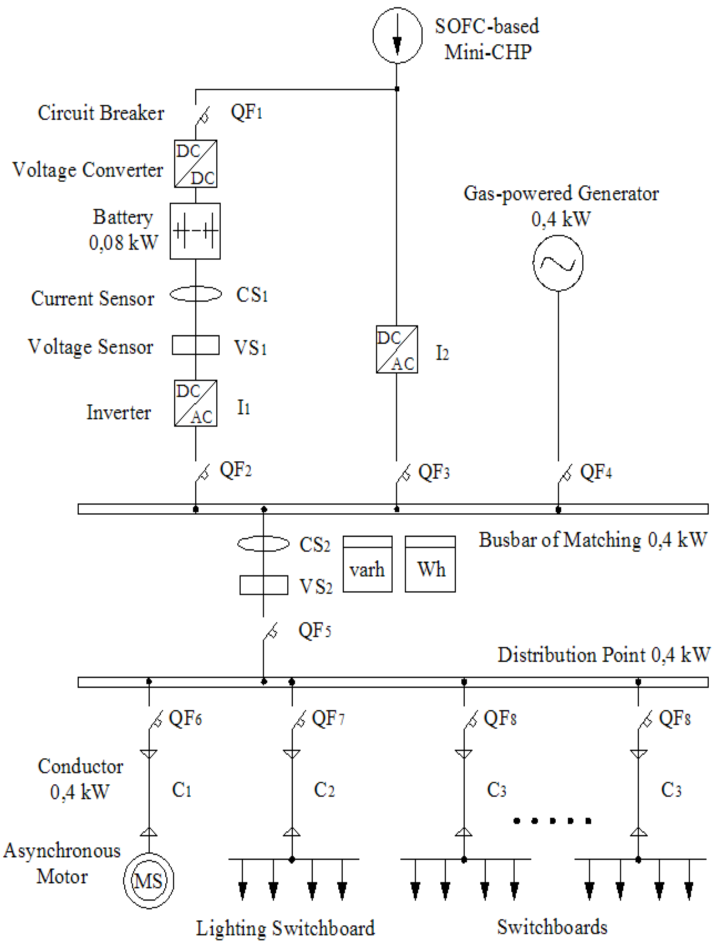


**Figure 4**: Single-line diagram of SOFC-based mini-CHP power supply system of remote agricultural enterprise

## COMPUTER MODELLING OF SOFC-BASED MINI-CHP

The authors have developed the algorithm to understand how components of the power supply system interact with each other, which results in avoiding shortage of electric energy and exceeding generation over consumption. The block diagram of the algorithm is shown in Fig. 5.

The input parameters of mini-CHP include electrical and thermal power. The mini-CHP can be started only when there is energy consumption from the agricultural enterprise.

When the overall electric load from agricultural enterprise ($P_{AE.E}$) is lower than the mini-CHP generated useful power ($P_{U.E}$), by which we mean the difference between power plant nominal power ($P_{CHP.E}$) and electric power which power plant uses to keep it running ($P_{OWN.E}$), the condition of back-up power source is monitored with its further switch-off.

In this case batteries start recharging. When they are full (actual capacity of the battery equals nominal capacity), electric power from mini-CHP is supplied to emergency discharge device (which can be a water boiler of the simplest design).

The authors have developed a Simulink model for agricultural enterprises power supply system based on this algorithm to ensure its smooth operation.

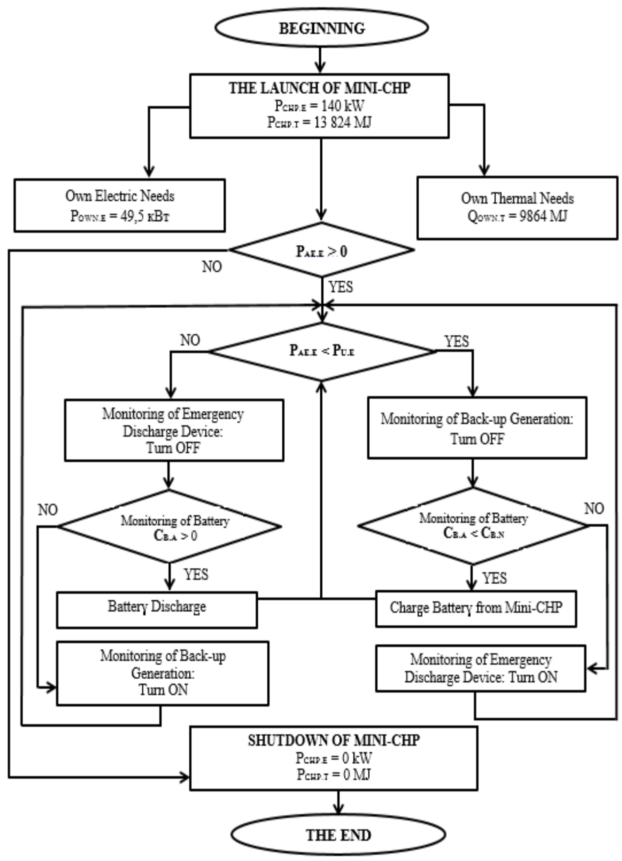


**Figure 5**: The block diagram of the algorithm

## RESULTS

At the core of this model lie both Simulink ready-to-use and programmable Matlab components. Fig. 6 shows the primary Simulink model when four subsystems function in accord with each other. This model can imitate a number of theoretical changes (oscillograms of currents and voltages together with their valid values) for two operational modes agricultural enterprises power supply system:

Mode 1: generation power ($P_{G.1}$) equals mini-CHP nominal power;

Mode 2: generation power ($P_{G.2}$) equals both mini-CHP nominal power and accumulation system, which is switched on during peak consumption periods.

It is worth mentioning here that the primary model needs to be polished by further researching its potential to tailor it for real life conditions.

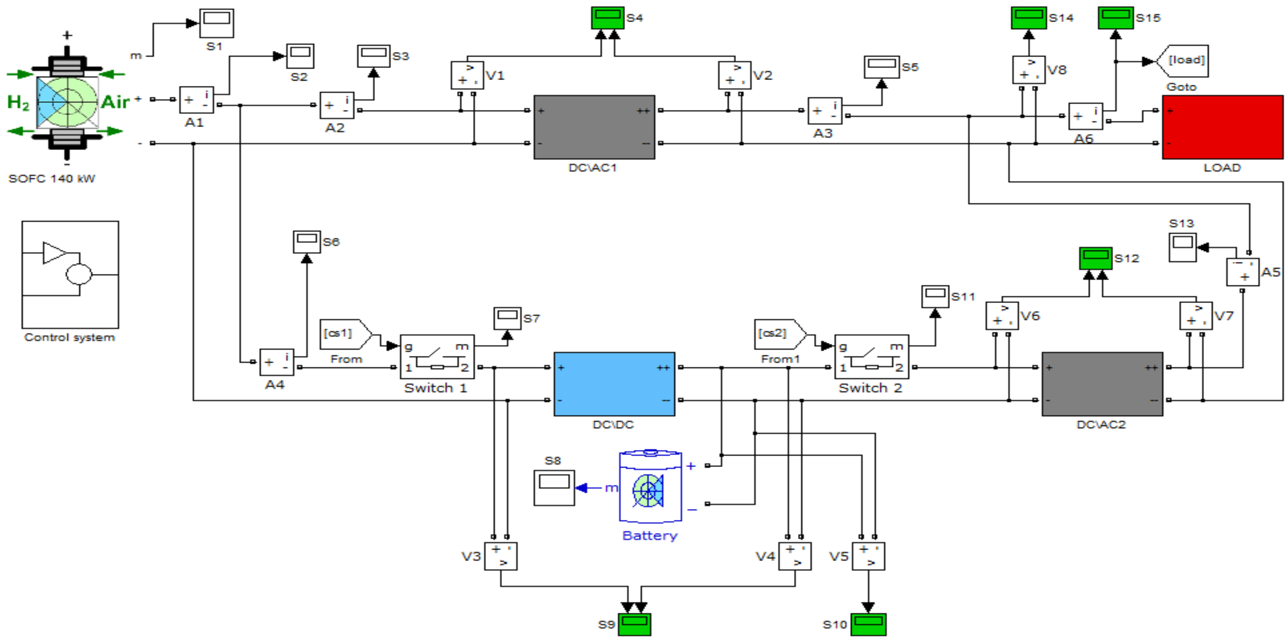


**Figure 6**: Primary Simulink model for agricultural enterprises power supply system based mini-CHP

The results of primary testing mini-CHP are represented in Figures 7-10.

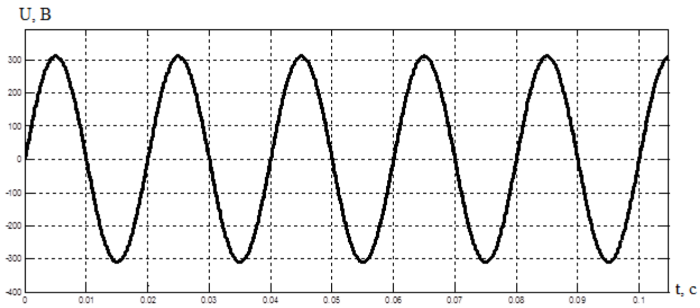


**Figure 7**: The oscillogram of voltage at the terminals of the load in «mode 1»

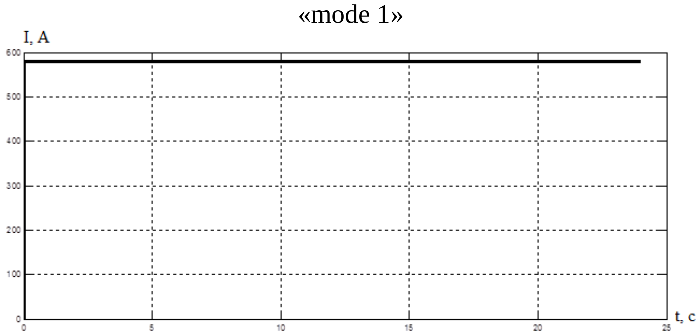


**Figure 8**: The valid value of the load current in the «mode 1»

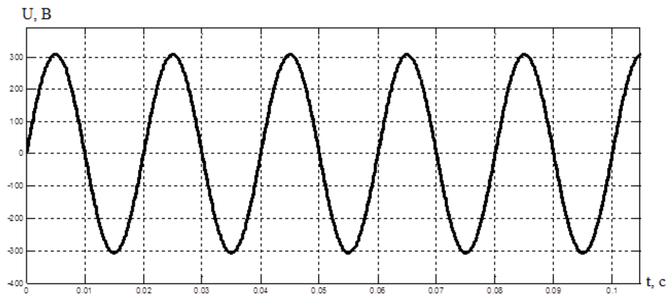


**Figure 9**: The oscillogram of voltage at the terminals of the load in «mode 2»

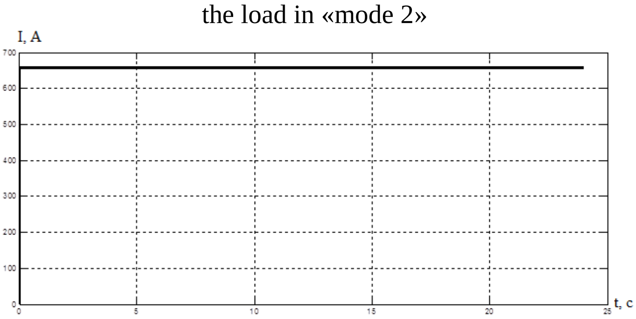


**Figure 10**: The valid value of the load current in the «mode 2»

The valid voltage value at consumer insignificantly decreases (within 1 per cent) while generation power increases, which does not contradict Russian standard on energy quality [14]. With that, the valid voltage value increases by 4.1 % while load and generation power go up too.

## DISCUSSION

The authors have obtained the following results:

1. They have developed a method to select appropriate power in SOFC-based mini-CHP.

SOFC-based mini-CHP can be referred to promising power sources, although there are no confirmed methods to select such power plants. The suggested method based on generating electric energy from biogas is capable of solving this problem.

2. The authors have also developed solutions how to integrate SOFC-based mini-CHP into agricultural enterprises power supply system.

The power supply system, which employs SOFC-based mini-CHP, is made up of four subsystems: main and back-up generation, conversion and accumulation. The accumulation and conversion subsystems solves the problems of SOFC-based mini-CHP low maneuverability and the integration such power plant into power supply system. The back-up generation subsystem provides the enterprise in the critical case, when consumed power exceeds generated power from mini-CHP and when the battery goes totally discharged.

3. The authors have also developed the algorithm and Simulink-model for agricultural enterprises power supply system based on SOFC-based mini-CHP.

The developed model allows obtaining electrical characteristics (oscillograms of current and voltage) at the source of power and terminals of the load, based on which can conclude that generation system and the consumptions are operating harmonized.

The paper describes the primary model, which does not allow researchers to do in-depth analyses. The authors hope to continue their research into the model to tailor it for real-life conditions of its performance.

## CONCLUSION

SOFC-based mini-CHP can be used to supply energy to low-power remote consumers (up to 1MW) which have facilities to produce biogas, which can then be converted to generate heat and electrical energy.

The achieved results can solve a number of problems, which can occur both at design and modernization stages of agricultural enterprises power supply system: the selection of SOFC-based mini-CHP appropriate power, SOFC low maneuverability, and the integration of SOFC-based mini-CHP into power supply system.

## ACKNOWLEDGEMENT

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