MODELLING AND CONTROL OF AN AUTONOMOUS ENERGETIC SYSTEM OBTAINED THROUGH TRIGENERATION

BY

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Abstract. The autonomous energetic system is for a residential building and it has as primary sources exclusively renewable resources (biomass and solar energy). For obtaining electrical energy, photovoltaic sources and a Stirling engine are used. They operate simultaneously in 1:3 ratio – electrical/thermal energy. Solar collectors and a pellet boiler are used to cover the necessary of thermal energy. The air conditioning in the summer regime is obtained using an adsorption plant. The energetic deficit is critic in the electrical subsystem where the load control is done through the adjusting of the Stirling engine power. The thermal power of this engine is a disturbance variable at the level of the thermal subsystem. The paper deals with the developing of a mathematical model of the whole system. The paper also proposes a control solution for the load regulation in the electrical and thermal subsystems and it presents the results obtained through numerical simulation.

Key words: Stirling engine, mathematical modeling, numerical simulation.

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1. Introduction

Worldwide, the importance of renewable energy sources is that, till 2020, the total consumption of such energy should reach 24% of total consumption. In this context, Romania has proposed to meet the two targets: the first refers to 2010, when 33% of the rough electrical energy consumption be

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covered from renewable resources and the second refers to 2020, when 24% of total energy consumption be covered from renewable resources, accordingly to the world trend.

From a technical point of view, research into the production of energy from unconventional sources follows several directions: photovoltaic systems, thermo-solar systems, biogas, hydrogen, wind systems etc. These types of energies represent a viable alternative to the situation when oil deposits will be exhausted and, moreover, the energy is produced by clean processes, protecting in this way, the environment.

A very important application of using energy supplied produced from renewable resources is the so-called green house. Generally, CHP (cooling, heating and power) systems are used. They provide the necessary electricity and heat, thus ensuring the energy independence from centralized energy systems. The CHP systems require electricity and heat supplying systems with several sources, which implies an optimal real time operating strategy in terms of the cost of the supplied energy [3]. In the mentioned paper a dynamic simulator (TRNSYS) is presented. Using TRNSYS a micro-CHP system was simulated, proving that it can be a viable and economical option for powering a green house. The same simulations have shown the necessity that this system must operate under optimal conditions to ensure an energetic efficiency to the entire green house system.

In [2] a heating system installed at the Centre for Renewable Energy Sources, located in Central Greece, aiming to ensure the heating requirements for a specific block office of 60 m² area is presented. The system was analyzed over a period of six months and it resulted that the contribution of solar energy during this period covers 53% of the heat necessary of the building.

Cogeneration systems (thermal and electrical energy) provide heating and electrical power in a more efficient way than the separate production. In the paper [4] a m-CHP unit based on a Stirling engine fueled with pellets that provide both electricity and heat has been analyzed. The performances and the dynamic behavior of the Stirling engine powered with pellets were analyzed by a test bench. Based on this analysis, a model of the heating system that includes a thermal accumulator was achieved. The study was completed by a numerical simulation analysis of the sensitivities in order to quantify the influence of the key parameters on the annual average performances of the system in a residential building.

This paper aims to analyze an autonomous power system using renewable energy for a residential building located in the campus of “Dunărea de Jos” University of Galați. The system is designed to meet the thermal energy needs (heat in winter, cold in summer and domestic hot water) and electricity needs, with the two components: the operating of the household equipments and the own consumption of the supplying system with thermal and electrical energy.
The paper structure is as follows: in the second section the technological structure of the autonomous energetic system is presented; the third section shows the mathematical model, the fourth section presents the control system; the results obtained through numerical simulation are shown in the fifth section and the last section is dedicated to the conclusions.

2. The Structure of the Autonomous Supplying System

Fig. 1 presents the structure of the autonomous supplying system with electrical and thermal energy.

![Fig. 1 – The structure of the autonomous supplying system.](image)

It consists of two subsystems: electrical energy supplying subsystem and the one with thermal energy. For power supply two sources are provided, i.e.: a Stirling engine – m.CHP (it also provides thermal energy in an 1:3 ratio - electrical/thermal) and photovoltaic systems. The electrical energy provided by the Stirling engine and the photovoltaic systems is stored in a battery of 48V/ 800Ah. It aims to provide the necessary electricity in the peak loads.

Considering the thermal energy, outside the Stirling engine, which delivers a maximum power of 10 kW, there are two energy sources more: a pellet boiler that provides maximum 30 kW and a solar collector system that can deliver a maximum 10 kW thermal power. The thermal energy produced by the three sources is stored in a thermal accumulator (th. storage), in which the temperature of the thermal agent varies between 70 – 80ºC. The heating system is supplied from this accumulator in the winter with thermal agent, the domestic hot water and the thermal source for the cooling system in the summer are also provided. It can be mentioned that the cooling is done using an adsorption system that needs a thermal energy of 30 kW.
3. The Mathematical Model of the Autonomous Supplying System

Fig. 2 presents the overall structure of the whole system.

Electrical subsystem. The main equation of the electrical subsystem is the one that describes the dynamic accumulation in the electro-chemical source. It can be written as follows:

\[
\frac{dW_B}{dt} = P_{Se}(t) + P_{PV}(t) - P_{al}(t) - P_{St}(t)
\]

where: \( W_B \) is the energy accumulated in battery, [J], \( P_{Se} \) and \( P_{PV} \) – the powers produced by the Stirling engine and PV [W] (photovoltaic source) respectively,
$P_{ul}$ and $P_{uj}$ – the powers corresponding to the useful load and internal consumption from the energetic system respectively (the pump engines etc.), [W]. The battery model links the voltage $V$ to the accumulated energy at the current moment.

A simplified model for the battery has been adopted:

$$V = V_m + \frac{V_M - V_m}{W_{BM} - W_{Bm}}(V - V_m)$$

where: $V_M$ and $V_m$ are the voltage values at maximum energy, $W_{BM}$ and minimum energy, $W_{Bm}$, respectively, accumulated in battery, [J]. A battery with the nominal voltage of 48 V has been chosen. In eq. (2) the following limits of the voltage were considered: $V_M = 49.5$ V and $V_m = 47$ V. Admitting a battery capacity of 800 Ah, it results $W_{BM} = 138.24$ MJ. The minimum value of the accumulated energy, to which the battery is considered practically discharged is $W_{Bm} = 17.28$ MJ.

The variable $V(t)$ is regulated through the control of the electrical power delivered by the Stirling engine. Depending on the reference $V^{sp}$ and the current value $V$ of the voltage, the battery is controlled in charging or discharging regime and the power variables $P_{Bi}$ and $P_{Bo}$, from these regimes, contribute to the balance of the produced power with the one required by load. The Stirling engine was modelled as a dynamic first order system, with a time constant of 60 sec.

![Graph](image_url)

Fig. 3 – Daily variation of the power variable $P_{PV}(t)$: in summer regime (solid line) and in winter regime (dash line).

The power produced by PV source has been determined based on the equations:
\( I = \int_{\lambda_1}^{\lambda_2} I_{\lambda} d\lambda \)

\( R = A \int_{0}^{T} I dt \)

where: \( I \) is the irradiance, \( I_{\lambda} \) - spectral irradiance, considered in the wavelength spectrum of interest, \( [\lambda_1, \lambda_2] \), \( R \) - radiation (measure of the optical power), \( A \) - surface receiving the light radiation (\( A = 12 \text{ m}^2 \)), \( [0, T] \) - the considered time interval (24 h). Using the usual data from literature, [1], and power conversion efficiency (the ratio between the maximum electrical power and the optical one), \( \eta = 0.1 \), the daily variations of the solar source power in summer and winter regimes were determined (Fig. 3). The daily evolution of the power \( P_{\text{sl}}(t) \) has been adopted as a plausible default graphic of the useful load. Instead, the evolution of the power \( P_{\text{sl}}(t) \), representing the internal consumption of the plant is random. It is determined by the vector \( \text{up}(t) \), whose components are discrete controls (0/1) given to the 15 motors of the plant (almost all belonging to the thermal subsystem).

**Thermal subsystem.** The mathematical model of the thermal subsystem has as a core the thermal balances at the level of the thermal accumulator and of the building. The thermal balance equation for the thermal accumulator is the following:

\[
\frac{dm_{w}c_{w}}{dt} = P_{\text{St}}(t) + P_{\text{PT}}(t) + P_{\text{ph}}(t) - P_{\text{hl}}(t) - P_{\text{acl}}(t) - P_{\text{dhw}}(t)
\]

where: \( m_{w} \), \( c_{w} \) represent the mass and the specific heat of the water accumulated in the thermal accumulator, \( T \) - the water temperature in the thermal accumulator, \( P_{\text{St}} \) - the Stirling engine thermal power, \( P_{\text{PT}} \) - the solar collector power, \( P_{\text{ph}} \) - the power provided by the pellet boiler, \( P_{\text{hl}} \) - the power consumed in the building to cover losses through transmission and ventilation, \( P_{\text{acl}} \) - the power consumed by the air conditioning plant, \( P_{\text{dhw}} \) - the power consumed by the domestic hot water circuit. The equilibrium between the thermal power, provided by the sources (Stirling engine and pellet boiler), and the power consumed for building heating/conditioning and for the domestic water is achieved through the water temperature control in the thermal accumulator to a setpoint, \( T^0 \). Whereas the thermal power of the Stirling engine is a random variable, resulted from the balance control of the load within the electrical subsystem, the temperature control is done by adjusting the power of the pellet...
boiler. This boiler was modelled as a dynamic first order system with a time constant of 100 sec. The second thermal balance equation is the following:

\[ m_a c_a \frac{dT_a}{dt} = k_c (T - T_a) - P_v(T_a, t_e, \xi) \]

where: \( T_a \) is the temperature in the building; \( m_a, c_a \) - mass and specific heat of the air in the building; \( k_c \) - convection transfer coefficient and \( P_v \) - power consumed in the house to cover losses through transmission and ventilation. The function \( P_v(T_a, t_e, \xi) \) depends on the outside temperature, \( t_e \), and other variables that define the thermal regime of the building, \( \xi \). This function is calculated on the basis of the thermal balance of the building. The model of the thermal balance includes the relationships detailed for the calculus of the thermal flux components in heating regime (in winter) and in air conditioning using an adsorption plant (in summer). Within this balance the following values were considered: \( t_e = -17^\circ C \) and \( T_a = 20^\circ C \), in winter regime, and \( t_e = 38^\circ C \) and \( T_a = 22^\circ C \) – in summer regime. Besides the thermal load corresponding to the heating/house conditioning, a significant contribution is given by the power variable \( P_{dhw}(t) \) that is consumed in the domestic water circuit. The daily evolution of this variable has been adopted through a plausible graphic, presented in Fig. 4.

The power produced by the solar collector is calculated by the relation:

\[ P_{rT} = A[I_0 \eta_0 - k_c (T_i - T_a)] \]

where: \( I_0 \) is the total solar irradiance, \([W/m^2]\), \( \eta_0 \) - the optical efficiency of the collector \( (\eta_0 = 0.9) \), \( T_i \) and \( T_a \) are the input temperature of the water in collector and the outside air temperature (variable during the day) respectively, \( A \) – the collector surface. On the basis of the daily evolutions of the solar irradiance and outside temperature, for the month of June, the daily variation of the solar collector power is illustrated in Fig. 5.

![Fig. 4 - Daily variation of the power variable P_{dhw}(t).](image-url)
Overall, the entire energetic autonomous plant is treated as a dynamic system having the following state vector:

\[
x = [W_B \ P_{St} \ T \ T_a \ P_{ph}]^T
\]

in which the first two components correspond to the electrical subsystem and the other – to the thermal subsystem. The two subsystems are strongly interconnected through the variables: \( P_{a}(t) \), (being in a 3:1 ratio with \( P_{w}(t) \)), through the vector \( u(t) \), that influences the power \( P_{a}(t) \) respectively.

4. Control of the Autonomous Energetic System

Even the structure of the controlled system suggests the use of a multivariable controller, in this stage a simple solution as a decoupled loop has been adopted (Fig. 6). The thermal process controller, \( R_T \), adjusts the power variable \( P_{ph}(t) \), and the battery voltage control is done by the adjusting of power variable \( P_{w}(t) \), using the controller \( R_v \) and the anticipation controller \( R_A \). The last mentioned controller gives a feed-forward control as a function of the measured variable \( P_{al}(t)+P_{sl}(t) \). Considering that the elements controlled by the voltage and temperature controllers (the Stirling engine and the pellet boiler) have a steady-state characteristic of saturation type, antiwind-up systems have been provided for these controllers. An important difficulty in the achievement of the Stirling engine control consists in the fact that it accepts only discrete controls (0/1), within the range 0 – 1.6 kW. For higher controls, the control could be performed through modulation (the continuous adjustment of the power). For the implementation of the voltage controller, a conversion block of the control signal has been designed. It receives at the input the continuous signal from the controller \( R_V \) and gives at the output a signal in a joint representation:
continuous signal, identical to the input one, when a power higher than 1.6 kW is required, or a PWM signal, with the average value equal to the input signal, for powers within the range 0 – 1.6 kW. Fig. 7 illustrates the operating of the conversion block. The time modulated pulse period is 1000 sec that means 17 min approximately, so that the request of the Stirling engine supplying mechanism is not great.

![Controller structure diagram](image)

**Fig. 6 – Controller structure.**

![PWM block control diagram](image)

**Fig. 7 – Controls applied to the input (dash line) and output (solid line) of the PWM block.**

5. Results Obtained Through Simulation

The objective followed through simulation was the preliminary validation of the autonomous energetic system feasibility, on the basis of the mathematical model determined in the present paper. In the same time the performances of the control system were investigated. Considering the fact that the processes are slow, the simulation was performed on a 3 days horizon,
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aiming to obtain the permanent regime to the variations of the battery voltage and of the temperatures in the thermal accumulator and in the building.

Figs. 8a and b present the evolutions of the temperature in the thermal accumulator, $T(t)$, and of the pellet boiler power, $P_{ph}(t)$, in winter regime. The setpoint for the temperature loop was chosen $T^{sp} = 72^\circ C$. In Figs. 8c,...,f are given the evolutions of the variables $V(t)$, $P_{al}(t)+P_{sl}(t)$, $P_{st}(t)$, $P_{ph}(t)$, in summer regime.
regime. The controller of the electrical subsystem is able to maintain the voltage around the setpoint $V^{sp} = 48\, V$, even the consumed power $P_{al}(t)+ P_{sl}(t)$ has great variations, including the ones given by the variable term $P_{sl}(t)$, that is determined by the operating of the conditioning plant. The great consumption of the electrical energy in the summer regime imposes the use of two Stirling engines. The total thermal power of the two Stirling engines, in a 3:1 ratio with the electrical power, is shown in Fig. 8 e. In this graphic it can be seen the operating periods in PWM controlling regime of the two engines. Obviously, this regime influences the pellet boiler evolution too (Fig. 8 f).

6. Conclusions

The autonomous energetic systems that are based on renewable resources, of the type presented in the paper, represent a field recently approached in the literature, in connection to the concept of intelligent building. A mathematical model, which can be considered appropriate for the feasibility analysis of the autonomous energetic systems has been elaborated in the paper. The results obtained through numerical simulation have shown that the model can be useful for the investigation of advanced control solutions for these systems.

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REFERENCES

MODELAREA ŞI CONTROLUL UNUI SISTEM ENERGETIC AUTONOM CU SURSE PRIMARE DE ENERGIE

(Rezumat)

În lucrare se prezintă un sistem energetic autonom pentru o clădire rezidenţială, care foloseşte ca surse primare de energie exclusiv biomasă şi energie solară. Astfel, pentru obţinerea energiei electrice se utilizează panouri fotovoltaice şi un motor Stirling. Acesta din urmă produce simultan energie electrică şi termică în raport 1:3. Pentru obţinerea energiei termice, pe lângă motorul Stirling, se utilizează panouri solare şi un cazan cu peleţi. În regim de vară, condiţionarea aerului este realizată cu o instalare cu adsorbţie. Controlul echilibrării sarcinii electrice se realizează prin ajustarea puterii generate de motorul Stirling. Puterea termică dată de motorul termic este considerată variabilă perturbatoare la nivelul subsistemului termic. În lucrare se dezvoltă un model matematic pentru întreg sistemul energetic şi se propune o soluţie de control pentru reglarea sarcinii în susistemele electric şi termic. Rezultatele au fost obţinute în regim de simulare numerică.