Intelligent Energy Guardian for Polygeneration Devices: Design, Implementation, and Experimental Evaluation

Szymon Podlasek[1,*], Paweł Knap[2]
AGH University of Science and Technology[1,2]
klalik@agh.edu.pl

Abstract: *The article presents an intelligent energy guardian for a polygeneration device. The proposed solution aims to optimize energy usage and minimize wastage by incorporating smart control algorithms that continuously monitor and adjust the energy flow between different subsystems of the device. The energy guardian utilizes machine learning techniques to learn the device's energy usage patterns and adapt to changing conditions, such as varying energy demands and supply constraints. The article outlines the design and implementation of the energy guardian, and presents experimental results that demonstrate its effectiveness in improving energy efficiency and reducing operational costs. Overall, the intelligent energy guardian offers a promising solution for enhancing the performance of polygeneration devices and promoting sustainable energy use.*

Keywords*: ENERGY MANAGEMENT, RENEWABLE ENERGY SOURCES, POLYGENERATION, LOSS REDUCTION, DATA ANALYSIS*

1. Introduction

In recent years, there has been a growing interest in polygeneration devices that can efficiently produce multiple forms of energy simultaneously. These devices offer a promising solution to meet the increasing energy demands while minimizing environmental impacts. However, the complexity and variability of energy generation and consumption patterns in polygeneration systems pose significant challenges in terms of maintaining optimal performance and ensuring the safety and reliability of the entire system.

To address these challenges, intelligent energy guardians have emerged as a crucial component in polygeneration devices [1-4]. An intelligent energy guardian acts as an advanced control system, constantly monitoring, analyzing, and optimizing the operation of the polygeneration system. It provides real-time decision-making capabilities, ensuring optimal energy generation, distribution, and consumption, while taking into account various factors such as load demands, energy storage, and renewable energy availability.

The article aims to provide a detailed overview of the design considerations involved in developing an intelligent energy guardian. It will discuss the selection and integration of sensors, data acquisition systems, and communication protocols to gather real-time information from different components of the polygeneration device. Furthermore, the article will delve into the implementation of intelligent algorithms and decision-making models that enable the energy guardian to optimize energy generation and consumption patterns [1-2].

To evaluate the effectiveness of the proposed intelligent energy guardian, a series of experiments will be conducted. These experiments will simulate various scenarios, taking into account different load demands, renewable energy availability, and storage capacities. The performance metrics such as energy efficiency, reliability, and system stability will be analyzed to assess the impact of the energy guardian on the overall operation of the polygeneration device.

The findings of this research have significant implications for the field of polygeneration and smart energy systems. The intelligent energy guardian has the leading to improved energy efficiency, reduced operational costs, and a more sustainable energy infrastructure. Moreover, the insights gained from this study can contribute to the development of intelligent control systems for a wide range of energy applications, paving the way for implement in Industry 4.0.

2. Description of the proposed solution

Energy (power) guard, in the classical sense, allows limiting the excess of contractual power that an industrial consumer orders from the distributor. It is a fixed fee paid by the consumer, and if it is not utilized, no compensation is provided. However, exceeding the contracted power leads to penalties and additional charges. Rising energy prices and the requirements imposed by the European Union on businesses necessitate changes, such as conducting audits of facilities to reduce costs, including determining energy demand during specific time intervals.

Furthermore, increasingly, companies are implementing solutions that enable partial coverage of their electricity demand through the installation of renewable energy systems. The most common example of such installations is photovoltaic panels, whose capacity is tailored to match the facility's peak demand. However, this popular solution has certain issues, with the most significant one being its dependence on weather conditions. Without the utilization of energy storage systems, this solution lacks the ability to buffer energy, even for short periods of time.

Fig. 1 Fragment of a sample polygeneration installation

The system analyzed in the article is based on generating electrical energy using solar radiation but incorporates a modernized Rankine cycle. In this case, heat is collected from solar collectors through an intermediate medium, such as thermal oil, which then heats a buffer tank. Subsequently, the thermal oil heats a heat exchanger acting as a low-boiling-point refrigerant evaporator in the steam turbine cycle. The low-boiling-point refrigerant, while expanding through a turbogenerator, converts mechanical energy into electrical energy, and then, upon condensation in another heat exchanger, provides useful heat [3,4]. Before returning to the evaporator, the low-boiling-point refrigerant is preheated by a heat exchanger powered by geothermal energy (Fig.1). The system is modeled for the purpose of analyzing the operation of such an energy system in conjunction with an intelligent energy guard [5].

The described control algorithm, in addition to known solutions such as an alarming system for high power consumption and managing the shutdown of non-critical processes in the event of exceeding the contracted power, also analyzes all facility processes [1]. It comprises data from the facility, the polygeneration system, and weather information (Fig. 2). Analyzing this data allows for reducing the energy drawn from the power grid and predicting the settings for the polygeneration system based on weather data and the predicted facility demand.

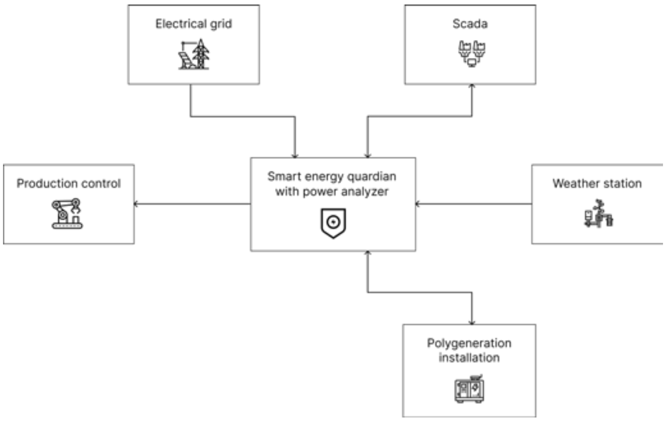

Fig. 2 Schematic diagram of the sample system**.**

The next part of the article will verify the possibility of adapting the energy guard to increase the total power generated by the polygeneration system, extend its operation, and adjust to the facility's demand based on data for a sample enterprise.

3. Data analysis

To conduct the analysis, a facility operating in a two-shift system, five days a week, from 6 am to 10 pm, was selected. For the purpose of the article, a representative working day of the facility has been chosen. The energy consumption profile is shown in Fig. 3 and covers a 24-hour period, including the operational period of the facility and the resting time, which as observed, also involves energy consumption.

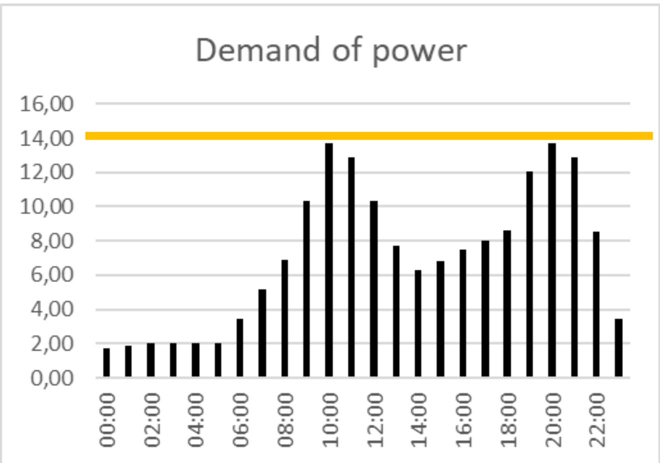

Fig. 3 Chart of daily power demand for a sample industrial facility and the minimum achievable contracted power.

To examine the impact of employing the intelligent energy guardian, a numerical model was used in the MATLAB environment, along with a built-in tool for conducting neural network training [6,7]. For this purpose, learning was performed using the Twin-Delayed Deep Deterministic Policy Gradient (TD3PG) algorithm. A detailed description of the actor-critic method employed was provided in the publication [8].

Below are the results of simulation experiments comparing the original control approach with the implementation of the intelligent energy guardian. The original approach aimed at maximizing instantaneous power, while the intelligent algorithm, based on demand and weather data, sought to adapt to the facility's needs and maximize operational uptime without shutdowns.

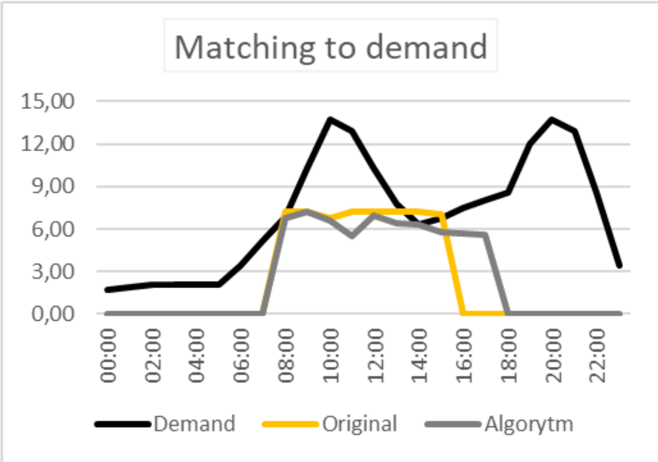

Fig. 4 Schematic diagram of the sample system**.**

Fig. 4 illustrates the relationship between the demand of the analyzed facility and the power generated by the polygeneration system using both the original control approach and the discussed algorithm. It is evident that both the operational uptime has been extended and the power demand has not been exceeded. The algorithm aimed to adapt to the demand as much as allowed by the weather conditions and the nominal power of the polygenerator.

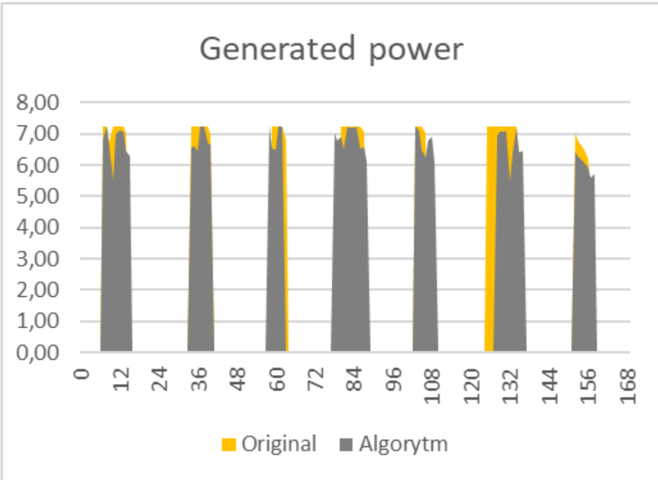

Fig. 5 Schematic diagram of the sample system**.**

Based on the daily analysis, it was decided to verify the difference in system performance over the course of a week. The charts shown in Fig. 5 and 6 illustrate the difference, respectively, for the generated power and the operational time of the polygeneration system. In both cases, there is a noticeable improvement in the performance of the polygeneration system when the intelligent energy guardian is applied. It can also be observed that there are stages of the polygenerator's operation where the original control temporarily prolongs the system's operation. However, these are isolated occurrences.

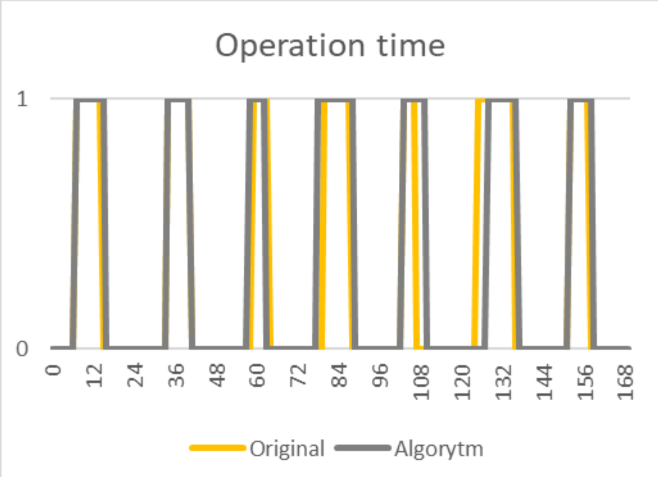

Fig. 6 Schematic diagram of the sample system.

Table 1 presents a comparison of the performance of the polygeneration system in different periods. In all cases, both in terms of power and operational time, using the intelligent energy guardian control proved to be more favorable. This is particularly evident in the daily example presented, which can be attributed to the atypical weather conditions of that day, better handled by the neural algorithm. However, a more reliable comparison is provided by the weekly and yearly periods, which average out the long-term operation of the system, taking into account various weather conditions. The last column of the table presents the percentage by which the implementation of the control algorithm increased the efficiency of the power installation.

Table 1*: Summary of control results*

	Original	Algorytm	Percentage of improvement
Daily power [kW]	57,15	62,92	10,09
Week power [kW]	346,78	392,27	6,58
Year power [kW]	14090,09283	14903,27	5,77
Daily duration [h]	8	10	25,00
Week duration [h]	49	55	12,24
Year duration [h]	2098	2402	14,48

4. Results

The results confirmed the validity of working on advanced energy guardians for industrial facilities. This article focused solely on one component of such a system, namely the management of the polygeneration installation. The advanced algorithm based on neural control allowed for a significant increase in energy generation on a daily, weekly, and yearly scale. Furthermore, it extended the operational time of the polygeneration system in each of these periods. However, it is evident that the system is unable to ensure energy self-sufficiency for the facility and only provides full energy demand coverage to a limited extent. This is particularly noticeable when the Normal Irradiance (DNI) decreases. The lack of solar radiation prevents the system from operating, which is why systems based on the Rankine cycle would be most suitable when utilizing waste heat from the facility, which would be available throughout its operation. It would also be reasonable to expand the polygeneration installation with other renewable energy sources to reduce carbon footprint and increase energy independence. The system could also allow for energy surplus storage in the form of compressed air, for example. This would enable the use of a higher-capacity installation that would not waste excess generated energy.

It is justifiable to analyze this solution for other components of industrial facility operation as well, such as adjusting the sequence of tasks based on momentary energy consumption. By combining data on orders, weather conditions, instantaneous and projected energy consumption, as well as generated and stored energy, it would be possible to successfully reduce the contracted power. Through a multi-level management system, it would be possible to increase energy generation during peak demand or predictively distribute multiple production processes over time to avoid such peaks. For these reasons, intelligent control algorithms, which form the basis of modern energy guardians, seem to fit perfectly into the direction of development outlined by Industry 4.0.

5. References

[1] D. Lee, Ch-Ch. Cheng, “Energy savings by energy management systems: A review" Renewable and Sustainable Energy Reviews Volume 56, 2016, .

[2] S. Fui Tie, Ch. Wei Tan, “A review of energy sources and energy management system in electric vehicles, Renewable and Sustainable Energy Reviews, volume 20, 2013.

[3] F Calise, R Figaj, N Massarotti, A Mauro, L Vanoli, “Polygeneration system based on PEMFC, CPVT and electrolyzer: Dynamic simulation and energetic and economic analysis”, *Applied energy 192, 2017*

[4] F Calise, RD Figaj, L Vanoli, “A novel polygeneration system integrating photovoltaic/thermal collectors, solar assisted heat pump, adsorption chiller and electrical energy storage..", Energy Conversion and Management 149, 2017.

[5] M Jankowski, A Borsukiewicz, "Multi-objective approach for determination of optimal operating parameters in low-temperature ORC power plant", Energy Conversion and Management 200, 2019.

[6] M Jankowski, A Borsukiewicz, K Szopik-Depczyńska, G Ioppolo, “Determination of an optimal pinch point temperature difference interval in ORC power plant using multi-objective approach”, *Journal of Cleaner Production 217, 798-807, 2019.*

[7] R. Figaj, K. Sornek, S. Podlasek, M. Żołądek, “Operation and Sensitivity Analysis of a Micro-Scale Hybrid Trigeneration System Integrating a Water Steam Cycle and Wind Turbine under Different Reference Scenario,” Energies ISSN 1996-1073. — 2020 vol. 13 iss. 21 art. no. 5697, s. 1–23, 2020.

[8] K. Lalik, M. Kozek, S. Podlasek, R. Figaj, “Q-learning neural controller for steam generator station in micro cogeneration systems,” Energies ISSN 1996-1073. — 2021 vol. 14 iss. 17 art. no. 5334, s. 1–13, 2021.