AN OPTIMIZED FUZZY LOGIC-BASED ENERGY MANAGEMENT STRATEGY FOR RENEWABLE ENERGY MICROGRID WITH HYDROGEN STORAGE SYSTEM

CHIẾN LƯỢC QUẢN LÝ NĂNG LƯỢNG DỰA TRÊN HỆ THỐNG LOGIC MỜ TỐI ƯU, ỨNG DỤNG CHO HỆ THỐNG LƯỚI ĐIỆN SIÊU NHỎ CÓ TÍCH HỢP CÁC NGUỒN NĂNG LƯỢNG TÁI TẠO VÀ HỆ THỐNG LƯU TRỮ HYDROGEN

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ABSTRACT

Renewable energy sources such as wind and solar have been developed in many countries all over the globe due to their ability to provide environmentally friendly energy. However, due to the stochastic behavior of these power sources, controlling energy systems with high renewable energy penetration remains a challenge. To solve the mentioned problem, this study presents a fuzzy logic control-based energy management system, which helps regulate the energy flow within a grid-connected microgrid that integrates hydrogen energy storage. The proposed technique is further optimized using the particle swarm optimization algorithm to increase the system's performance and reliability. The results have proved that the energy management strategy has the following merits: (1) energy balance is secured, (2) devices' lifespan has been prolonged, and (3) a better fuel economy has been achieved.

Keywords: *Hydrogen storage system, energy management strategy, fuzzy logic control.*

TÓM TẮT

Các nguồn năng lượng tái tạo như gió và mặt trời đã được phát triển ở nhiều quốc gia trên toàn cầu do khả năng cung cấp nguồn năng lượng thân thiện với môi trường. Tuy nhiên, do đặc tính bất ổn của chúng, việc kiểm soát các hệ thống năng lượng có mức độ thâm nhập năng lượng tái tạo cao vẫn còn là một thách thức. Để giải quyết vấn đề đã đề cập, nghiên cứu này trình bày một chiến lược quản lý năng lượng dựa trên điều khiển logic mờ, giúp điều tiết năng lượng trong lưới điện siêu nhỏ có tích hợp hệ thống lưu trữ năng lượng hydrogen. Chiến lược được đề xuất còn được tối ưu hóa thông qua việc ứng dụng thuật toán tối ưu hóa bầy đàn nhằm tăng hiệu suất và độ tin cậy của hệ thống. Các kết quả mô phỏng thu được đã chứng minh rằng chiến lược quản lý năng lượng đạt được những ưu điểm bao gồm: (1) đảm bảo cân bằng năng lượng trong hệ thống, (2) tuổi thọ của thiết bị đã được kéo dài và (3) hydrogen sử dụng đã được tiết kiệm hơn.

Từ khóa: *Hệ thống lưu trữ hydrogen, chiến lược quản lý năng lượng, điều khiển logic mờ.*

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1. INTRODUCTION

Along with the development of technology and society, the electricity demand also rises significantly and swiftly, reflected by the fact that the total energy demand of the globe is set to grow by close to 5% in 2021 and 4% in 2022. However, almost half of the demand is met by fossil fuel, threatening to push CO_2 emissions from the power sector to a record level [1]. Using green energy technology is considered the most promising solution to reduce pollution. As a result, the number of research and projects related to renewable energy increased dramatically, with most of them choosing solar and wind as the main power source due to their ability to generate clean energy at a reasonable cost for investors. However, because of their stochastic behavior, the microgrid (MG) requires an energy storage system (ESS) to ensure power balance within the system. Batteries are often installed as a short-term storage option, while hydrogen storage acts as a long-term storage system [2]. Although the overall fee for hydrogen storage is still high, several studies prove that it will drop significantly in the upcoming years [3].

An effective energy management strategy (EMS) is an inseparable part of the hybrid power system that wants to achieve uninterrupted, safe, and low energy consumption [4]. Therefore, designing a strategy with a suitable control technique becomes an important task. Fuzzy logic control (FLC) has excellent compatibility with renewable energy-based MG because of its ability to use data and information that are vague and lack certainty. Many authors have applied this technique to the hybrid storage system that includes both hydrogen and battery storage. In [5, 6] the authors proposed an optimized FLC-based EMS that aims to enhance the MG's performance, reduce the fuel consumed, and ensure the power balance. In their EMS, the hydrogen storage system act as the primary backup power source, and the battery supports the hydrogen system when the power demand is too large. However, as mentioned before, hydrogen is often used as a long-term storage option because the energy stored in the hydrogen tank can be preserved for a long time. Therefore, the battery should be the primary backup and take charge of the short-term disturbance while the hydrogen storage system focuses on the system's long-term energy balance.

In this study, an optimized fuzzy logic-based EMS is proposed for a grid-connected AC microgrid, as shown in Figure 1. In this simulated microgrid, two different types of energy storage systems are integrated, including a battery storage system and a hydrogen storage system. Unlike the aforementioned EMS, the load demand will be satisfied by PV output power, and when an energy-shortage scenario occurs, the battery will be utilized as the main backup power source. A 72-hour-simulation has been carried out in MATLAB/Simulink environment to validate the performance of the proposed energy management strategy.

This paper first describes the microgrid structure and topology in Section 0, while Section 0 presents the proposed fuzzy logic control-based energy management strategy. Simulation results are shown in Section 0, and the conclusions of this article are placed in Section 0.

2. SYSTEM STRUCTURE AND MODELLING

Figure illustrates the modeled grid-connected microgrid, which consists of a photovoltaic (PV) system as well as a hydrogen and battery storage system. These devices are connected to an AC bus through power converters, which are assemblies of the DC device itself. The AC bus is linked to the main grid via an AC/AC inverter. During the daytime, when the PV system output power is high, the MG is primarily supplied by solar power, and the excess energy is stored in the battery and/or in the form of hydrogen by using the electrolyzer. On the other hand, when the solar irradiance is low, the battery and fuel cell serve as the main power source to meet the load demand.

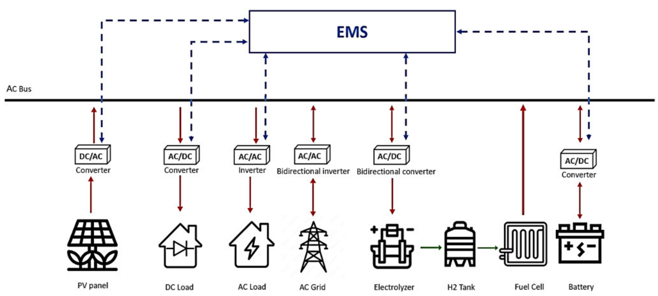

Figure 1. Grid-connected hybrid renewable energy microgrid

The simulation model of this microgrid is simulated in MATLAB/Simulink environment, as demonstrated in Sections 2.1 to Section 0. A detailed description of the hybrid renewable energy storage system is shown in Table 1.

Table 1. Parameters of system components

Subsystems	Descriptions	Values
PV System	Numbers of PV panel	1000
	Total maximum power (kW)	350
Battery	Nominal capacity (kWh)	5,650
	Maximum power (kW)	500
	State of charge (SoC)'s range (%)	40-90
Fuel Cell	Maximum power (kW)	250
Electrolyzer	Maximum power (kW)	500
Hydrogen Tank	Nominal capacity (kg)	50
	Level of hydrogen (LoH)'s range (%)	10-90

2.1. Modeling of PV Array

The PV-generated power can be calculated using the equation below based on solar irradiance and temperature[7, 8]:

$$P_{PV} = N_{PV} \times P_{PV\_Rated} \times \frac{G}{G_{ref}}[1 + K_t(T_a + (0.0256 \times G) - T_{ref}] \quad (1)$$

where P_{PV} is the PV system's output power (W), N_{PV} is the number of PV panels, P_{PV_Rated} is the PV panel's rated power under standard test conditions (W), G is the solar irradiance (W/m^2), and T_α is the ambient temperature (°C). G_{ref}, T_{ref}, and K_t are equal to 1000 (W/m^2), 25 °C, and -3.7.10^{-3} (1/°C), respectively

2.2. Modeling of Battery Storage System

In the studied microgrid, a lithium-ion battery system is used. The dynamic battery's state of charge (SoC) can be calculated using the following equation [9]:

$$SoC = SoC_{Initial} + \frac{\eta_{ch} \times P_{Batt,\,ch} \times \Delta t}{C_{Batt}} - \frac{P_{Batt,\,disch} \times \Delta t}{\eta_{disch} \times \Delta t} \quad (2)$$

where η_{ch} and η_{disch} are the charging and discharging efficiencies (%), $P_{Batt,ch}$ and $P_{Batt,disch}$ are the battery charging and discharging power (W) over timeslot t, C_{Batt} is the nominal capacity of the battery (kWh) and $SoC_{Initial}$ is the initial state of charge of the battery (%).

2.3. Modeling of Hydrogen Storage System

The hydrogen storage system includes a proton exchange membrane fuel cell (PEMFC), a PEM electrolyzer (PEMEL), and a hydrogen storage tank. The PEMFC's role is to convert the excess energy into hydrogen which will be stored in the hydrogen tank and can be used as PEMEL's fuel to produce energy when an energy shortage happened.

The phenomenon of fuel cells using hydrogen to generate electricity, as well as the

the electrical energy produced by the fuel cell can be modeled and calculated using the following equation [7]:

$$H_{2\_density} = \frac{P_{FC}}{\eta_{FC}} \times \Delta t \times \frac{H_{2\_density}}{Q_{HV}} \quad (3)$$

where P_{FC} is the fuel cell stack output energy (kW), $H_{2\text{-}consumed}$ is the amount of hydrogen consumed by the PEM fuel cell (kg), and ηFC is the efficiency of the PEM fuel cell (50%). Q_{HV} and $H_{2\text{-}density}$ are the equivalent heating value of hydrogen (3.4kWh/m^3) and hydrogen density (0.09kg/m^3), respectively.

The electrolyzer is an electrochemical device that uses excess energy to produce hydrogen, with the amount of generated hydrogen ($H_{2\_produced}$) can be calculated as [7]:

$$H_{2\_produced} = \eta_{ELEC} \times P_{ELEC} \times \Delta t \times \frac{H_{2\_density}}{Q_{HV}} \quad (4)$$

where $H_{2\text{-}produced}$ is the amount of produced hydrogen (kg), P_{ELEC} is the energy input to the PEM electrolyzer (kW), and η_{ELEC} is the electrolyzer efficiency, which is also 50%.

The level of stored hydrogen (LoH) in the hydrogen tank can be calculated by considering the initial amount of stored hydrogen and the amount of hydrogen produced and consumed. In this study, the hydrogen level is presented as:

$$LoH = H_{2\_Initial} + \frac{\Delta H_{2\_produced}}{\Delta t} - \frac{\Delta H_{2consumed}}{\Delta t} \quad (5)$$

where LoH is the hydrogen level in the hydrogen tank (%), $H_{2\text{-}Initial}$ is the initial hydrogen stored at the beginning of the simulation (kg). It is important to note that the PEMFC and PEMEL do not operate at the same time, which means that the operating power of the PEMFC and the amount of consumed hydrogen at a timeslot equals zero if the electrolyzer is producing hydrogen in that same timeslot and vice versa.

3. PROPOSED OPTIMIZED FLC-BASED ENERGY MANAGEMENT STRATEGY

EMS is the core part of the hybrid power MG, which directly determines the performance of the system. While guaranteeing the main target of meeting the power demand of the hybrid MG, using appropriate control methods to optimize the power distribution of various energy sources and components can improve the system's performance dramatically. Moreover, a suitable EMS is also beneficial to achieve a stable output of power, making full use of the advantages of each power source, prolonging the device's lifetime, and raising the efficiency of the power system.

Fuzzy logic controller is a well-known artificial intelligence control technique due to its excellence in controlling complex systems without an exact mathematical model of the system. However, FLC's performance depends heavily on its fuzzy membership (FM) and fuzzy rule. As a result, designing an effective FLC is a complex task because there are various parameters that need to be tuned. Hence, developing an optimization algorithm to tune those parameters without relying on experts' knowledge seems reasonable. In this case, a meta-heuristic algorithm called particle swarm optimization (PSO) is adopted. PSO is one of the most common methods that optimizes a problem by the personal best value and compare it to the global best value after each iteration. It is different from other optimization algorithms in such a way that it is not dependent on the gradient or any differential form of the objective.

The objective function and optimization process of the FLC will be demonstrated in Subsections 0 and 0, respectively

3.1. Fitness Function

The first step for PSO to work properly is to select the suitable fitness function. In this case, to minimize the consumed fuel, which is hydrogen, the author chooses the energy consumption minimization strategy (ECMS) as the fitness function for the optimization process. Furthermore, to lessen the dependence on the main grid, the energy exported to the grid will be multiplied by a penalty weight. The battery's equivalent energy consumption can be calculated using an equivalent factor (α) that is dependent on the battery SoC. Since the fuel-cell hydrogen consumption and the battery equivalent energy consumption are dependent on the fuel cell and the battery's output power, respectively, the energy consumption-related cost function (C) can be written as [10]:

$$C = \int (P_{FC}(t) + \alpha(t).\ P_{Batt}(t) + \beta.\ P_{Grid\text{-}Imp}(t))\ dt \quad (6)$$

$$\alpha(t) = 1 - 2 \times \mu \times \frac{SoC(t) - 0.5 \times (SoC_{max} + SoC_{min})}{(SoC_{max} + SoC_{min})} \quad (7)$$

Where μ is a constant that is called the battery's SoC coefficient and assigned 0.6 to control the battery SoC, β is a penalty weight and assigned 1000 to lessen the imported energy.

To maintain the power balance and prolong components' lifetime, some constraint are defined as follows:

- Power balance constraint:

$$P_{net} = P_{Load} - P_{PV} = P_{FC} + P_{Batt} + P_{Grid} \quad (8)$$

- Devices' constraint:

$$P_{FCmin} < P_{FC} < P_{FCmax} \quad (9)$$

$$P_{charg,max} < P_{Batt} < P_{discharg,max} \quad (10)$$

$$SoC_{min} < SoC < SoC_{max} \quad (11)$$

$$LoH_{min} < LoH < LoH_{max} \quad (12)$$

$$P_{ELEC,min} < P_{ELEC} < P_{ELEC,max} \quad (13)$$

- ECMS constraint:

$$0 < \alpha(t) < 2 \quad (14)$$

3.2. Rule-Based Optimized Fuzzy Logic Control Energy Management Strategy

As mentioned before, FLC-based EMS's performance depends heavily on its fuzzy rule and FM. In this paper, the fuzzy membership functions are optimized using PSO to minimize the objective function, while the rule is pre-defined by the author to lessen the computation time. In this section, the Rule-based optimized FLC designing process will be demonstrated.

After deciding the objective function, the next step of the optimization process is to determine the variable that needs to be optimized. As seen in Figure 2, three trapezoidal Membership Functions (MFs) are assigned to the battery SoC, three trapezoidal MF are assigned to the level of hydrogen LoH, six trapezoidal MFs are designated to the differential power $P_{Diff} = P_{Load} - P_{PV}$, and finally, five variables fuzzify the fuel-cell power are the optimized parameters. To make the optimization process faster, the boundaries of those parameters are determined based on the prior knowledge of the designer and the components' limitations. To maintain the shape of the trapezoid and cover all possible scenario, some constraints will be taken into consideration as follows:

$$x(i) < x(i+1)\ ;\ i=1:18; \quad (15)$$

$$x(i) < 0\ ;\ i=1:9; \quad (16)$$

$$x(i) > 0\ ;\ i=10:18 \quad (17)$$

$$y(i) < y(i+1)\ ;\ i=1:9 \quad (18)$$

$$z(i) < z(i+1)\ ;\ i=1:9 \quad (19)$$

$$o(i) < o(i+1)\ ;\ i=1:5 \quad (20)$$

Where x(i); i=1:18, y(i); i=1:13, z(i); i=1:13, o (i); i=1:5 represent the differential power, the battery SoC, the level of hydrogen LoH and fuel-cell power respectively. Figure shows the FM optimization process.

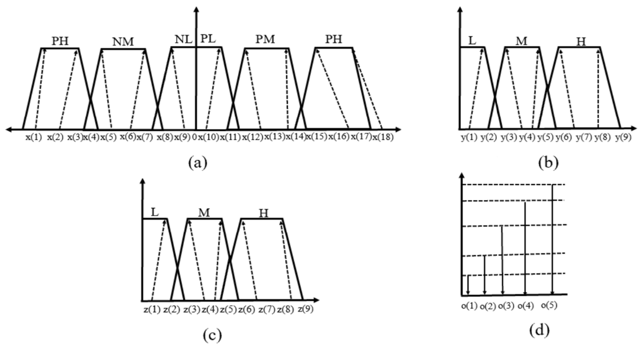

Figure 2. MF parameters: a) Differential power b) SoC c) LoH d) Fuel Cell Power

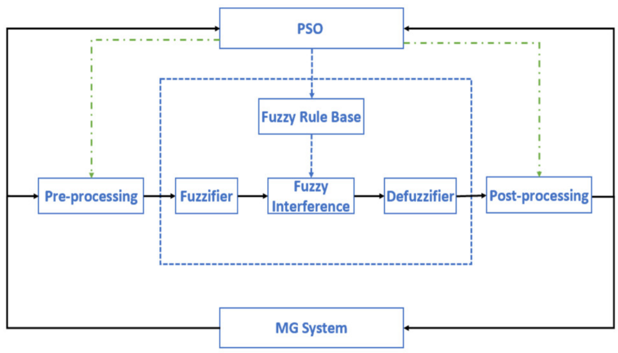

Figure 3. Basic structure of fuzzy logic control tuning process using PSO

4. SIMULATIONS RESULTS

To evaluate the rule-based optimized fuzzy logic EMS, a simulation is carried out in MATLAB/Simulink environment, where the microgrid model and the proposed EMS are modeled for 72 hours. The results have proved the EMS's effectiveness in balancing the battery and electrolyzer 's output power. All of the constraints mentioned before, such as the battery's SoC, and fuel cell discharge power, are also kept within the reasonable boundary, which prolong the components' lifetime. Figure 4 illustrates the simulation result which included the MG's power flow, the battery state of charge, and the level of stored hydrogen.

Furthermore, as can be seen in Figure 5, the value of fuel consumption decreases dramatically after the optimization process. Furthermore, as can be seen in Figure, the value of fuel consumption decreases dramatically after the optimization process. In the first 30 iterations, the total fuel consumed reduces significantly. After that, the decreasing rate of ECMS's value becomes slower, and even remains fixed in the last 60 iterations. Finally, after 100 iterations, the grid now saved up approximately 40% of its fuel compared to the initial value.

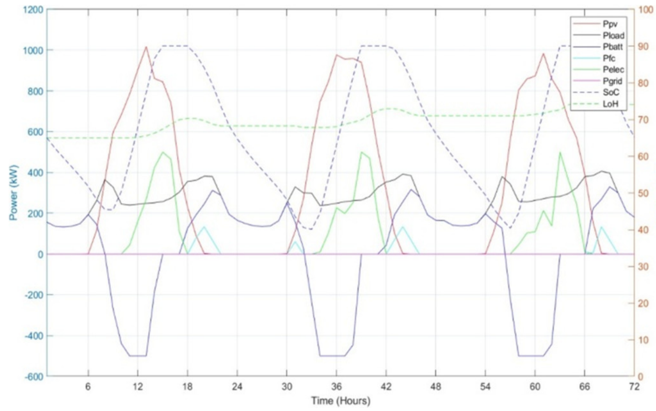

Figure 4. The microgrid power flow, battery state of charge, and level of stored hydrogen

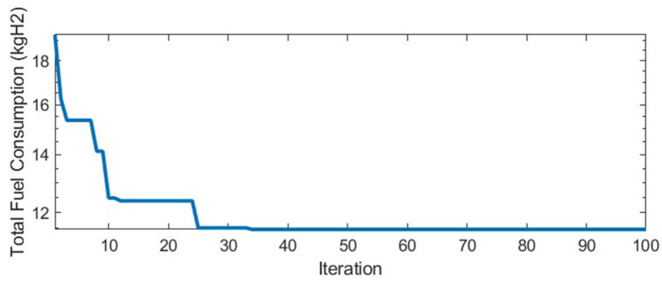

Figure 5. Total fuel consumption of the microgrid

5. CONCLUSION

In this paper, the authors have proposed an optimized fuzzy logic control-based energy

management strategy that aims to minimize fuel consumption while also being able to maintain the battery's state of charge and the system's power balance. A grid-connected hybrid renewable energy microgrid consisting of a PV system and a hybrid storage system (battery and hydrogen) is also simulated in Simulink/MATLAB to evaluate the proposed EMS. The results have proved the effectiveness of the EMS in controlling the energy flow of the microgrid, as well as maintaining the SoC and LoH.

Future works will focus on optimizing the rule base of the FLC as well as combining with this research on optimizing FLC 's FM. By utilizing an optimization algorithm to tune all FLC's parameters, an optimized fuzzy-based EMS can be designed without prior knowledge.

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THÔNG TIN TÁC GIẢ

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Trường Điện - Điện tử, Đại học Bách khoa Hà Nội