Design and development of a low cost highly efficient Microgrid control in Chikushi Campus

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Abstract

In order to reduce the load demand of buildings in Japan, this study proposes a novel and low-cost Maximum Power Point Tracking (MPPT) control scheme, using a fuzzy logic control (FLC) algorithm, which can be applied to a simple residential microgrid, consisting of a wind turbine, PV array, and battery storage. Compared with the existing MPPTs, the proposed MPPT provides rapid power control with small oscillations. The dynamic simulation of the proposed MPPT was performed in MATLAB-Simulink, and the model results were validated using an experimental setup installed in the Chikushi campus, Kyushu University, Japan. For a more accurate analysis, a new indoor microgrid test system, including an artificial solar power simulator and wind turbine emulator, was set up at the Energy and Energy and Environmental Systems (EES) laboratory that allows the proposed MPPT to be tested more accurately, taking into account sudden changes in sunlight and wind speed. The results revealed a 2% surplus power generation potential from the FLC-based MPPT system (about 26.2 kWh/y excess electricity from each kW installed capacity of solar panels in the Chikushi campus), which can guarantee a lower Levelized cost of electricity (LOCE) for the microgrid.

Introduction

Background

Urban regions in Japan are at the forefront of the country's climate change debate. With buildings accounting for high electrical demand and GHG emissions in Japan, enabling higher penetration of renewable-based microgrids can significantly reduce their load demand. Hybrid residential microgrids can help Japanese local governments to increase resilience, reduce emissions, and achieve other policy goals such as redevelopment or smart city implementation. A renewable-based microgrid consists of an advanced control system that integrates the customer's electrical loads, manages distributed resources (solar/wind/biomass) and energy storage, and coordinates with the electricity transmission and distribution networks. The output power of a hybrid renewable microgrid varies on environmental conditions such as solar irradiance, wind, and operating temperature. Therefore, the Maximum Power Point Tracking (MPPT) technique is used to extract the maximum capable power of the microgrid with respective solar irradiance, wind speed, and temperature at a particular instant of time point. MPPTs are electronic devices that regulate the charge of the storage system like batteries by controlling the point at which the renewable power generators produce the highest amount of electrical energy. Several algorithms were developed to efficiently track the maximum power point, such as Incremental Conductance (INC), Hill Climbing, or Perturbation and Observation (P&O). There are two concerns with the existing MPPT algorithms:

- Most of them suffer from the drawback of being slow tracking, due to which the utilization efficiency is reduced;
- Furthermore, intermittency and rapid irradiation, and temperature changes may cause the Maximum Power Point (MPP) to be oscillating around one of the multiple local peaks of power.

Objectives of research

Although the advanced controllers can add a high level of control, they are more complex and system-specific compared to other more general algorithms that are less complex and require less information and sensors. Rather, cost-conscious policymakers often remain reluctant to invest financial resources and political capital in needed transformative changes to residential microgrids. In order to develop a low cost highly efficient hybrid residential microgrids that can be integrated with buildings or rural areas, a low-complex MPPT, high power quality output system for achieving Total Harmonic Distortion (THD) below 1% in a steady-state, without the need of a battery specific converter to control the charging and discharging modes has yet to be developed. In order to overcome the drawbacks mentioned on the existing tracking systems, such as the P&O method, this study aims at introducing a MPPT system based on fuzzy logic control (FLC), which provides rapid control, and small oscillations once it reaches the MPP, under varying weather conditions. The proposed FLC-based MPPT controls the DC-DC converter connected to the solar panel and wind turbine. The determination of input and output magnitude is the most notable feature of the FLC-based MPPT. The FLC determines the numerical input as a linguistic magnitude based on its own rules. It then selects the linguistic output corresponding to the linguistic information and converts it into an output value as a number. Thus, the FLC-based MPPT is faster and more accurate than other MPPT controllers, such as P&O, because it has the flexibility to change the magnitude of the output values depending on the position of the points, resulting in more power output from the HRES. The dynamic simulation of the proposed MPPT will be carried out and validated using a real experimental setup installed in the Chikushi campus, Kyushu University. The annual savings potential from the implementation of the system will be estimated through real-time monitoring and measurement of the performance of the system.

Development of the proposed MPPT simulator

Hybrid microgrid detailed simulation

The proposed standalone HRES in this research consists of a wind turbine, PV array, and battery storage. The MATLAB simulation model of the proposed HRES system and control scheme is shown in Figure 1. The PV block consists of three PV modules connected in series, each having a rated power of 160 watts. The output of the PV system is connected to a 2200 μF DC link capacitor. A saturation block is used to simulate the maximum speed the turbine can tolerate, and again is used to convert the per unit mechanical torque to its real value. A 2200 μF DC link capacitor is connected to the output. First, the wind speed, pitch angle, and generator speed are fed to the wind turbine block where the power is calculated, and the per-unit torque is output. The per-unit torque is converted to the actual torque by multiplying it with the base torque, which is calculated in accordance with the rated speed and power of the wind turbine. The estimated torque is fed to the PMSG, and the three-phase voltages are generated. The rectifier converts the three-phase AC voltages into DC. An Absorbed glass mat (AGM), Lead-acid battery with 30 Ah of capacity is utilized in the proposed system design. The proposed model utilizes an IGBT Buck converter for each of the PV and Wind turbine systems. It is modeled by an IGBT/diode pairs PWM signal controlled, followed by an inductor, a freewheeling diode, and a capacitor. The upper part is the P&O algorithm with its initial Duty cycle (D), D max, D min, and delta D set to 0.7, 0.95, 0.25 and 10−5, respectively, where D is the duty cycle. Both PWM generators are set to 30 000 samples per second and a sampling time of 5 μs. The bulk Charge voltage is set to 14.5 V and the Float charge voltage to 13.5 Volts for the battery (13.5–13.8 V) for Float and (14.4–14.9 V) for Bulk. The model decides the operating condition by reading the output current of the inverter's filter; if it exceeds 0.01 A, then it is assumed to be connected and works in the MPPT mode; else, it works in the Battery Charging mode. The input of the inverter is connected to two 6600 μF capacitors, both used to sustain the DC link's voltage fluctuations and harmonics caused by the ON/OFF switching of the buck converters as well as the changing dynamics of the system. An IGBT-based single-phase full-bridge inverter is connected to an LC filter and Linear

Transformer to filter the inverter's harmonics and step up the AC Voltage to the required 110 Voltage. The LC filter was used on the output of PWM inverters when the target control is the Voltage. It filters out unwanted harmonics and keeps the Total Harmonic Distortion of the system under the maximum allowed value.

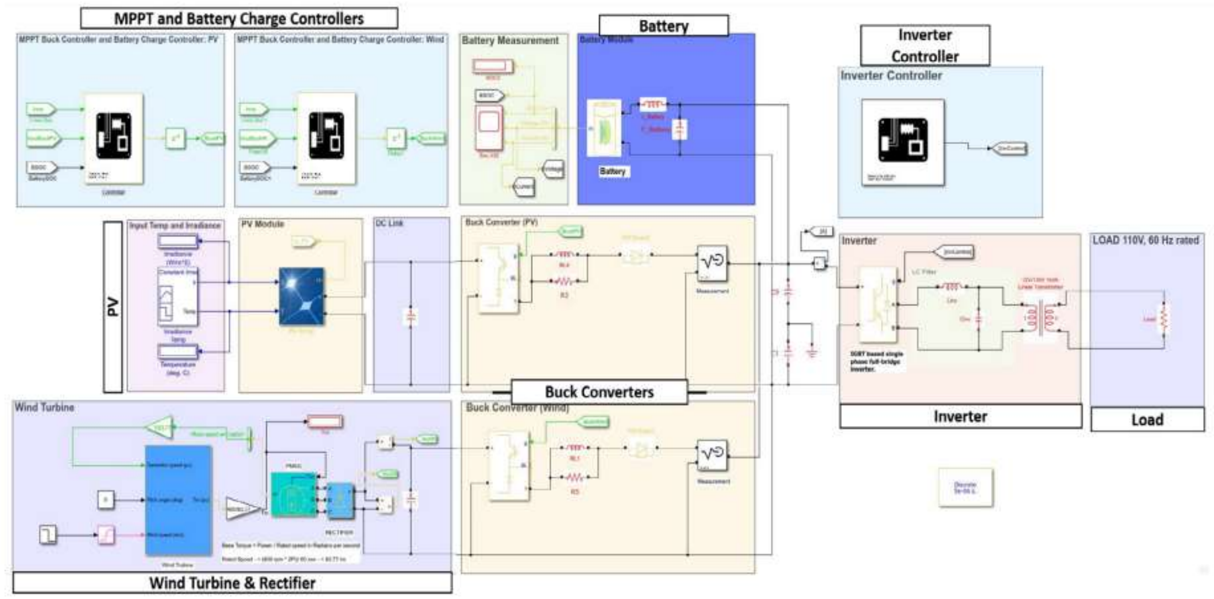


Fig 1. Hybrid microgrid with a P&O developed in MATLAB Simulink in this research [1]

Design of the proposed FLC-based MPPT controller

Fuzzy logic is a type of multi-valued logic that can express linguistic variables by using values from 0 to 1, similar to human thinking. The fuzzy logic controller comprises three components: fuzzification, rule interface, and defuzzification. In the stage of fuzzification, numeric input variables are transformed into linguistic variables. Typically, the input variables of the controller are the error (E) and the variation of error (CE). The error shows the operating point of the PV system concerning the MPP, where it should be zero, and its variation shows how this point moves in the power-voltage curve. The transformation is carried out by applying the membership functions set for different input variables ranges, and its value varies between 0 and 1. The interface is responsible for implementing the rule-based functions that define the behavior of the controller. The controller output will be a linguistic variable that establishes the duty ratio of the converter and iteratively makes the error tend to zero. In the defuzzification stage, the membership functions are applied to obtain the numerical output values. The FLC judges the OP position by using two inputs. These are the slope of the P-V curve's tangential line $\left(\frac{dP}{dV}\right)$ and displacement direction of the operating point $\left(\frac{d^2P}{dV^2}\right)$. These two inputs are expressed following equations, respectively. Figure 2 shows the whole PV Simulink model, including P&O and FLC MPPT systems. Figure 3 shows the schematic diagram of the buck converter.

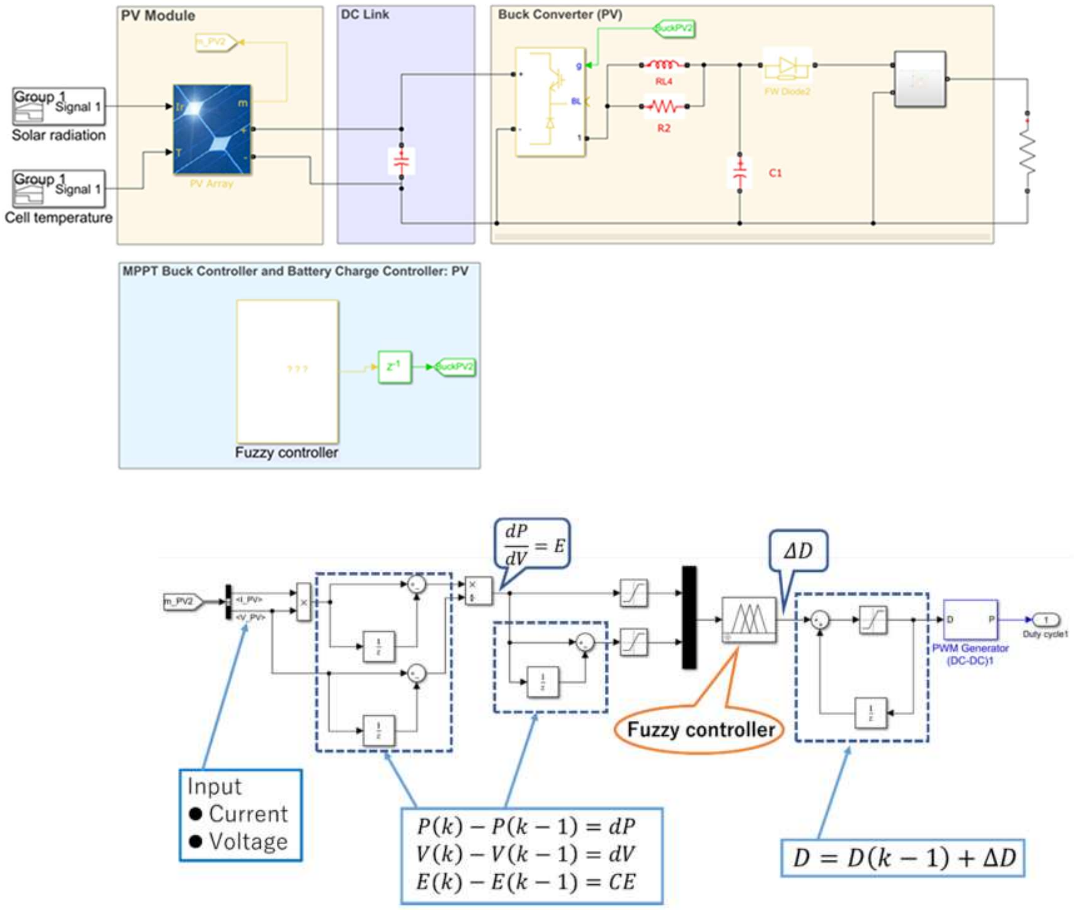


Fig 2. FLC-based MPPT for solar PV developed in this research [2]

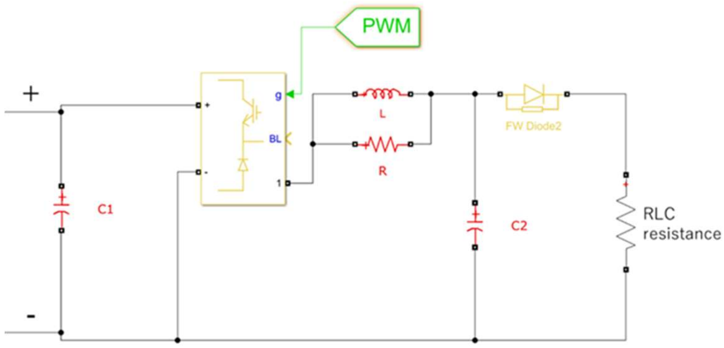


Fig 3. Schematic diagram of the buck converter connected to the FLC-MPPT [2]

Figure 4 shows the wind turbine section, which consists of the wind turbine itself, back converter, and MPPT controller. A battery is also connected to the load part in parallel in order to keep the voltage applied to the load constant and prevent errors that may occur during the simulation. These input values are converted to linguistic variables through membership functions. Figure 5 expresses membership functions used in this research. Linguistic variables are divided into five categories: NB (negative big), NS (negative small), ZE (zero), PS (positive small), PB (positive big).

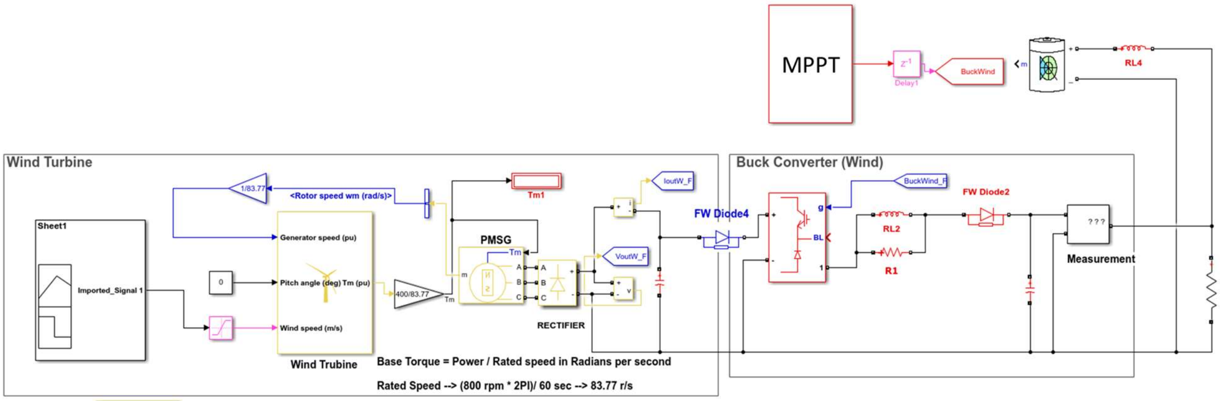


Fig 4. FLC-based MPPT for wind turbine developed in this research [2]

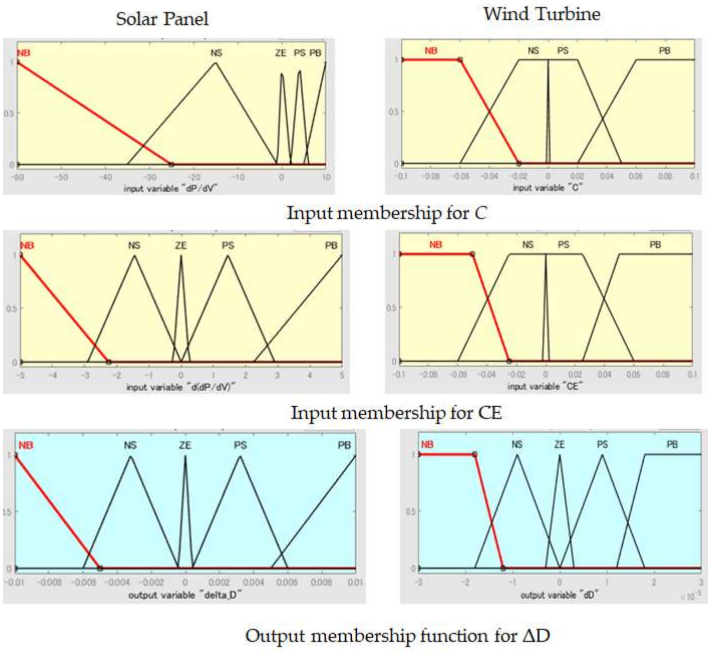


Fig 5. Fuzzy rules for PV panel and wind turbine

FLC-based MPPT test and validation

Experimental system

The developed control system was tested and validated, using an outdoor hybrid renewable test setup, located in the Chikushi campus. The experimental setup is located on the rooftop of building E at the Chkushi campus, Kyushu University. The proposed system consists of three PV modules with a total power of (480 W), a wind turbine (400 W), a lead-acid battery (30 Ah), an inverter, and the proposed MPPT controller. The solar panel surface temperature was measured by using a LM335 temperature sensor, which was installed on the surface of the panel. The incident solar radiation on the PV panels was measured, using MS-40S Pyranometer. The solar analyzer (PROVA 200A) was used to measure the short-circuit current and open voltage of the solar panel to extract the I-V curves under the various solar irradiations and ambient temperatures, as shown in Figure 6.

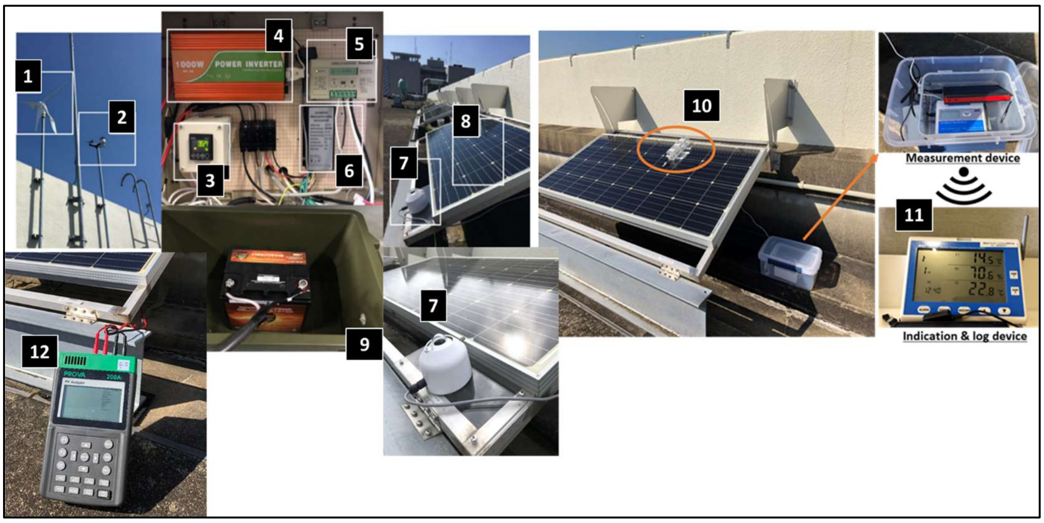


Fig 6. Experimental setup in this study: (1) Wind turbine, (2) Weather measurement station, (3) Power Datalogger, (4) Inverter, (5) PV DC converter and MPPT controller,(6) Wind DC converter and MPPT controller, (7) MS-40C Pyranometer, (8) PV modules, (9) Battery, (10) LM335 thermocouple, (11) Temp Datalogger, (12) Solar analyzer PROVA 200A.

The experiment was performed, considering a sunny, cloudy, and rainy day in each month (see Table 1). Figure 7 shows the comparison between the P&O-based and the proposed FLC-based MPPTs in this research for a short period of 10 minutes of simulation on this sunny day. This figure shows that the FLC-based MPPT extracts higher power with lower oscillation than the P&O controller. The better performance of the FLC is more evident at the higher levels of solar irradiation. The simulation results reveal that the output power based on the FLC-based MPPT is significantly higher than the P&O-based MPPT on cloudy days. This is because the P-V curve slope is extremely small due to the low solar radiation (see Figure 8).

Tab1. Selected dates for testing the simulation model in this study.

Sunny day	Cloudy day	Rainy day
1-Jan	13-Jan	22-Jan
4-Feb	7-Feb	12-Feb
20-Mar	22-Mar	28-Mar
14-Apr	15-Apr	19-Apr
1-May	25-May	26-May
8-Jun	4-Jun	25-Jun
16-Jul	17-Jul	6-Jul
29-Aug	28-Aug	7-Aug
14-Sep	20-Sep	12-Sep
20-Oct	8-Oct	22-Oct
5-Nov	19-Nov	18-Nov
12-Dec	29-Dec	22-Dec

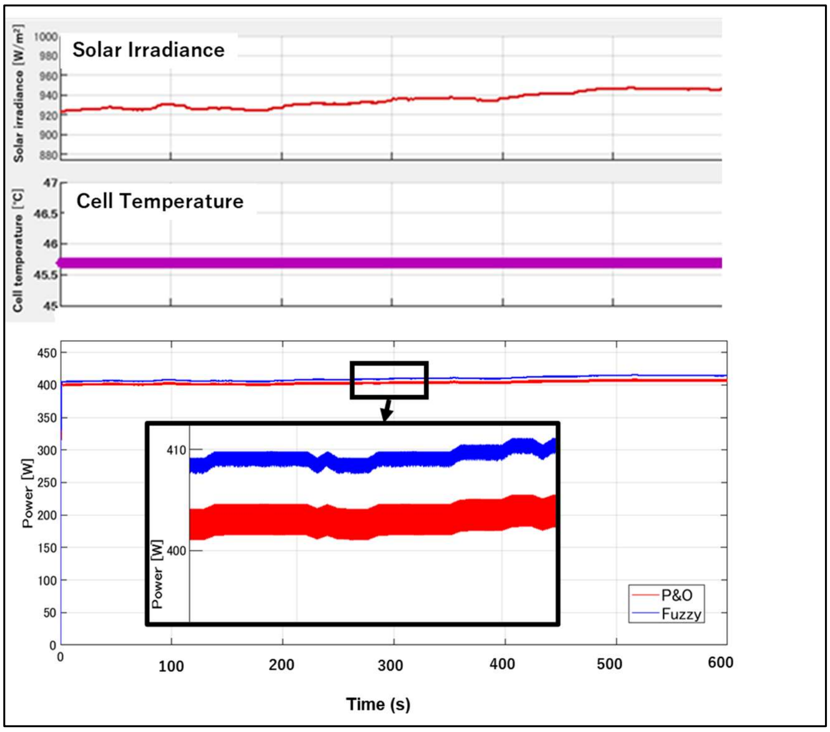


Fig 7. Comparison between the FLC-based and P&O-based MPPT systems for the PV (sunny day)

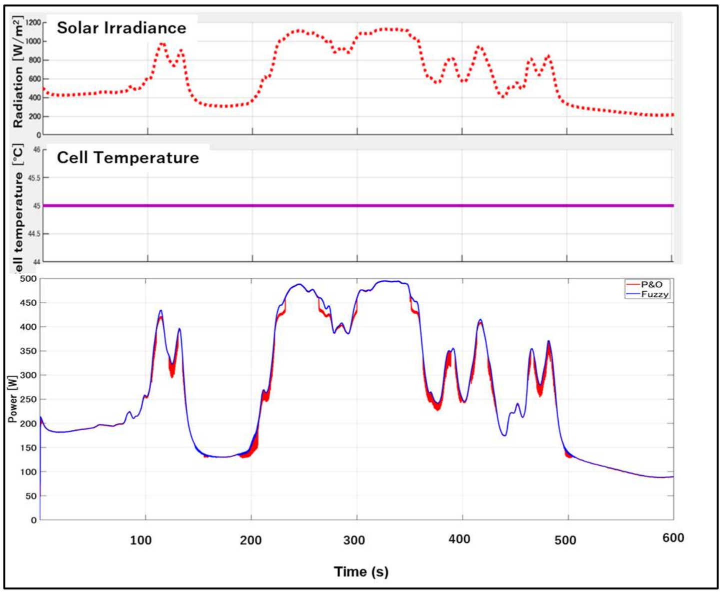


Fig 8. Comparison between the FLC-based and P&O-based MPPT systems for the PV (cloudy day)

The deviation from the P&O-based MPPT appears during the fast-changing of environmental conditions, such as rapid changes in solar irradiation or ambient temperature, which is basically due to its lower tracking speed, especially when the variation of power caused by the different intensity of irradiation is larger than the one produced by the perturbation. Compared with the FLC-based MPPT, the fixed step-size perturbation applied to the P&O-based MPPT cannot satisfy both dynamic and steady-state response conditions, since big perturbations provide a rapid reach of MPP, but also cause large oscillations. On the other hand, small changes remove these oscillations but give a slow performance to the MPPT. Furthermore, partial shading can cause the MPP tracker to be oscillating around one of the multiple local power peaks. Another drawback of the P&O-based MPPT is that it cannot recognize the difference between local and global MPP. Therefore, the expected output power is lower than the FLC-based MPPT. Figure 9 shows the comparison between the FLC-based and P&O-based MPPTs for the wind turbine on April 1, 2020. As shown in this figure, there are almost no differences between fuzzy and P&O controller results for the wind power generator. Although the proposed FLC offers excellent performance in controlling solar panels, it doesn't significantly improve the wind turbine's maximum power, particularly at low wind speed. This is because the wind control system includes mechanical (pitch control) and electrical power sections, but only the electrical part was considered in the simulation model. The simulation results for an entire period of one year are reported in Table 2. The results revealed a potential of 2% extra power generation from the proposed HRES, using the FLC-based MPPT system. According to the results, by implementing the FLC-based MPPT system, about 26.2 kWh/y excess electricity can be extracted from each kW installed capacity of solar panels in the Chikushi campus.

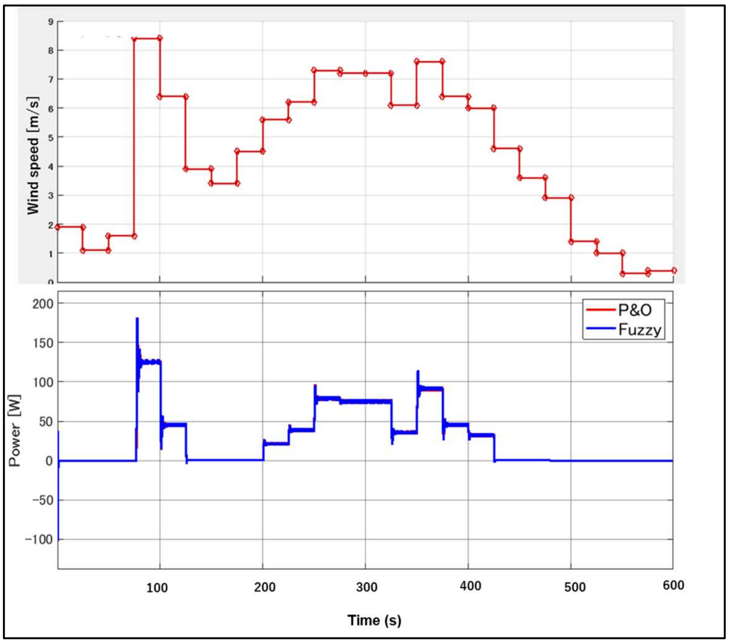


Fig 9. Comparison between the FLC-based and P&O-based MPPT systems for the wind turbine (windy day).

Tab 2. Surplus output power from the FLC-based MPPT compared to the P&O-based MPPT.

	P&O-based MPPT[kWh]	**FLC-based MPPT [kWh]**	**Difference [kWh]**	**saving [%]**
January	33.41	34.16	0.76	2.27
February	38.55	39.37	0.82	2.13
March	52.92	54.47	1.55	2.94
April	66.05	67.92	1.87	2.83
May	62.33	63.73	1.40	2.24
June	66.27	67.54	1.27	1.92
July	26.20	26.57	0.37	1.42
August	54.01	55.02	1.01	1.86
September	52.68	53.91	1.24	2.35
October	59.61	60.69	1.07	1.80
November	49.67	50.59	0.92	1.84
December	15.79	16.09	0.29	1.86
Total	577.49	590.06	12.57	**2.18**

Development of the indoor microgrid experimental setup

For a more accurate analysis, a new indoor microgrid test system, including an artificial solar power simulator and wind turbine emulator, was set up at the EES laboratory, Kyushu University that allows the proposed FLC-based MPPT to be tested more accurately, taking into account sudden changes in sunlight and wind speed (Figure 10).

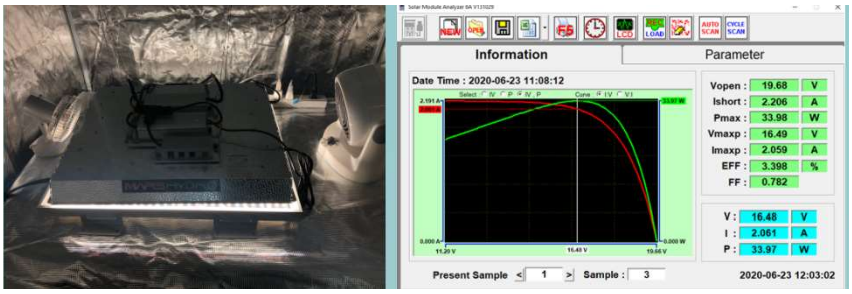
Fig 10. Indoor microgrid experimental setup designed and developed in this research

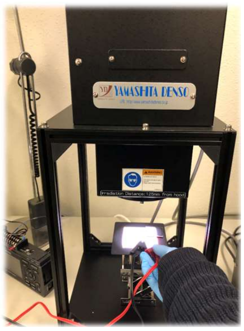
The indoor microgrid test setup consists of the following parts:

- **Solar I-V Test:**

  -LED light with a light Intensity at 910 uMol and SI of 500 w/m^2

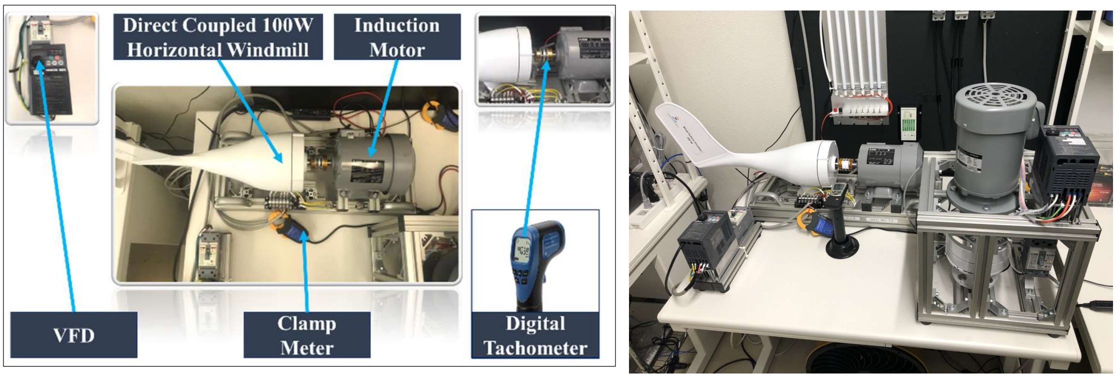
  - PV analyzer PROVA 200





- **Standard type solar simulator (Single light type):** A high-pressure xenon lamp as a light source, irradiate the measurement sample with light with an irradiation intensity of 1 SUN with a spectral distribution similar to sunlight (AM 1.5 G) received on the ground.

- **Wind Turbine emulator:** Dynamometer coupled with the PMSG of a 100 W horizontal-axis and vertical-axis wind turbine. The source of direct-driven PMSG is an induction motor that is directly coupled to the PMSG turbine, and its speed can be controlled by a variable frequency device (VFD) from 0Hz to 50 Hz that behaves as a proxy of wind speed variation.



The results of the accurate power control and battery State of Charge (SOC) management based on using the proposed FLC-based MPPT for a given dynamic load under a highly variable solar irradiation and wind speed are shown in Figure 11.

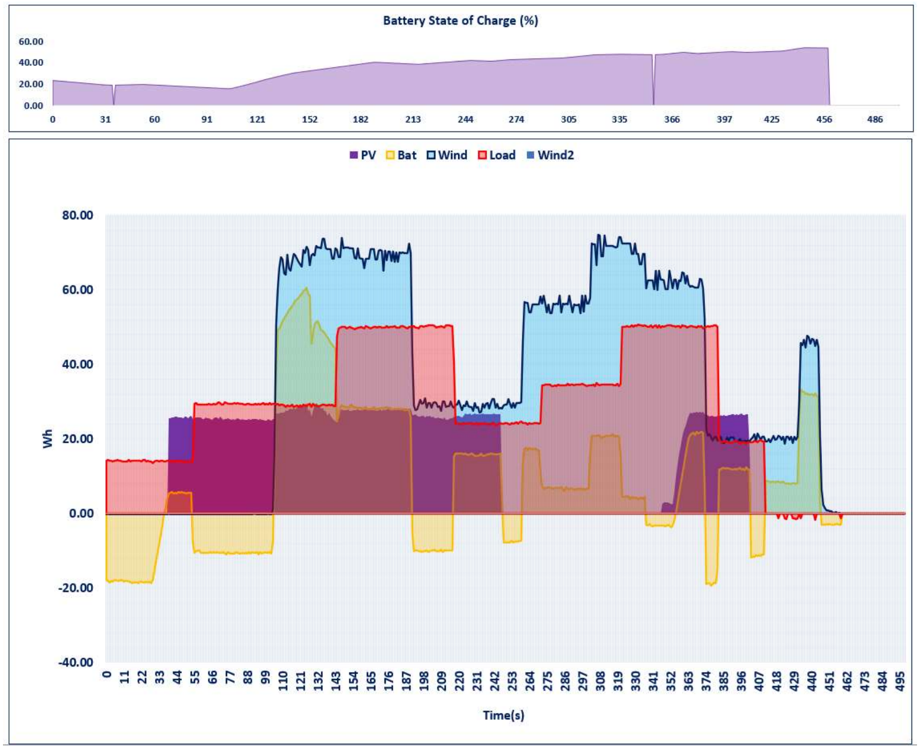


Fig 11. Test of the proposed FLC-based MPPT under variable solar irradiation and wind speed

Summary

This study proposed a novel MPPT based on fuzzy logic control, which provides rapid power control with smaller oscillations under variable weather conditions. The dynamic simulation of the proposed HRES system was performed in MATLAB -Simulink. The research results indicated the FLC-based MPPT's better performance in optimal power controlling of the HRES. Compared to the existing commercial MPPTs in the market, deploying the proposed MPPT can realize an extra 26.2 kWh of electricity per annum from each KW installed capacity of solar panels at the Chikushi campus. While costs are important, the advantage of using such MPPT can facilitate the rapid deployment of hybrid renewable-based microgrids in the residential sector in Japan.

Research Achievements

Peer-review Journal papers

[1] Shaqour A., Farzaneh, H., Yoshida Y., Tatsuya H. (2020). *Power Control and Simulation of a Building Integrated Stand-Alone Hybrid PV-Wind-Battery System in Kasuga City*, Japan, Energy Reports, 6, 1528-1544.

[2] Hinokuma, T., Farzaneh, H., Shaqour, A. (2021). *Techno-Economic Analysis of a Fuzzy Logic Control Based Hybrid Renewable Energy System to Power a University Campus in Japan*. Energies, 14 (7), 1960.

[3] Shaqour, A., Farzaneh, H., Almogdady, H. (2021). *Day-Ahead Residential Electricity Demand Response Model Based on Deep Neural Networks for Peak Demand Reduction in the Jordanian Power Sector*. Applied Sciences, 11(14), 6626.

[4] Farzaneh, H.; Malehmirchegini, L.; Bejan, A.; Afolabi, T.; Mulumba, A.; Daka, P.P. (2021). *Artificial Intelligence Evolution in Smart Buildings for Energy Efficiency*. Applied Sciences, 11, 763

Conference Papers

Sohail, K. Farzaneh, H. (2021) *Wind Turbine Minimum Power Loss Optimization using Non-linear Mathematical Programming*, EcoDesign 2021, Tokyo, Japan, 1-3 December 2021

Master Thesis

Tatsuya Hinokuma. *Design and development of a hybrid renewable energy system using fuzzy logic controller for maximum power tracking*, Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Japan, March 2021