DESIGN AND ANALYSIS OF A STANDALONE HYBRID PHOTOVOLTAIC/THERMAL (PV/T)-WIND-BATTERY MICROGRID SYSTEM FOR ENHANCED HOUSEHOLD ENERGY ACCESS

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DESIGN AND ANALYSIS OF A STANDALONE HYBRID PHOTOVOLTAIC/THERMAL (PV/T)-WIND-BATTERY MICROGRID SYSTEM FOR ENHANCED HOUSEHOLD ENERGY ACCESS

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ABSTRACT:

This study has two parts. In the first part, the research presents the dynamic modeling and simulation of an off-grid DC microgrid consisting of a photovoltaic panel, wind turbine, and battery incorporating power control. In addition, an indoor test system was achieved by developing a 48*hr* real-time experimental validation of the simulation model with meteorological datasets from Fukuoka, Japan. Furthermore, a 72*hr*-simulation scenario analysis revealed a sufficiency factor above 1.

The second part of the research aims to develop a modeling framework to evaluate the dynamic performance of a hybrid photovoltaic/thermal (PV/T) system integrated with a DC microgrid. First, a thermal-electrical optimization model based on power maximization from the PV/T system is developed for the design. Secondly, a user-defined PV/T component mask is developed in Matlab-Simulink using the optimal parameters. The component is then integrated with the wind turbine/battery and compared with a conventional PV/wind/battery microgrid in terms of power generation based on a 72-*hr* scenario simulation.

KEYWORDS: Hybrid Renewable Energy System, Microgrid, Validation, Power Control, Photovoltaic thermal (PV/T), Flow rate, Optimization

INTRODUCTION:

1. Hybrid Microgrids: Microgrids are essential for next-generation energy systems because they efficiently integrate distributed energy resources. Several researchers have comprehensively studied the dynamic modeling, optimization, and control operation of integrated energy systems. An extensive review reveals that more research on hybrid energy systems with experimental validation needs to be conducted [1]. Therefore, an integrated hardware and software architecture required for running a real-time simulation of a scaled-size hybrid renewable microgrid is developed and validated.

2. PV/T integrated with Hybrid Microgrids: PV systems have low conversion efficiencies, ranging from 6-25% [2], mainly due to cell temperature. The photovoltaic thermal (PV/T) system is the most contemporary technology to achieve greater conversion efficiency. Accordingly, investigations on PV/T systems using specialized numerical models have been suggested to assess their performance [3]. Regardless, their key role in hybrid microgrids of improving overall reliability, under stochastic conditions has not been paid much attention. To this end, this research presents a comprehensive modeling framework that can be used to analyze the dynamic performance of a PV/T/wind/battery microgrid.

MODEL DEVELOPMENT, SIMULATION, AND VALIDATION:

1. Hybrid Microgrids: An indoor experimental system in Figure 1. was developed in the Energy and Environmental Systems (EES) laboratory at Kyushu University, Japan, to validate the proposed simulation model. It comprises a 50*W* PV panel, a 100*W* horizontal axis windmill, a 12*V*/10*Ah* AGM Deep Cycle battery, a DC load generator, and an MPPT wind/ solar hybrid controller to integrate all the system components.

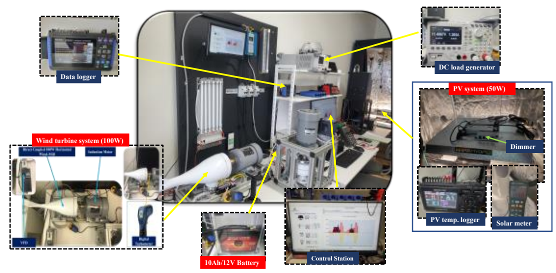

Figure 1. Indoor experimental setup

2. PV/T integrated with Hybrid Microgrids: The first part involves finding the optimal design conditions and the working fluid flow rate that enables the maximum output power from the PV/T system, considering a thermal-electric model based on equation (1). Next, the PV/T system is developed based on the optimal parameters and integrated into the DC microgrid as in Figure 2.

$$Max.\ \ P = \left(I_L - I_o\left[exp\left(\frac{(V+IR_S)}{a}\right) - 1\right] - \frac{V+IR_S}{R_{sh}}\right) \quad (1)$$

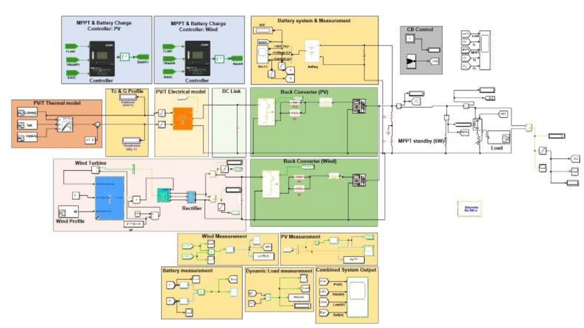

Figure 2. Simulink Microgrid model

RESULTS AND DISCUSSION:

1. Hybrid Microgrids: The simulation model developed in MATLAB/Simulink was validated with the experimental system by comparing the results for a 48*hr* period with hourly meteorological data from 1st to 2nd July 2021 in Fukuoka, Japan, shown in Figure 3.a). In Figure 3.b), the battery exhibits a charging and discharging pattern based on the load and resource availability.

For comparison, the experimental results were averaged every 20 seconds for an hour, while the decimation in the simulation logging was adjusted to 10,000 for a reduction in the log data's effective sample rate. The hourly averaged experimental and simulation results for the PV, wind, battery, and load matched well in Figure 3.c) to f). Generally, suggesting that the model can simulate the dynamic operation of a hybrid microgrid.

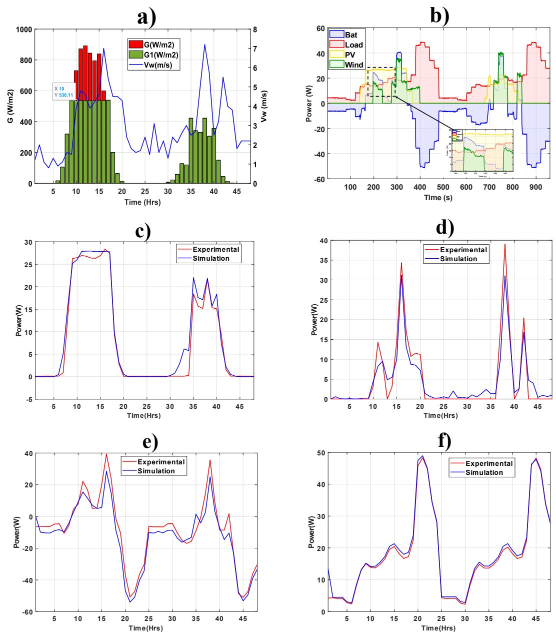

Figure 3. a) Meteorological data, b) Energy balance, c) PV, d) Wind, e) Battery, f) Load

2. PV/T integrated with Hybrid Microgrids: Figure 4. shows the total daily electricity production for the scenarios, highlighting the PV and PV/T. The plot only shows generation energy sources, including solar, wind, and battery- during the discharging period, as it acts like a power source. The rainy scenario has the least wind and solar power generation for both the PV and PV/T but, surprisingly, the highest battery power. The sunny scenario, as expected, has the greatest solar generation contribution of 5.296*kWh* and 5.387*kWh* for PV and PV/T, respectively. Among the sources, wind power is the least due to the small capacity of the wind turbine generator, which would have been greatest in the windy scenario. Additionally, the battery provided the most power overall compared to wind and solar. Generally, a reduction in cell temperature contributes to an enhancement in power production due to cooling but is also affected by its microclimate especially the heat index, insolation, and PV/T design features. The results revealed that the surplus cumulative electricity generation from the PV/T system-based microgrid, when compared to the PV system-based microgrid, was 2.12, 2.74, 1.72, and 0.31% for the cloudy, rainy, sunny, and windy scenarios, respectively.

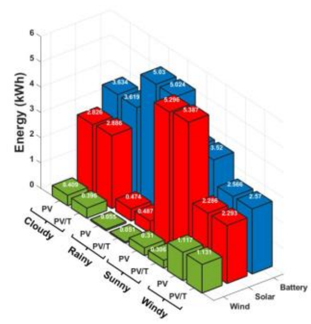

Figure 4. Total daily electricity production in the scenarios

CONCLUSION:

The research was twofold. Firstly, an off-grid hybrid PV/wind/battery DC microgrid was modeled, simulated and validated for a 48*hr*-period depicting minimal RMSE of 1.733, 2.656, 5.881, and 1.511 for PV, wind, battery and load respectively. Furthermore, the 72*hr*-simulation scenarios (sunny, windy, rainy, and cloudy) in Fukuoka, Japan showed that the model is self-sufficient. However, prolonged operation in rainy conditions affects the battery with voltages drastically dipping to 11.5*V* and below. This can be solved by increasing generation. Interestingly, conventional PV(s) have low efficiencies of 6-25% due to cell temperature. This supports the second part of the study, where a photovoltaic/thermal (PV/T) system replaces the PV system due to its merits.

Consequently, a PV/T system was integrated with the DC microgrid to assess its performance. The PV/T was optimally modeled to find the operational parameters usually not specified. A flow rate of 0.0028*kg/s per tube* was obtained. The PV/T was then integrated with the rest of the microgrid using the optimal parameters for performance analysis. A 3-day scenario evaluation showed that the surplus generation from the PV/T-based microgrid was 2.12%, 2.74%, 1.72%, and 0.31% for the cloudy, rainy, sunny, and windy scenarios, respectively, compared to the conventional PV - based type. This is due to the cooling of cells. Moreover, the battery's SOC is significantly improved due to minimal discharge attributed to the extra power that covers part of the load.

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