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OPTIMAL DESIGN AND OPERATION OF AN OFF-GRID HYBRID RENEWABLE ENERGY SYSTEM IN NIGERIA'S RURAL AREA, USING FUZZY LOGIC AND OPTIMIZATION TECHNIQUES

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ABSTRACT

This research focuses on the technical and economic analysis of implementing an off-grid Hybrid Renewable Energy System (HRES) in a community called Olooji, situated in Ogun state, Nigeria. A size optimization model is developed based on the novel metaheuristic Particle Swarm Optimization (PSO) technique to find the optimal configuration of the proposed off-grid system and a Fuzzy Logic Controlled Energy Management System (EMS) will be developed for dynamic power control and energy management of the proposed HRES. The result from this study is important for quick decision-making and effective feasibility studies for optimal techno-economic synopsis of implementing mini-grids in rural communities.

KEYWORDS

Hybrid Renewable Energy System (HRES), Particle Swarm Optimization (PSO), Fuzzy Logic Control (FLC)

1. INTRODUCTION

Nigeria, the most populous country in Africa, has one of the lowest rates of electrification in the world. About 43% of the Nigerian population, representing 85 million people, have no access to grid electricity. Nigeria currently has an entire installed electricity generation capacity of around 12.5GW, out of which just about 3.1GW gets to the final consumers. Considering the Nigerian population of over 200 million people and a rule of thumb estimates of 1,000MW for a million people, Nigeria will only get the electricity needed to support full industrialization when the country can produce up to 200 GW of electricity. Nigeria has a massive capacity for generating electricity from its numerous green energy resources, with a daily energy potential of 934 GWh from Biomass, 120 GWh from solar, 84 GWh from hydro, and 44 GWh from wind [1]. However, the usage of renewable energy systems is usually in hybrid form as the availability of all renewable energy sources is not dependable. Storage systems such as batteries or hydrogen fuel cells and emergency generation equipment such as a diesel generator are always included in the hybrid renewable energy systems to back up against fluctuation and to ensure reliance. Due to several numbers of equipment involved in HRES, excessive sizing leads to exorbitant capital, and insufficient sizing leads to an unreliable system. The two situations are unwanted. This research aims to develop an optimal sizing model that finds the least cost configuration of the HRES system, which is then integrated into an EMS model that ensures optimal energy scheduling during HRES operation in an off-grid community. Integration of the two systems will produce a combined model that ensures energy reliance at the optimal cost.

2. SIZE OPTIMIZATION MODEL

Figure 1 shows the typical structure of the considered HRES. The system contains solar photovoltaic modules, a wind turbine, a battery, an inverter, a diesel generator, and the consumer load. The inverter is assumed to contain an energy management system that controls the power flow between the load demand and the different energy sources.

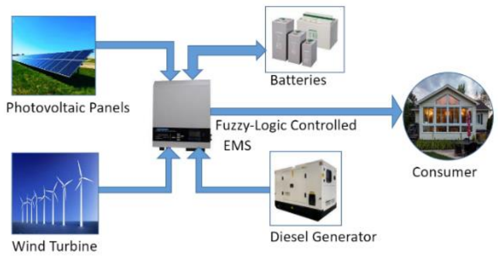

Fig. 1. Hybrid Renewable Energy System Structure

The PSO algorithm is used to determine the optimal sizes of the HRES equipment by minimizing the cost (LCOE) function.

$$LCOE\left(\$/_{kWh}\right) = \frac{Annualized\ Cost(\$)}{Annual\ Energy\ Supplied\ (kWh)}$$

The cost function is subjected to technical and reliability (LPSP) constraints.

$$LPSP = \frac{\sum P_{load} - P_{pv} - P_{wind} - P_{battery} - P_{DG}}{\sum P_{load}}$$

The renewable energy resource data, equipment characteristics, and load consumption data of the community are used to determine the optimum value for the equipment. The load is preferably powered using renewable energy (RE), and power is drawn from the battery only when renewable energy is insufficient. The system uses a diesel generator for emergency supply when the RE is unavailable and the battery energy is inadequate for the demand. The developed model used January (dry season) and August (rainy season) data, representing the two seasons in Nigeria [2]. Two scenarios were considered. In the first scenario, the boundary conditions used were expanded to allow the algorithm to choose the equipment values without restrictions. In the second scenario, the boundary conditions were restricted to limit the battery size to realistically and economically obtainable.

3. OPTIMAL ENERGY MANAGEMENT SYSTEM

An optimal energy management system will ensure an energy balance between the demand and the supply and guarantee maximum utilization of the available renewable energy. For efficient and optimal power control, the fuzzy logic controller was designed to schedule among the energy sources and establish the energy balance of both the supply and demand sides. The solar irradiation data, the wind data, the equipment sizing obtained from the PSO optimization model and the load consumption data of the Olooji community were considered to analyze the performance and effectiveness of the fuzzy logic controller. The Fuzzy Logic Controlled Energy Management System (FLC-EMS) was designed in MATLAB Simulink IDE.

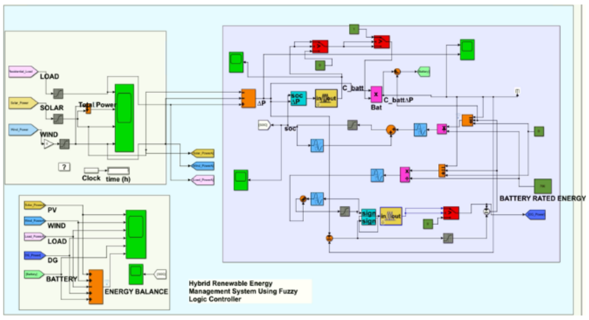

Fig. 2. The designed FLC-EMS in MATLAB Simulink IDE

The FLC-EMS uses two FLCs denoted as FLC1, which manages the battery charging and discharging and FLC2, which manages the diesel generator operation. Tables 1 and 2 show the control rules to be implemented by FLC1 and FLC2, respectively.

Table 1: Rule Table for FLC1

ΔP(t)/SOC	Multiplier (C_{batt})						
	ML	L	SL	S	SH	H	MH
NH	MH	MH	MH	MH	MH	MH	ML
NS	MH	MH	MH	MH	MH	MH	ML
NL	MH	MH	MH	MH	MH	MH	ML
PL	ML	ML	ML	ML	MH	MH	MH
PS	ML	ML	ML	ML	MH	MH	MH
PH	ML	ML	ML	ML	MH	MH	MH

Table 2: Rule Table for FLC2

ΔP(t)'/SOC	$P_{DG}(t)$						
	ML	L	SL	S	SH	H	MH
NH	VL	VL	VL	VL	VL	VL	VL
NL	VL	VL	VL	VL	VL	VL	VL
NS	VL	VL	VL	VL	VL	VL	VL
PL	VL	VL	VL	VL	VL	VL	VL
PS	S	S	S	VL	VL	VL	VL
PH	H	H	MH	MH	VL	VL	VL
PMH	VH	VH	VH	MH	VL	VL	VL
PVH	VH	VH	VH	MH	VL	VL	VL
PMVH	VH	VH	VH	MH	VL	VL	VL

4. RESULTS AND DISCUSSION

The LCOE for scenarios 1 and 2 was estimated at 0.48 USD/kWh (@ LPSP= 0.20%) and 1.17 USD/kWh (@ LPSP= 0.05%), respectively. For the two scenarios, wind power was not used because the wind speed in the case study community is deficient. Hence, using the wind turbine to meet the extra energy required would be more expensive. The second scenario required a diesel generator that was not needed in the first scenario; this raised the LCOE by more than 150% due to the excessive cost of fuel required to run the diesel generator. For the FLC-EMS, the SOC was kept within the required range that would ensure battery longevity. The energy balance of the HRES system for each time unit measures the effectiveness of the EMS. The energy balance is the summation of all energy sources minus the load and is expected to be zero if the supply meets the demand at each time. Figures 3 and 4 are the combined diagram of all energy sources for January and August, respectively. These figures show that the energy balance (blue line) is equal to zero for each hour, indicating that the FLC-EMS effectively ensures energy balance.

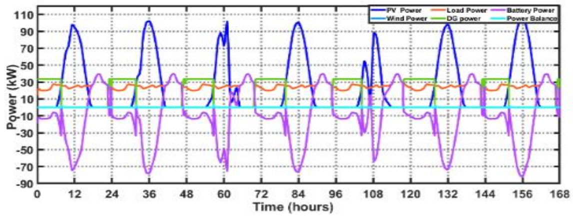

Figure 3: Power distribution for One week in January

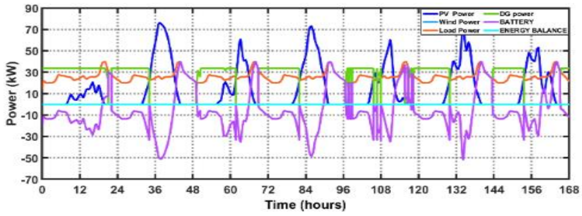

Figure 4: Power distribution for One week in August

5. CONCLUSION

Two scenarios were considered for optimal sizing using the proposed HRES. In the first scenario, the LCOE for electrifying the off-grid rural community was found to be 0.48 USD/kWh with the HRES components estimated as: 130kW PV, 0kW wind turbine, 1370kWh battery, and 0kW DG. However, because of the high capital associated with using the maximum battery capacity, a second scenario where half of the maximum capacity would be used was considered. In this scenario, the LCOE for electrifying the off-grid rural community was found to be 1.17 USD/kWh with the HRES components estimated as: 100kW PV, 0kW wind turbine, 700kWh battery, 25kW DG. The results revealed that wind energy could not be considered as an energy source in the two scenarios because of the low wind speed in the region. The FLC-EMS rules were designed based on expert knowledge and were used to schedule among the energy sources to meet the load demand while prioritizing renewable energy and ensuring energy balance. Results from this study can be used as a general overview and a quick feasibility study to determine the technical and economic implications of implementing and operating HRES in off-grid rural communities in Nigeria.

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