INTEGRATION OF WATER DESALINATION SYSTEMS ON ELECTRICAL MICROGRIDS FOR REMOTE COASTAL COMMUNITIES

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ABSTRACT
Remote coastal communities in developing countries face significant challenges for access to both electricity and freshwater. Water desalination systems emerge as a potential solution to provide freshwater, however their high energy requirements have been one of the main limitations for the deployment of such systems. Electrical microgrids are a decentralised alternative which can provide access to electricity for these communities. The impact of the integration of the water desalination systems to these electrical microgrids must be explored, to extend the auxiliary services that can be provided by a microgrid. This work seeks to analyse, by using numerical simulations, the design, integration and management of an electrical microgrid, where a part of its energy demand will be used by a desalination system. The developed methodology presents the creation of a model in MATLAB/Simulink® with photovoltaic generation, residential loads, critical loads and the desalination system. A fuzzy logic controller is implemented for the energy management system, with the objective of maintaining the production of fresh water based on the electric energy demand of the various loads within the microgrid. This fuzzy logic model takes into consideration solar power production, variable electrical energy demand and critical loads with constant electrical energy demand. The simulation results demonstrate how it was possible to define a set of rules that allowed regulating the operation of the desalination system connected to the microgrid, making decisions to shape the demand curve handling the freshwater flow provided by the desalination system.
Keywords: desalination systems, microgrids, photovoltaic generation.

1 INTRODUCTION

In remote coastal communities, sustainable access to fresh water is a challenge due to the scarcity of water sources. With the increase in population and the effects of climate change, this problem is further exacerbated. Electric microgrids have emerged as a viable solution to improve the energy autonomy of these communities, leveraging renewable sources and advanced storage systems. However, the integration of desalination systems within these microgrids presents a significant but complex opportunity.

This multifaceted approach not only aims to address the growing concerns about water security and climate change, but also promotes energy self-sufficiency and minimizes the environmental impact associated with obtaining potable water. The integration of advanced desalination technologies with renewable energy, such as photovoltaic (PV) solar energy, presents itself as a promising strategy in the pursuit of sustainable and scalable solutions for potable water supply [1]. Desalination with renewable energies today represents only 1% of the world's desalination capacity. Reverse osmosis (RO) based systems are employed in most existing renewable energy desalination systems with 62% [2]. PV solar cells are the most widely used renewable energy source for desalination, representing 43% of all current desalination installations [3].

WIT Transactions on Ecology and the Environment, Vol 262,
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/SDP240471

The Dominican Republic, due to its high solar irradiation, presents an interesting case to study the integration of desalination systems based on renewable energy. Specifically, the northwest region is an attractive study case due to the high solar irradiation and the intense drought season [4]. Furthermore, the electrical distribution system on this region faces challenges regarding the accessibility of remote coastal communities to the electrical utility, for this reason the deployment of microgrids could be a solution for electricity access to this communities. Additionally, they have limited availability to freshwater sources which makes the study of desalination an imperative need in this region.

Renewable energy sources are abundant and environmentally friendly, thus presenting a promising alternative to desalination units. For this reason, the water–energy nexus is a crucial step towards sustainable development [5]. The combination of desalination technologies with PV solar energy not only has the potential to meet critical water access needs in remote coastal communities, but also establishes a replicable and sustainable model that could be adapted for implementation in other communities facing similar challenges worldwide. This comprehensive approach not only improves the quality of life of local inhabitants but also contributes to building resilience against global climate and environmental challenges.

In this context, it is important to highlight the relevance and potential of emerging technologies in the field of desalination and renewable energy. Continued research and development in these areas are essential to drive innovation and improve the efficiency of integrated systems [6]. Additionally, the use of modelling and simulation tools, such as MATLAB/Simulink®, plays a crucial role in the design, analysis, and optimization of these systems, allowing a comprehensive evaluation of their feasibility and performance [7].

All these statements highlight the relevance to study the integration of energy-desalination systems for an efficient and sustainable microgrids configuration. Microgrids are defined as a group of distributed generation systems and local loads with the capability of functioning independently or connected from the main electrical grid [8]. One of the main elements for the transition to the smart grid paradigm are microgrids [9], therefore, considering the water–energy nexus in energy management system (EMS) for a microgrid with desalination loads is relevant.

2 METHODOLOGY

The developed methodology for this work is focused on the development of an energy managements system within a microgrid which can provide water–energy nexus based operating decisions. This methodology and corresponding phases are the following:

i. The selected remote coastal community in Dominican Republic is analysed to establish the operating conditions of the electrical microgrid considering the demographic and geographic information available.
ii. Characterization of the desalination system within the available desalination technologies to be integrated with the electrical microgrid, considering water production vs energy requirements.
iii. Creation of the MATLAB/Simulink® simulation model using as an input the energy requirements of the analysed remote coastal community and the desalination system.
iv. Design of the fuzzy logic system using MATLAB/Simulink® Fuzzy Logic Designer toolbox. The requirements for the membership functions and the decision rules are defined.

2.1 Remote coastal community: Pepillo Salcedo, Montecristi, Dominican Republic

This community is in the northwestern region of Dominican Republic, with a reported number of 2,199 households in 2022 [10]. Furthermore, this region is being promoted for additional tourism development, thus demographic growth and new tourism projects are expected. This will create new limitations to the scarce water and energy resources in the region [11]. In Fig. 1 the satellite imagery of the community is presented, as can be seen, the location is near the coast, providing access to seawater. In addition, the low building density allows for the installation of a PV solar plant without affecting the residential or commercial land use. Moreover, a local hospital is in the zone, which can be considered as critical load.

Figure 1: Google Maps capture of the Pepillo Salcedo community in Montecristi, Dominican Republic.

Regarding the availability of solar energy resource, as presented in Pena and Gordillo [12], this zone presents one the highest irradiation level in the country. This opens the opportunity for the development of microgrids systems with considerations for using the excess energy for secondary services, such as water production. Table 1 shows the maximum power demand to be covered in this community for a microgrid considering future residential and commercial growth. As can be seen a total of 240.0 kW of electrical power will be considered for the electrical microgrid to match the maximum expected demand. From the total number of reported households, a consideration of 4.5% are taken to be close to the coastal area for the installation of water pipelines to the desalination system.

Table 1: Power requirements for residential/commercial/critical loads.

Load description	**Required electrical power**
Residential loads (100 homes)	60.00 kW
Commercial loads (2 hotels)	140.0 kW
Critical loads (1 hospital)	50.00 kW

2.2 Desalination system review

Water scarcity is a critical issue in remote coastal communities, exacerbated by population growth and industrial demands. The integration of water desalination systems with electrical microgrids, particularly those powered by renewable energy, offers a sustainable solution to meet fresh water needs in these areas [13]. Desalination technologies include RO, multi-effect distillation (MED), and multi-stage flash distillation (MSF). Each technology has specific energy requirements and operational characteristics that influence its suitability for integration with renewable energy sources. Some of the technologies available are:

- RO: Utilizes semipermeable membranes to separate salts from water, requiring a significant amount of electrical energy, generally supplied by PV solar systems [14].
- MED: Employs multiple stages of evaporation and condensation, being effective when combined with thermal energy sources, such as solar thermal collectors [15].
- MSF: Involves the sequential evaporation of water into vapor through multiple stages, benefiting from thermal energy provided by concentrated solar power plants [14].

Various studies have demonstrated the feasibility and benefits of integrating renewable energy with desalination systems. Ghaffour et al. [13] evaluated the use of PV energy for RO desalination. Despite higher initial costs, the study found that PV-powered RO systems could be economically viable for small-scale applications in remote areas. For this reason, this kind of system is chosen in the methodology of this work. As a reference system for the desalination plant, the model proposed in Karabelas et al. [16] is chosen. This is a RO system of 10 m^3 production of fresh water per hour. The specific energy consumption for the system detailed by the authors is 2.374 kWh/m^3. For simulation purposes, we will round this value to 2.4 kWh/m^3, thus for a production rate of 10 m^3/hour a power input of 24 kWh is required. For more information regarding the configuration of the chosen desalination system please refer to Karabelas et al. [16]. Fig. 2 details the components of an RO desalination system.

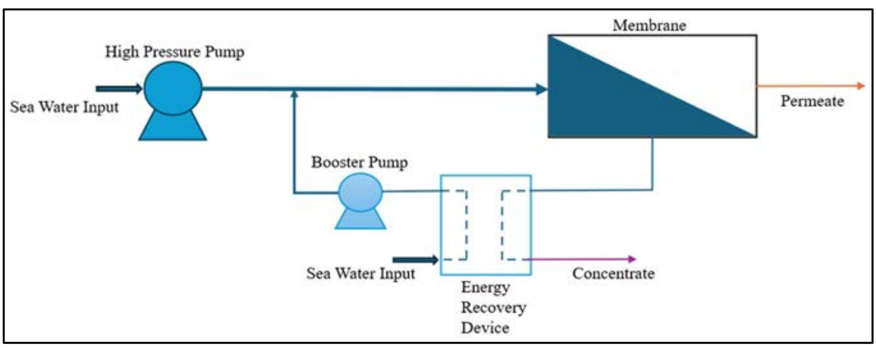

Figure 2: RO system with energy recovery device as presented in Karabelas et al. [16].

2.3 Microgrid model: MATLAB/Simulink® implementation

For the study of the microgrid system an energy management perspective will be implemented. These considerations, from the hierarchical control perspective, only takes into account the steady state functioning of the distributed generation and loads inside the microgrid [17]. Thus, the constructed model will focus on gathering the steady state information of the root means squared (RMS) values of electrical power. The Specialized Power System toolbox of Simscape Electrical is used with version 2023a of MATLAB/Simulink® for constructing the model. Fig. 3 shows the block diagram of the implemented MATLAB/Simulink® model.

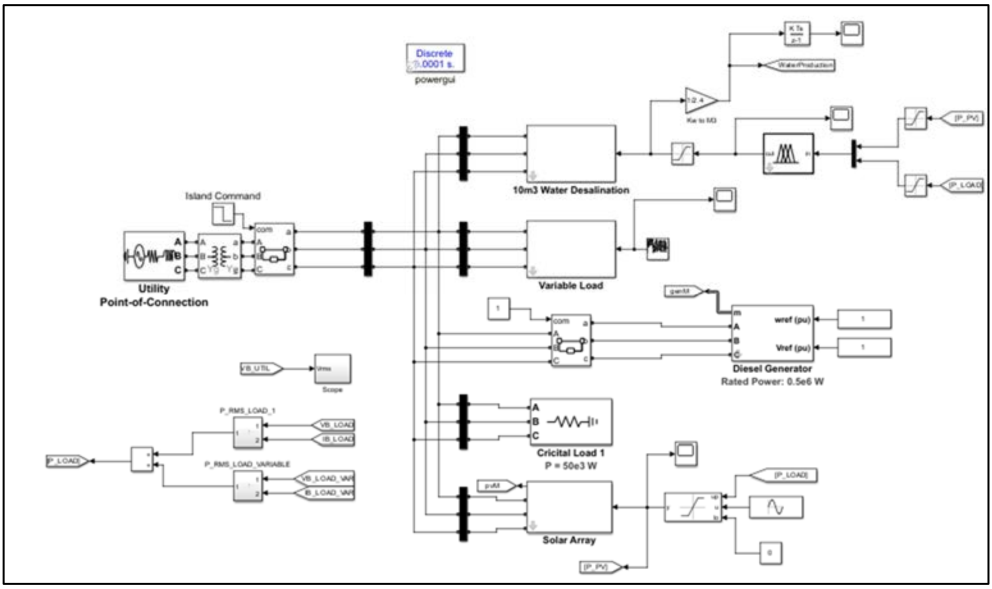

Figure 3: Implemented microgrid model for the proposed scenario with the integration of desalination load.

The critical load is considered as a fixed 50 kW load, while the commercial/residential loads are considered variable. The time span of the simulation is 60 seconds, due to the computational requirements. To correctly explore the functioning of the PV generation with the variable loads, a hypothetic sinusoidal waveform for the evolution of the irradiance is considered. For the variable load, a random repeating sequence is introduced, with a variation between 50 kw to 240 kw. As the PV generation system is working in grid connected mode, a diesel generator is integrated to the microgrid to ensure stability and provide the voltage/ frequency reference in case of islanded operation. The simulation is conducted in discrete time with a time step of 10^{-4} s. In the instant of 15 seconds, the microgrid is disconnected from the main utility, in this way the presented simulation accounts for both cases, grid connected and disconnected operation.

Regarding the water desalination plant, it is represented by a variable load controlled by a fuzzy logic implementation. As shown in the previous section, the selected model requires 2.4 kW for 1 m^3 of water production, this is model as a liner gain, with a saturation for the maximum production of $10m^3$ of water production. The operating voltage of the microgrids is 12.47 kV which is a common distribution network voltage in the Dominican Republic, and the operating frequency is 60 Hz.

2.4 Fuzzy logic controller (FLC) for EMS

Microgrid's EMS must consider various situations for the decision of the operation of the diverse elements inside the microgrid. FLC presents themselves as a heuristic alternative for model-based EMS systems. MATLAB-Simulink® offers a complete toolbox for the design of FLC which can be integrated into numerical simulations constructed in Simulink. The FLC relays on the creation on membership functions to map a set of rules between inputs and outputs based on the expected functioning of the system under control. The proposed FLC in this work has the following functional parts:

- Two inputs with three membership functions each one.
- A total of seven rules mapping the membership functions to the output.
- One output with two membership functions.

For the FLC, the available PV power generation and the power demand from the loads are taken as the two inputs (with maximum input value of 240 kW). The output is the power to be used by the desalinization plant (with a maximum of 24.0 kW). Fig. 4 presents the structure of the proposed FLC design done in MATLAB/Simulink®. The Mamdani Type 1 block refers to the rule based defuzzification system as presented in Nguyen et al. [18]. The selected rules are shown in Fig. 5.

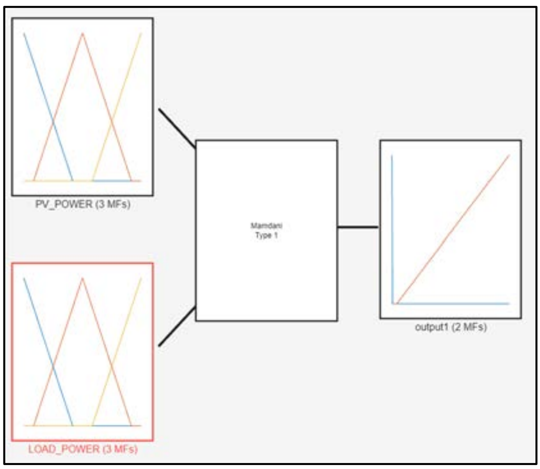

Figure 4: Proposed FLC structure. A Mamdani Type 1 fuzzy inference is used.

System: mamdanitype1

Add All Possible Rules | Clear All Rules

	Rule	Weight	Name
1	If PV_POWER is low and LOAD_POWER_DEMAND is low_p then output1 is low	1	rule1
2	If PV_POWER is high and LOAD_POWER_DEMAND is low_p then output1 is high	1	rule2
3	If PV_POWER is low and LOAD_POWER_DEMAND is medium_p then output1 is low	1	rule3
4	If PV_POWER is high and LOAD_POWER_DEMAND is medium_p then output1 is high	1	rule4
5	If PV_POWER is low and LOAD_POWER_DEMAND is high_p then output1 is low	1	rule5
6	If PV_POWER is medium and LOAD_POWER_DEMAND is high_p then output1 is low	1	rule6
7	If PV_POWER is high and LOAD_POWER_DEMAND is high_p then output1 is low	1	rule7

Figure 5: Proposed FLC structure. A Mamdani Type 1 fuzzy inference is used.

3 RESULTS

This section presents the results of executing the simulation detailed in the methodology developed for this work. A total of 60 seconds of simulation time was run using MATLAB/Simulink® with the discrete solver. An extreme variation of available PV power is introduced during the simulation to test the capability of the FLC controller of regulating the production of water. Furthermore, random loads variations were introduced to test the repeatability of the controller. The resulting waveforms are shown in Fig. 6. As can be seen, the variations of voltage and frequency are compensated by the diesel generator, ensuring a stable primary hierarchical control on which the FLC based EMS can make decisions regarding the water production from the desalination plant.

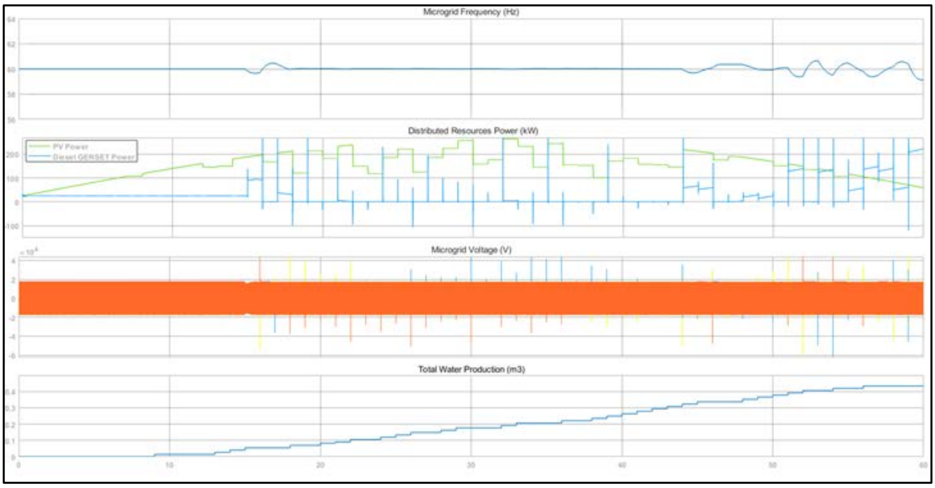

Figure 6: Simulation results covering the energy–water nexus implemented with the FLC for the microgrid.

Small voltage and frequency variations can be seen when an abrupt load power change is presented. This verifies that the simple implementation of the primary level hierarchical control is working as expected, using the voltage/frequency reference frame provided by the diesel generator. Various moments can be identified from the results of the simulation, the microgrid operates in grid connected mode for the first 15 seconds. In this period, any disturbance regarding the power production is absorbed by the main electrical grid and the diesel generator is maintained in a fixed operating point, synchronized with the electrical utility.

At 15 seconds, the PCC is disconnected from the utility by the relay receiving the operated in islanded mode command. At this moment, the diesel generator oversees voltage/frequency regulation. As solar power increases, the power supply by the diesel generator decreases, as can be observed in Fig. 6. For avoiding injecting current into the diesel generator, the power setpoint of the PV system is saturated to the power required by the load. The waveform observed follows the random changes of the simulated variable load. The spikes presented on the waveforms correspond to the damping offered by the generator to the abrupt changes in power demand. Adding transitions rates was no considered with the purpose of testing with extreme cases the stability of the conducted simulation.

The correct functioning of the voltage/frequency regulation inside the microgrids enables evaluating the FLC control system. The information of the available PV power and the required electrical demand is provided to the FLC control, which outputs the power command to the desalination plant. The defuzzification process is conducted for providing the power input to the water desalination plant.

This output of the FLC system controls the power demand of the desalination plant and, using a conversion constant, generates the water production output. The resulting power commands given by the FLC are shown in Fig. 7. As can be seen when comparing Fig. 6 and Fig. 7, the relationship between the PV generation and the load power demand affects the power setpoint for the desalination process.

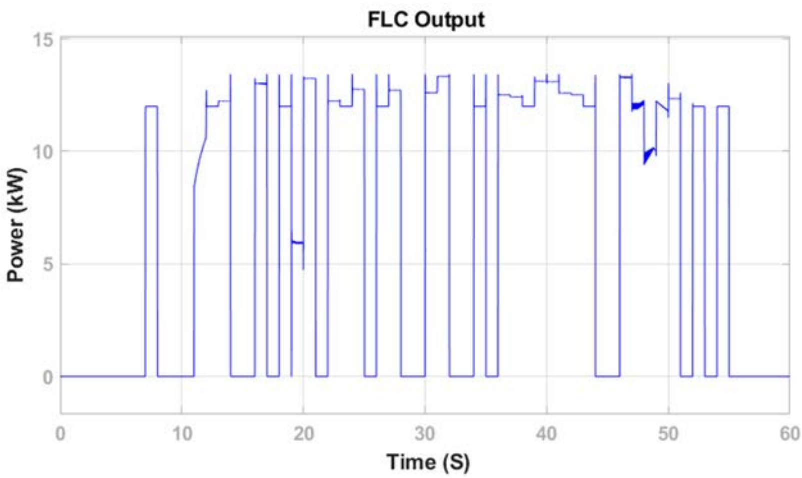

Figure 7: FLC power output command for desalination plant.

The decisions made by the FLC system reflect the logic considered for the selected rules. The first consideration is low power, which is considered under rules 1, 3, and 5 presented in Fig. 5. In each of these cases, the output power for the desalination plant is low. As just two memberships functions are considered for the output of the FLC controller, its functioning reflects and ON–OFF behaviour for the low power production. For medium and high solar power, a membership function with a lineal profile is considered, as shown in Fig. 4. This configuration explains why the system waits until there is plenty of PV power available, considering a low load power demand, to provided higher set point values for the water desalination plant. Furthermore, as water desalination has been selected as one of the main priorities for the system, if there is enough available power from the diesel generator, in occasions, the FLC controller may decide to use PV power to produce fresh water, instead of providing power to non-critical loads. This factor is reflected in rule number 4, where medium power demand may be a trigger condition for a high clean water production from the water desalination plant.

Finally, it is worth noting that there is room for improving the membership functions and the defuzzification process of the proposed FLC controller. Regardless, the results provided have shown how that the FLC controller can provide a tertiary level of control focused on the coordination of water desalination loads inside of a microgrid working in both, islanded and connected operation.

4 CONCLUSION

The viability of using a FLC for implementing an EMS system focused on the water–energy nexus has been shown. It was possible to conduct a numerical simulation with various operational conditions to examine the stability and capabilities of the proposed strategy. The implemented rules for the FLC are a good starting point for continuing the exploration of these kinds of strategies for the integration of desalination systems inside microgrids. Furthermore, the feasibility of using excess energy from microgrids to power desalination systems as secondary service, and its importance for remote coastal communities have been shown.

In the proposed study case, based in the selected community in the Dominican Republic, the execution of this kind of projects could help to ensure the accessibility to both, water and electrical energy resources. Finally, future work will focus on improving the rule set and the membership functions of the FLC, focusing on expanding the algorithm with considerations of optimality. Another aspect to consider will be the aggregation of additional inputs to improve the decision-making process of the FLC.

ACKNOWLEDGEMENT

This research was funded by the National Fund for Innovation and Scientific and Technological Development (FONDOCYT) of the Ministry of Higher Education, Science, and Technology of the Dominican Republic (MESCYT) through the project FONDOCyT-2020-2021-3C1-148.

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