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Design of a Fuzzy Cognitive Maps variable-load energy management system for autonomous PV-reverse osmosis desalination systems: A simulation survey

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HIGHLIGHTS

- Design of a fuzzy cognitive maps variable load energy management system.
- Investigation of the exchange of an ON-OFF energy management system with a variable load one.
- Variable load operation can present remarkable drinking water production increase on a yearly basis.

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ABSTRACT

In the last decades, much effort has been made in order to couple desalination technologies with renewable energy systems consisting usually of photovoltaics, wind-turbines and batteries, in order, on one hand to reduce cost, and, on the other hand, to be able to power desalination units in regions where electricity availability is low. Normally, the reverse osmosis desalination units operate at nominal point of operation. However, it has been reported that operation of reverse osmosis desalination units at partial load presents lower specific energy consumption. In this paper a variable load Energy Management System (EMS) based on Fuzzy Cognitive Maps (FCM) is developed. In order to assess variable load operation two cases studies are investigated through simulation. For both cases studied, initially a PV-battery system is sized through optimization for a desalination unit operating only at full load. The difference between the two case studies is the capacity factor of the desalination unit considered; for the first case a capacity factor of the desalination unit of about 30% (which translates to about 7 h daily operation at full load) is considered and for the second case study a capacity factor of about 70% (translating to about 17 h of daily operation at full load). Then, the ON-OFF EMS is considered to be exchanged with the FCM variable load EMS that was developed and the yearly drinking water production is compared. The obtained results clearly show that, for an already installed PVROD system, an upgrade to a variable load operation scheme can present considerable increase in the drinking water production from the same system ranging from nearly 41% for the first case study to nearly 54% for the second.

1. Introduction

In our days still 18% of the global population has no access to electricity and there is still 10.6% of the global population without access to improved water [1]. A significant number of this population lives in coastal or island areas, with access to sea water and usually with solar and/or wind energy potential. In the last decades much effort has been made in order to couple desalination technologies with renewable energy systems [2] consisting usually of photovoltaics, wind-turbines, along with a storage subsystem in the form of batteries, in order, in one hand to reduce cost [3], and, in the other hand, to be able to power desalination units in regions where electricity availability is low [4] in an environmentally friendly manner [5].

Abbreviations: CS1, Case Study 1; CS2, Case Study 2; EMS, Energy Management System; FCM, Fuzzy Cognitive Map; NPC, Net Present Cost; PSO, Particle Swarm Optimization; PVROD, PV-Batteries Reverse Osmosis Desalination Plant; RO, Reverse Osmosis; VAR-LOAD EMS, Variable Load Energy Management System; WHO, World Health Organization.

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Nomenclature

C_n	n concept of the Fuzzy Cognitive Map [–]
P_b	battery penalty [€]
P_w	Water Penalty [€]
SOC	State of Charge [%]
SOC_{high}	set point of battery SOC from which and above the desalination unit should be turned on [%]
SOC_{low}	set point of battery SOC from which and below the desalination unit should be turned off [%]
W_{ij}	weight of FCM concept [–]

Reverse Osmosis (RO) desalination uses a semipermeable membrane in order to remove ions, molecules and larger particles from a water source. The feed water is pressurized by a pump and the semipermeable membrane allows water molecules to pass while blocking salts and other contaminants. The two outputs of this process are the potable water and the brine. Seawater RO desalination is an energy intensive process, due to the high pressure needed (40–60 bar). Most of the energy (75–90%) is dumped in the brine feed [6]. This is why energy recovery approaches have been developed, which can lower the overall energy consumption of the desalination units up to 60% [7]. Normally, the reverse osmosis desalination units operate at nominal point of operation. The idea of operating at variable load operation has been proposed and investigated, mainly to allow the better matching of the intermittent power production of the renewable energy technologies and of the desalination unit [8–11]. One of the most important findings of variable load operation of a reverse osmosis desalination unit is that it presents lower specific energy consumption when operating in part load [12]. In [13], it was found that part load operation can decrease the specific energy consumption up to ~20%. At the same time, previous research has shown that, the operation of the membrane with varying feed flows and pressures remains unaffected [14,15]. In order to utilize this optimally in an autonomous renewable energy desalination system, advanced energy management and control is needed. Such an Energy Management System (EMS) could be then retrofitted in existing systems for facilitating variable load operation.

When operating a desalination unit in full load mode, with a renewable energy system incorporating batteries, the controller of the system has to decide when to activate and when to deactivate the desalination unit. A common approach used for such control in renewable energy systems is the hysteresis control scheme [16,17]. The hysteresis is used in order to prevent the desalination unit from being activated and deactivated continuously. The main disadvantage of the above-mentioned approach is that it is unable to facilitate variable load operation. Passive part load operation, in the sense that the desalination unit follows the produced power by a renewable energy system has been investigated with success [11,18,19]. Moreover, computational intelligence approaches have been investigated for the part load operation of multi-stage desalination plants, where the plant consists of multiple stages, but each stage operating at nominal point of operation [20]. Computational intelligence has also been used for the optimized scheduling of operation of desalination systems powered by renewables taking in account the presence of tanks [21], as well as their variable operation [22].

Fuzzy Cognitive Maps are a computational intelligence approach that can address adequately the management of systems and processes based on human reasoning process [23]. They have been utilized successfully for supervisory management in complex control systems [24,25]. Applications of FCMs in the energy field range from control applications [26], to decision support systems [27] and the supervisory management of complex energy systems such as in the autonomous polygeneration microgrids topology for the optimal energy management and facilitation of variable load operation of desalination units, fuel cells and electrolyzers in a holistic manner [28–30]. Moreover, Fuzzy Cognitive Maps present a considerably lower parameters number to be optimized in relation to other approaches like fuzzy logic [31].

Based on the above presented state of the art, the following points can be highlighted:

- Part load operation of desalination units is technically feasible and presents lower specific energy consumption when operating in part load.
- Cases in literature utilize variable operation in desalination systems powered by renewables, but in these cases the desalination unit passively operates based on the produced energy by the renewable energy system, mainly for battery-less systems.
- Fuzzy Cognitive Maps have been successfully used in the supervisory management of energy systems and present the advantage of easier optimization of their parameters.

Given that a big number of PV-RO systems including batteries have already been installed and are in operation currently around the world, this paper investigates the possibility of upgrading their energy management system, to a newly developed variable operation one in terms of potable water production. Moreover, the design of an EMS for an autonomous PV-Batteries Reverse Osmosis Desalination plant (PVROD) based on FCMs, that can actively control the point of operation of the desalination system, enabling effective part and full load operation is presented. The FCM uses as inputs the produced power of the photovoltaics, the predicted power of the photovoltaics for the next time step and the state of charge of the battery bank. The prediction approach used is based on Grey System theory and has been presented in [32]. In order to properly evaluate through simulation the designed controller, it was decided to first design and size a PVROD for a given location operating only at full load mode of operation and then use the designed controller to evaluate its impact in the operation and water production of the PVROD. The design and sizing of the system takes place with the utilization of Particle Swarm Optimization (PSO). PSO is a population based stochastic optimization approach developed after the social behavior of flocks of birds or fish [33] and which has been used successfully in energy related optimization problems [34,35]. The optimized system is then considered to be retro-fitted with the developed EMS. The operational parameters of the EMS are optimized using PSO. Finally comparisons are made in terms of potable water production throughout the year and the mode of operation. Taking into consideration that different design and sizing approaches exist, two case studies are investigated. The first case study (CS1) is based on reaching a capacity factor of the desalination unit of about 30% (this translates to about 7 h daily operation at full load) and the second case study (CS2) is based on reaching a capacity factor of about 70% (translating to about 17 h of daily operation at full load). From the obtained results it is clear that great improvement in terms of potable water production on a yearly basis is achieved for both cases.