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Modeling, control, and dynamic performance analysis of a reverse osmosis desalination plant integrated within hybrid energy systems

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ABSTRACT

An RO (reverse osmosis) desalination plant is proposed as an effective, FLR (flexible load resource) to be integrated into HES (hybrid energy systems) to support various types of ancillary services to the electric grid, under variable operating conditions. To study the dynamic analysis of such system, special attention is given here to the detailed dynamic modeling and control design of RO desalination process that employs a spiral-wound membrane module. In particular, the solution-diffusion model modified with the concentration polarization theory is applied to predict RO performance over a large range of operating conditions. Simulation results involving several case studies suggest that an RO desalination plant can provide operational flexibility to participate in energy management at the utility scale by dynamically optimizing the use of excess electrical energy. The incorporation of additional commodity (fresh water) produced from a FLR allows a broader range of HES operations for maximizing overall system performance and profitability.

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1. Introduction

The U.S. electricity grid is evolving due to changes in society's concerns for global climate change. The major cause of global climate change is generally accepted to be the growing emissions of GHG (greenhouse gas) as a result of fossil fuels use [1]. The global electricity supply sector generates the largest share of GHG emissions (38% of total CO_2 emissions), while the transportation sector contributes 34%, the industrial manufacturing sector 18%, and residential and commercial heating sector 10% [2]. The electric power industry is adding significant capacities of non-emitting, variable REN (renewable) energy sources, especially wind and PV (photovoltaic) solar. Those additions are helping stakeholders meet state Renewable Portfolio Standards [3] and will aid in meeting U.S. federal goals for reduced emissions.

Daily and seasonal load variations are currently managed on the grid through the use of dispatchable generation (i.e., generation technologies that can be turned up, down, on, and off to match the load) [4]. Increasing penetration of variable REN generation raises technical and economic challenges in terms of electric grid integration and stability due to the increasing variability and uncertainty in net load[1] [6–8]. In general, up to approximately 20% penetrations of variable REN generation can be accommodated through the use of operating reserves and other ancillary services[2] [9,10]. Beyond a 20% penetration level, additional flexible generation or other methods are required to manage the variability. Potential solutions include making residential/commercial and industrial loads more responsive, and adding compensatory energy storage to the system.

Typical load-following flexible facilities (e.g., simple-cycle gas turbines) do not operate at full capacities because they operate to meet intermediate or peaking load [3]. On the other hand, electricity-only baseload generators[3] (e.g., nuclear power and fossil fuel-fired combined cycle power plants) often pay the grid to take electricity if they are not able to reduce power when requested by the ISO (independent system operator) due to increased deployment of REN generation and production tax credits[4]; they result in

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[1] Net load is the remaining demand that must be met by conventional generation sources after variable generation is subtracted from the total load (demand) [5].

[2] Ancillary services are functions performed by generation (and possibly responsive load) to support the basic services of the electric grid, including balance of generation and load in near real-time.

[3] Baseload generators are high-capital-cost low-operating-cost technologies that should operate at full capacities to maximize profits.

[4] Production tax credits are a federal incentive that provides financial support for the first ten years of a REN energy facility's operation [5].

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cost and regulatory inefficiencies for many hours during the year. Even though flexible operation of electricity-only baseload generators is technically achievable and is currently conducted in certain regions, this operational mode is not recommended based on cost, profitability, and safety considerations [5]. This requires new technology and energy systems deployment approaches that could utilize excess plant capacity (thermal and/or electrical), when REN generation is active and/or electrical demand is low, for value-added processes beyond electricity production. Consequently, the questions for the future electricity grid are how to utilize available energy resources in an efficient and cost-effective manner with capital-intensive electric generating assets (1) to generate economical "load-following" power in a "load-dynamic" manner (2) to improve grid flexibility and support various types of ancillary services (in wholesale electricity markets), and (3) to produce additional commodities for the combined electricity, industrial manufacturing, and transportation sectors, thus promoting competitive manufacturing approaches [3,9]. One such energy solution is a "hybrid" energy system, which, in this paper, is defined as a single facility that produces multiple products – with at least one being an energy commodity such as electricity, transportation fuels, hydrogen/oxygen gas mixture, and fresh water – from multiple energy inputs using complementary energy conversion subsystems [3,5,11].

The unique aspect of the concept of industrial scale HES (hybrid energy systems) with high REN energy penetration (greater than 20% of HES generation capacity), with respect to electric grid integration and stability, is their ability to provide various types of ancillary services (e.g., regulating, ramping, load following, and contingency reserve) while allowing operation of both REN and baseload generation sources at levels that maximize economic benefit. As energy conversion subsystems are internally coupled and share the same interconnection within the given HES configurations, they are integrated "behind" the electrical transmission bus [5]. This requires industrial scale plants effectively acting as FLRs (flexible load resources) within the given HES configurations to operate under highly flexible conditions, as opposed to their typical (constant) operating conditions. In many cases these FLRs can respond to changing net load more rapidly than generators. The key operating properties in determining the adequacy of FLRs for supporting various ancillary services to the electric grid include [12]:

- Initial response time: The time it takes to respond to a change in a power set-point.
- Ramp rate: The rate at which the amount of power consumption can change.
- Settling time: The time it takes to settle after a power set-point change.
- Duration: The time during which the FLR must be able to maintain the required change in a power set-point after settling time.
- Power capacity: The total rated power for the FLR. The size ranges from kilowatts to megawatts and is important for establishing the amount of response available during any given instant.
- Minimum turndown: The lowest operating point, after which the FLR must turn off. A higher minimum turndown reduces the amount of power capacity that can be used for supporting ancillary services.

Several types of FLRs suitable for HES applications include:

- Steam electrolysis to produce hydrogen/oxygen gas mixture [13],
- Natural gas reforming to produce various commodities: hydrogen, ammonia, methanol, olefins, and synthetic fuels [9,13–16],
- Coal-to-liquid synthetic fuels [15], and
- Desalination to produce portable (fresh) water [11,17–21].

Among the above applications, desalination, in particular via RO (reverse osmosis) process, is perceived as an attractive option for a FLR as its electrical integration with HES exhibits relatively low-order complexity. Furthermore, an RO desalination plant (or simply referred to as an RO plant) can be operated at its minimum turndown for as long as requested [18].

In this work, a HES concept – whose core capability is the ability to utilize an excess generation capacity at times of reduced grid demand and/or of increased REN generation to produce clean fresh water via RO desalination – is considered. The primary objective is to investigate the dynamic performance characteristics of an RO plant integrated within HES configurations under flexible operation. Since the implications of high variability and uncertainty in the time-varying REN energy generation and electricity demand can only be effectively understood in a dynamic setting, it is essential to develop a detailed "dynamic" model of a highly responsive load (i.e., RO plant) in the considered HES. Several tests are carried out to demonstrate its capability to manage the high variability of REN generation and/or electricity demand (load) – while supporting (1) a commodity production (i.e., fresh water) with desired quality level and (2) ancillary services as needed by the electric grid. In particular, the RO system technical performance is evaluated in terms of response time, ramp rate, and load-following response. In the case studies addressed here, the VEL (variable electrical load) requested to an RO plant by a supervisory controller is compared to the actual power consumption in RO process. Furthermore, the RO performance indicators – such as salinity; salt rejection; fresh water flow rate; and controlled feed (operating) pressure associated with a HP (high-pressure) feed pump, which in turn affects the quality and throughput of the fresh water – are monitored accordingly. Note that the mathematical model is developed for applications for both seawater RO and BWRO (brackish water reverse osmosis) desalination. However, the case studies are developed based on options considered in Refs. [11,18], in which a nuclear-solar PV hybrid energy system was proposed as a regional option in Arizona to support the production of fresh water via a BWRO plant[5]; the application of this work is limited to BWRO desalination.

The reminder of this paper is organized as follows. The HES option considered in this study is presented in Section 2. Section 3 presents the dynamic model development and regulatory control strategies for RO desalination process. This section also briefly describes the key assumptions made in sizing the HES and their individual components for the case studies. Section 4 provides the case studies results with detailed discussion involving dynamic performance of RO desalination, under variable REN generation. Finally, Section 5 concludes this paper.

2. HES configuration

HES can have diverse purposes and configurations. In this work, a particular HES option is envisioned to be an industrial microgrid connected to the power grid as illustrated in Fig. 1, which includes several components: a PHG (primary heat generation) plant, a TEC (thermal-to-electrical conversion) system, a REN power generation

[5] The Navajo reservation is located in the northeast corner of Arizona and contains 250 million acre-feet [81.5 trillion gallons] of brackish water.