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Reverse osmosis desalination process optimized for maximum permeate production with renewable energy

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HIGHLIGHTS

- Jointly optimal control with renewable solar energy is proposed.
- Duty of high pressure pump and openness of retentate valve are jointly controlled.
- Duty and openness for maximum permeate production with constraints are found.
- Jointly optimal control can succeed with tighter constraints, unlike PID control.

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ABSTRACT

This paper deals with an optimal control for the reverse osmosis (RO) desalination process of a pilot desalination plant equipped with a high pressure pump and a retentate valve and operated by renewable solar energy. The goal of the optimal control is to maximize the permeate production, with constraints on the trans-membrane pressure on the RO membrane and the total dissolved solids of permeate, by joint control of the duty of the high pressure pump and the openness of the retentate valve. The trans-membrane pressure, the total dissolved solids of permeate, and the permeate production rate are empirically modeled by two-dimensional second order equations in terms of the duty and the openness. The duty and the openness providing the maximum permeate production rate with the constraints satisfied are found by the two-dimensional genetic algorithm (GA). This joint control is different from other existing approaches which separately control the duty and the openness. Time-varying behaviors of the trans-membrane pressure, the total dissolved solids of permeate, and the production rate obtained by the proportional-integral-derivative (PID) control are shown with those by the two-dimensional GA. The two-dimensional GA achieves maximum permeate production rate while satisfying the constraints, even when the PID control fails.

1. Introduction

Massive desalination plants have been built for provision of drinking water, agricultural water resources, and industrial water to nations in water shortage like those in Middle Asia and North Africa. Technical advancements in the modules and subsystems of desalination plants, such as high permeability membranes, various types of sensor devices, and energy-efficient pumps, have led to increased efficiency in producing permeate water and reduced energy consumption during desalination. Efficient control schemes, like the proportional-integral-derivative (PID) control [1], and structural optimizations, e.g., plant structure making use of energy recovery device (ERD) [2,3] in reverse osmosis (RO) desalination, have also contributed to increased energy efficiency. The ERD is particularly effective for large scale RO plants, but it is less efficient for small scale plants due to the high cost of installation [4]. For small scale desalination plants, an actuated retentate valve is used instead of the ERD. On the other hand, widespread support for utilizing renewable energy, particularly solar and wind energy, to get electricity without producing carbon dioxide has made the renewable energy the main energy resource for desalination [5,6]. For communities on islands, the renewable energy is often one of few options available for desalination process. Though other types of renewable energy can be used for desalination, the rapid development of cost-effective photovoltaic (PV) technology in the past years has made the solar energy the most important one [7,8]. However, the intermittency of renewable energy leads to unstable operation of the desalination plants and can cause side-effects like the fouling on the RO membrane that can eventually

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Nomenclature

CCD	central composite design
D_{HP}	duty of high pressure pump
$D_{HP}(t)$	time-varying D_{HP}
D_{TDS}	permeate total dissolved solids
$D_{TDS}(t)$	time-varying D_{TDS}
ERD	energy recovery device
MSF	multi-stage flash
O_r	openness of retentate valve
$O_r(t)$	time-varying O_r
PID	proportional-integral-derivative
P_M	trans-membrane pressure on reverse osmosis membrane
$P_M(t)$	time-varying P_M
PV	photovoltaic
Q_P	permeate flow rate
$Q_P(t)$	time-varying Q_P
Q_S	permeate salt flow rate
RO	reverse osmosis
TDS	total dissolved solids
VFD	variable frequency drive

lead to difficulty in maintaining target pressure and target permeate production rate [9,10]. From this perspective, the renewable resources are mostly used only as substitutes for grid or diesel power. Nonetheless, an optimal process maximizing the utilization of renewable energy is worthy of full-fledged research for eventual goal of grid-free desalination.

Nowadays, distillation based desalination, e.g., multi-stage flash (MSF), and RO are the most popular desalination methods. Plant structure for the RO process is simple and the RO process consumes much less energy, approximately one quarter of the energy consumed by the MSF process for an equal amount of permeate production [11–13]. The operating range of trans-membrane pressure P_M is primarily determined by the type of RO membrane and the total dissolved solids (TDS) of the feed water. An improper P_M level might incur high stress on the membrane, often leading to degraded performance in permeate production [14,15]. Therefore, optimum control of the RO desalination process, including control for proper P_M level, is crucial not only to prevent fouling but also to meet the desired levels of P_M, TDS of permeate D_{TDS}, and permeate production rate Q_P [16,17]. Optimum control of the RO desalination process has been extensively studied in the literature [4, 5]. Feedback control schemes, like the proportional-integral (PI) control and the PID control, are popularly adopted for desalination process. The PI control provides zero steady state error and the PID control enables reliable system operation [18]. In [19], a feedback control scheme to adjust the openness of the retentate valve was investigated and in [20] the PI control for the high pressure pump to achieve the desired feed flow rate was studied. However, it is difficult for the PI control and the PID control to efficiently respond to the time-varying operating conditions with renewable energy [21]. Moreover, since the system model of the desalination process, which is represented by performance metrics including P_M, D_{TDS}, and Q_P and expressed in terms of control variables such as the duty of the high pressure pump D_{HP} and the openness of the retentate valve O_r, is not taken into account, they cannot provide optimal solutions. Other techniques such as artificial neural networks [22, 23] and the genetic algorithm (GA) [24–27] have been used for optimal control of the desalination process. The GA searches for the optimal solution by repetitive assessment of optimal candidates until the optimal one is found [28–30]. In [24], the GA was used for optimal control of the operating temperature to obtain improved desalination efficiency. As an alternative, the mixed-integer nonlinear programming (MINLP) model can also be used to control the desalination process [31].

In this paper, a desalination process driven by renewable energy and controlled by a high pressure pump and a retentate valve is studied. The goal of the desalination process is the maximum utilization of PV power or, in other words, obtaining maximum Q_P while satisfying two constraints on P_M and D_{TDS}, both of which are given in ranges rather than specific values. This is to be achieved by finding jointly optimal values of the D_{HP} and the O_r for each step of desalination process. In general, it is very hard to implement joint (combined) control scheme for multiple modules to meet the required desalination performances [32]. To find the jointly optimal values of them, individual fitting equations of the performance metrics P_M, D_{TDS}, and Q_P are obtained by regressions of actual measurements and the fitting equations can be updated with new measurements. Each fitting equation is a two-dimensional second order equation in terms of two control variables D_{HP} and O_r. A simple two-dimensional second order equation takes a convexity property and allows the use of the central composite design (CCD) [33,34] enabling efficient updates of fitting equations. Based on the CCD, only 9 sample points of a two-dimensional second order fitting equation are needed to determine the coefficients of the regression equation. Therefore, a single new measurement in addition to 8 sample points of the current fitting equation is sufficient to obtain an updated fitting equation. Searching for the optimal values of the D_{HP} and the O_r, which provides constrained maximum Q_P, is executed by the GA [27]. The GA is two-dimensional because two control variables, D_{HP} and O_r, are involved for optimization. The smoothly time-varying property of feed brackish can be taken into account by the time-varying fitting equations of P_M, D_{TDS}, and Q_P. The effectiveness of the proposed scheme for jointly optimal control of the D_{HP} and the O_r can be extended to a larger number of modules (variables) and/or a larger number of performance metrics. Since the proposed scheme is suited to mitigate the limitation of time-dependent renewable energy resource, it can be used for standalone type desalination plants.

Organization of this paper is as follows. In Section 2, the structure of the pilot desalination plant is explained. Remarks on the modules and the subsystems are presented and relevant system parameters affecting desalination performance are listed in tables. The operational characteristics of the desalination process are expressed by the relations between D_{HP} and measurements of P_M, D_{TDS}, Q_P and also between O_r and measurements of those. Section 3 gives details of the optimal control scheme. Two-dimensional fitting functions of P_M, D_{TDS}, and Q_P as well as the regression based on the CCD are explained in this section. Section 4 presents experimental results. Plots of the time-varying performance metrics P_M, D_{TDS}, and Q_P obtained by the PID control and the two-dimensional GA are shown in figures. Finally, Section 5 concludes this paper.

2. Structure of pilot desalination plant

This section describes the structure of the pilot desalination plant. It is built to produce permeate with a rough production rate of 1 m^3/h. Desalination process control and structure of RO desalination plant are shown in Fig. 1. Electric resource for the RO desalination plant in Fig. 1(b) is supplied by one of two different sources: PV solar panels and grid-connected battery. Power electronics in Fig. 1(b) indicates the converter for generation of 540VDC electricity to drive the high pressure pump. When the PV panels are selected as the electric power source maximized utilization of PV power becomes critical. Since the output voltage of the solar panels is managed to be approximately constant, input power is measured by the current level read by the current sensor.

2.1. RO based desalination plant

Overall desalination process is divided into the pretreatment process and the RO desalination process. Pretreatment process run by separate power source involves the pretreatment equipment indicated in Fig. 2. Adequate pretreatment prevents fouling on the membrane and lowers