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Jointly optimized control for reverse osmosis desalination process with different types of energy resource

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ABSTRACT

High energy efficiency for low operating cost of desalination can be obtained from operational optimizations as well as component-wise innovations. This paper is concerned with an energy-efficient operation for reverse osmosis (RO) desalination process involving a joint control of multiple modules. Energy resource considered for desalination is of two types: intermittent solar energy and steady grid energy. With solar energy, the energy efficiency is measured by total permeate production obtained while the solar energy is available. With grid energy, the energy efficiency is measured by the power consumed to get unit permeate production rate. Achieving maximum energy efficiency is equivalent to solving constrained optimization. For the constrained optimization, obligatory constraints are given by the permissible ranges of trans-membrane pressure on RO membrane and total dissolved solids of permeate, and optional constraint is given by the permissible range of permeate production rate. Constraints as well as the objective function are modeled by the empirical second order equations in terms of control variables of multiple modules. Jointly optimal values of the control variables are found by the sequential quadratic programming. Experimental results obtained by the jointly optimal control demonstrate superior performances as compared to those acquired by marginally optimal control schemes.

1. Introduction

Desalination is the process for removal, or reduction, of salt and other minerals from seawater or brackish water to provide drinking water and industrial water. As of June 2015, more than 18,000 desalination plants were operated in more than 150 countries to serve more than 300 million people [1]. Among various desalination methods, distillation based desalination, such as multi-stage flash distillation (MSFD), and reverse osmosis (RO) desalination are most popularly used. Plant structure for the RO desalination is simple and energy efficiency of the RO process is approximately four times that of the MSFD process [2]. With the large magnitude of desalination industry, energy efficiency during desalination is a critical factor from the perspective of operational cost [3]. It is important even with renewable energy resource typically associated with low operational cost, since the intermittency of it fundamentally limits operation time. Under such operation condition, high energy efficiency is essential for the successful execution of permeate production plan. For these reasons, lots of works attempting to achieve high energy efficiency have appeared in the literature.

Structural optimizations such as the one making use of energy recovery device (ERD) [4], one accomplishing reduction of the cost for permeate production [5], and one enabling decentralized desalination process [6] can contribute to the achievement of high energy efficiency during RO desalination. The ERD serves well for large scale RO desalination plants, but the installation cost is excessively high for small scale plants [7]. For small scale desalination plants like ours for this work, an actuated retentate valve is used instead. Feedback control schemes like the popular proportional-integral-derivative (PID) control in Ref. [6] and nonlinear control in Ref. [4] are suboptimal, because their system models are not taken into account at all or insufficiently taken into account. The system model of desalination should be established in terms of performance metrics which can be changed by the control variables of desalination plants. The control variables indicate

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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
F_{DTS}	feed total dissolved solids
MSFD	multi-stage flash distillation
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_r	brine flow rate
Q_f	feed flow rate
Q_P	permeate flow rate
$Q_P(t)$	time-varying Q_P
Q_S	permeate salt flow rate
RO	reverse osmosis
SEC	specific energy consumption
$SEC(t)$	time-varying SEC
SQP	sequential quadratic programming
TDS	total dissolved solids
VFD	variable frequency drive

adjustable system parameters determining the operational characteristics of the plant. Therefore, proper selection of the control variables is one of the key factors for the establishment of the system model effective for successful optimal control. In this work, the control variables “duty” of the high pressure pump and “openness” of the retentate valve determine the performance metrics individually or jointly.

Control scheme for desalination can be different, depending on the type of energy resource. Widespread support for renewable energy to get electricity without producing CO_2 has made it a major energy resource for desalination. The renewable energy can be combined with other type of energy, such as nuclear energy, to increase operational efficiency. In Ref. [8], solar energy is combined with nuclear energy for RO desalination and in Ref. [9] solar energy and wind energy are alternatively combined with nuclear energy for RO desalination. Among various types of renewable energy for desalination, solar energy obtained from cost-effective photovoltaic (PV) solar cells is the most important one [10] and it is popularly being used for desalination [11]. As a powerful alternative, the wind energy is also often used for desalination [12]. Though the renewable energy is usually used only as substitute for grid or diesel power due to its intermittency, an optimal process maximizing the utilization of it is worthy of extensive work for grid-free desalination. When the solar energy alone is used for desalination without costly battery storing surplus solar energy, purpose of the control scheme is maximized utilization of the solar energy, which might be equivalent to maximum permeate production while the solar energy is available. However, with energy resource supplied by the power grid, intermittency of the energy resource is not an issue and energy efficiency measured by the power consumed for unit permeate production rate might be an objective. If the price of grid electricity varies with time, an objective that takes economic aspects into account may be more relevant. Also, if solar energy is used in combination with grid electricity, some mixed objective would be more appropriate.

The operating range of trans-membrane pressure P_M on RO membrane is mainly determined by the type of RO membrane and the total dissolved solids (TDS) of the feed water. Excessively high level of P_M might introduce high stress on the membrane and improperly low level of P_M causes degraded performance in permeate production [13]. Therefore, optimal controls during the RO desalination process, including the control to maintain proper P_M level, are important for maintenance of membrane as well as desired levels of performance metrics such as total dissolved solids of permeate water D_{TDS} and permeate (water) production rate Q_P [14]. Optimum control schemes for the RO desalination process have been investigated in Ref. [15] and specific methodology how to achieve energy-efficient desalination have appeared in the literature [16]. The PID control is efficient for stable operation of desalination, but the system model represented by performance metrics P_M, D_{TDS}, and Q_P cannot be taken into consideration. Alternatively, artificial neural networks [17], genetic algorithm [18], multi-objective genetic algorithm [19], non-dominated sorting genetic algorithm [20], and sequential quadratic programming (SQP) [21] have been used for optimal control of the desalination process. Artificial neural networks work well in most operating conditions when trained with sufficient amount of data, but it does not always provide optimal solutions. The genetic algorithm allows the implementation of the efficient system model and it is able to find out optimal solutions. However, its performance significantly depends on algorithm parameters and its computational complexity increases non-linearly with the growing number of control variables. The SQP searches for the optimal solution by repetitive assessment of optimal candidates until the optimal one is found [22]. It has been used for diverse applications, including optimization of utility systems [23]. While process optimization based on this technique is mainly concerned with single stage desalination, the work shown in Ref. [24] attempts to combine single stage RO desalination with a countercurrent membrane cascade for recycle to increase energy efficiency. Unlike the genetic algorithm, the SQP does not depend on algorithm parameters, with an exception of the termination threshold, and its computational complexity is not increased as much as the genetic algorithm with the increased number of control variables.

Few works for RO desalination have considered different types of energy resource together, e.g., intermittent (renewable) energy and stable (grid) energy, for their process optimizations. Also, works dealing with different types of energy resource did not pay much attention to jointly optimal control of multiple modules. In this paper, a desalination process of a pilot plant driven by solar energy and alternative grid energy, which is jointly controlled with a high pressure pump and a retentate valve, is investigated. Jointly optimal values of the duty and the openness of the two modules are obtained by the SQP. Goals of our work is to show that 1) proposed joint control scheme based on the SQP makes it possible to achieve optimized performances with different types of energy resource and 2) energy efficiency, measured by the performance metrics, of the joint control scheme is in general equal to or higher than those obtained by other control schemes involving a single module. With the solar energy, the goal of the jointly optimal control is to get