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Artificial neural networks applied to manage the variable operation of a simple seawater reverse osmosis plant

Pedro Cabrera[a,*], José A. Carta[a], Jaime González[b], Gustavo Melián[c]

[a] Department of Mechanical Engineering, University of Las Palmas de Gran Canaria, Campus de Tafira s/n, 35017 Las Palmas de Gran Canaria, Canary Islands, Spain
[b] Department of Electronics and Automatics Engineering, Universidad de Las Palmas de Gran Canaria, Campus de Tafira s/n, 35017 Las Palmas de Gran Canaria, Canary Islands, Spain
[c] Water Department, Canary Islands Institute of Technology (ITC), Playa de Pozo Izquierdo s/n, 35119 Santa Lucía, Gran Canaria, Spain

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ABSTRACT

For the purpose of managing the operation of a small-scale prototype of a sea water reverse osmosis desalination plant installed on the island of Gran Canaria (Spain) and enabling it to function with fluctuating power input, artificial neural network (ANN) models were incorporated into its control system. The ANN models were developed to generate feed flow and operating pressure setpoints (with the restriction of having to maintain the permeate recovery rate within a certain range) after taking into account not only the available electrical power but also the temperature and conductivity of the feedwater.

It is concluded that the ANN models that were used after training and validation were able to successfully manage the random and widely varying available electrical power. The statistical hypothesis testing that was also performed showed no significant statistical differences (at 5% level) between the errors (both MAE and MAPE) committed when adapting power consumption of the plant to the available electrical power in the various operational tests using different feedwater characteristics.

1. Introduction

1.1. Renewable energy applications for freshwater production

Proposals to use wind energy in seawater desalination first began to appear in the scientific literature in the 1970s and ’80s [1]. A few of the projects that were implemented demonstrated the feasibility of the operation of reverse osmosis plants driven by wind turbines with rated powers ranging between 4 and 11 kW [2–4]. Since then, many more research, development and innovative projects have been undertaken in this field [5–7]. Though several types of renewable energy sources and of desalination technologies have been proposed and different scales of use considered, most studies and projects have concentrated on the use of photovoltaic and wind energy systems for small-scale (maximum capacity of 50 m^3/day) seawater desalination in arid-remote and coastal areas, using reverse osmosis technology [8,9].

The vast majority of small-scale desalination systems based on the exploitation of wind energy have used batteries as an energy storage system, with the reverse osmosis membranes generally operating under constant pressure and flow conditions [9]. Consequently, despite the variable nature of the renewable energy being generated, the reverse osmosis plants have operated at constant power. As pointed out by Miranda and Infield [10], the drawback of using such energy storage systems is the increased capital and operating costs that they entail.

1.2. Strategies for the variable operation of a wind-powered reverse osmosis desalination plant

The literature survey undertaken revealed various alternatives to wind energy-driven desalination systems that use battery banks as a means of mass storage of energy. In their place, systems have been proposed and developed that employ energy management strategies aimed at maximising exploitation of the wind resource [10–22].

Systems on this basis have been considered and developed for the variable operation of the desalination plant; in other words, to enable the desalination plant to adapt its energy consumption to the variable nature of the renewable energy source.

In this context, different operational strategies have been proposed in the theoretical studies which have been published [10–13] for the variable operation of a simple wind power driven reverse osmosis unit. In these studies, an acceptable operational window is defined for the reverse osmosis plant. The limits of this window are defined by the

* Corresponding author.
E-mail address: pedro.cabrerasantana@ulpgc.es (P. Cabrera).

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Nomenclature

A	ammeters
ANNs	artificial neural networks
b	constant used in the Box–Cox transformation of the coefficients of self-correlation, Eq. (6)
B-1, B-2,…, B-16	blocks of the reference power factor
C_f	seawater conductivity (μS/cm)
DL, dl	degrees of freedom, Eq. (5), Eq. (8)
e_i	i^{th} estimated value
k	lag, Eq. (3), Eq. (4), Eq. (6)
m_1	mean of the errors (MAE or MAPE) of a feedwater characteristics level, Eq. (4)
MAE	mean absolute error
MAPE	mean absolute percentage error
n	number of estimated and observed values
NB	number of blocks of the reference power factor
NL	number of levels of the feedwater characteristics factor
L-1, L-2, L-3, L-4	levels of the feedwater characteristics factor
o_i	i^{th} observed value
$P_{cut-in(1-Pressure\ vessel)}$	electrical power necessary for operation of at least one pressure vessel (kW)
$P_{cut-in(2-Pressure\ vessel)}$	electrical power necessary for operation of two pressure vessels (kW)
p_f	operating pressure (bar)
p_{fr}	reference pressure of the control system (bar)
P_{RO}	power consumed by the SWRO desalination plant (kW)
PSV	proportional Solenoid valve
PV-1, PV-2	pressure vessels
P_{wt}	variable electrical power supplied by the generation system (kW)
Q	statistic of Ljung and Box, Eq. (3)
Q_c	critical value of the Q statistic, Eq. (5)
Q_f	feed flow rate (m^3/h)
Q_{fr}	reference feed flow rate of the control system
R_j	sum of the ranks of j of feedwater characteristics, Eq. (7)
$r(k)$	represents the (linear) autocorrelation coefficient of order k, Eq. (4)
$r^{\lambda}(k)$	Box–Cox transformation used to normalise the autocorrelation coefficients $r(k)$, Eq. (6)
S	Friedman statistic, Eq. (7)
SV-1, SV-2	solenoid valves
SWRO	seawater reverse osmosis
T_f	feed seawater temperature (° C)
V	voltmeters
w_{ij}	synaptic weights which define the strength of a connection between the presynaptic neuron i and the postsynaptic neuron j of an ANN
α	level of statistical significance
χ^2	chi-squared distribution
λ	power of the Box–Cox transformation, Eq. (6)

maximum feed water flow rate, minimum permeate recovery rate, maximum concentration of salts in the product water, minimum brine flow, minimum brine to permeate ratio and maximum average flux. To define the acceptable operational window for a given sea water reverse osmosis (SWRO) desalination plant, it is therefore necessary to know the characteristics of the membrane system used, the properties of the feedwater (temperature and conductivity) and the concentration values of the product water. Generally, the software supplied by the membrane manufacturers is used to establish the theoretical operating limits. Within each window, each pair of operating pressure and feed flow values defines an acceptable operating point of the SWRO desalination plant. However, in the aforementioned theoretical studies [10–13], the acceptable operational window is established for given feedwater temperature and conductivity, for a specific age of the elements and a given fouling factor. However, no consideration is given to the possible daily and/or seasonal variation of the feedwater temperature and conductivity nor of the influence that these parameters might have on the modification of the acceptable limits of the operational window of the SWRO desalination plant under consideration. Lower pressures are required when the seawater temperatures are high and its concentration low to ensure the same conversion rate as when the temperatures are low and the concentrations high[1].

Similarly, no consideration is given to deterioration of the membrane system over time or degradation as a result of fouling. Fouling of the membrane surfaces means an additional resistance to osmotic pressure [23]. To compensate for productivity losses as a consequence of fouling, the feedwater pressure of the membrane system should be raised [23–25]. After defining the acceptable operational limit and selecting the operational strategy (for example: a) constant feed pressure and variable feed seawater flow rate, b) constant feed seawater flow rate and variable feed pressure, c) variable pressure and feed flow rate, such that the permeate recovery rate remains constant, d) variable pressure and feed flow rate, such that the brine flow rate remains constant, etc.), an estimation is made of the power required (supposing a specific efficiency which in the studies is considered constant) by the drive system (high-pressure motor pump) [13].

It should be noted that no definition (in the afore mentioned theoretical studies [10–13]) nor method of implementation (in the experimental works undertaken in which the operating parameters are varied [14–19]) is provided of the energy management tools required to generate the feed flow and operating pressure setpoints (following the selected operating strategy and considering the characteristics of the membrane system used, the variability of feedwater temperature and conductivity, and membrane system deterioration due to ageing and fouling) and thereby enable continuous adaptation of the energy consumption of a SWRO desalination plant to wind power variations.

Based on the theoretical studies they carried out, Pohl et al. [13] concluded that when an SWRO plant has to adapt to a widely varying wind turbine power output, the best results in terms of specific consumption of energy, product water quality and feed pressure variation margins are obtained by the strategy with constant permeate recovery. They also add that the results obtained should be verified by practical experience or special tests. In this respect, the most advanced work undertaken to date is that of Carta et al. [19]. They described a small-scale prototype seawater reverse osmosis (SWRO) desalination plant in which the control system designed for it determines the number of pressure vessels in action at any given moment and regulates their operating pressure and flow rate (within the acceptable limits of the membrane system used). A strategy is followed that attempts to maintain the permeate recovery rate[2] (defined as the percentage of feedwater flow rate converted to product water flow rate) within a narrow range of variation (between 13.5% and 13.6%). During the period of testing described in reference [19], operating data of the SWRO desalination plant were recorded using seawater at a total dissolved solids concentration of 37,170 mg/l and an average membrane input temperature of 23 °C.[3] Using these data, simple models were trained and used to generate transfer functions which, having as

[1] For further information as to how the temperature and concentration of the feed seawater affect the performance of an SWRO plant, see references [23–25].

[2] Sometimes also known as the “conversion rate”.

[3] The feedwater characteristics did not undergo any significant changes during the period of testing.