Operational analysis of an innovative wind powered reverse osmosis system installed in the Canary Islands

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Abstract

This paper presents an operational analysis of the prototype of an innovative fully autonomous wind powered desalination system. The system consists of a wind farm, made up of two wind turbines and a flywheel, which operates in isolation from the conventional power grids and which supplies the energy needs of a group of eight reverse osmosis (RO) modules throughout the complete desalination process (from the pumping of sea water to the storage of the product water), as well as the energy requirements of the control subsystems. The analysis of the electrical and hydraulic results obtained from this prototype, installed on the island of Gran Canaria in the Canarian Archipelago, shows the technical feasibility of the system design and the automatic operational strategy programmed for it. Amongst other tasks, the automatic operational strategy controls the number of RO plants that have to be connected or disconnected at any given moment in order to match the variable wind energy supply. The results obtained thus far have not revealed any significant variation in the level of quality or average volume of the product water, nor any physical deterioration to the main components of the system as a result of the start-ups and shut-downs required as a result of the variations in the wind energy supply or oscillations of the electrical parameters of voltage and frequency. In conclusion, the system under analysis can be applied to sea water desalination, both on a small and large scale, in coastal regions with a scarcity of water for domestic and/or agricultural use but with wind energy resources.

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1. Introduction

The world is experiencing a water crisis (Clarke, 1993; Gleick, 1993; Gleick, 2000; Cosgrove and Rijssberman, 2000; Petrella, 2001). According to the Food and Agriculture Organization (FAO), 20 countries suffered from water scarcity problems in 1990, while by 1996 this figure had risen to 26 countries (230 million people). The United Nations Environment Programme (UNEP) calculates that from now until 2027 approximately one-third of the world’s population will suffer serious water scarcity problems. The reasons for this include the rising demand for fresh water caused by world-wide population growth and the worsening of the quality of the existing aquiferous resources as a result of contamination and the increasing industrial and agricultural demands on such resources. The consequences of water scarcity will be especially felt in arid and semi-arid areas of the planet (Falkenmark, 1994; Seckler et al., 1999), but they will also be noticeable in coastal regions undergoing rapid growth, as well as in the larger cities in the developing world (Seckler et al., 1999).
The technological advances achieved over the last 30 years in the field of desalination have enabled considerable reductions in investment costs and energy consumption and, consequently, desalination projects can be regarded as an alternative means of satisfying water demand (Tsiontis, 2001; Serageldin, 1999). In fact, desalinated sea water and underground saline water have become one of the main sources of water in the arid regions of the Middle East, which has nearly two-thirds of the world desalination plant capacity (Mallevalle et al., 1996). Further, in certain areas in Spain and in particular the Canary Islands, and the south-east and eastern Spain, the scarcity of water has resulted in a significant use of desalinated sea water for agricultural purposes (Medina, 2000, 2001; Veza, 2001).

However, desalination of seawater is an energy intensive process (Gaparini, 1982; Kamal and Tusel, 1982). Most desalination today uses fossil fuels, and thus contributes to increased levels of greenhouse gases. Although the International Atomic Energy Agency (IAEA) has employed the argument concerning environmental damage caused by the use of fossil fuels and proposed that nuclear energy be used for large scale sea water desalination (Konishi and Misra, 2001), there have been other, more numerous, voices that are more inclined in favour of an approach to the problem that is more ecological (Menéndez, 1998) and safer (Rittenhouse, 1979), proposing the use of renewable energy sources, fundamentally wind and solar, for small scale sea water desalination (Petersen et al., 1979; Feron, 1985; Keeper et al., 1985; McBride et al., 1987; Manwell and McGowan, 1994; Carta et al., 1995; Hasnain and Alajlan, 1998; Colangelo et al., 1999; Vujic and Krneta, 2000; Weiner et al., 2001; Herold et al., 1998; Suleimani and Nair, 2000; Herold and Nesikakis, 2001; Carta and González, 2001; Belessiotis and Delyannis, 2001; García, 2001). Furthermore, as several authors have pointed out (Carta and Calero, 1994; Contaxis et al., 1994; Baltas et al., 1996; Infield, 1997; Voivontas et al., 1999; Benjemaa et al., 1999; Houcine et al., 1999; Belessiotis and Delyannis, 2001), a large potential market, particularly around the Mediterranean sea, and on islands, has been identified for wind powered desalination installations.

The desalination systems employing renewable energy sources that have been installed have suffered from the principal inconvenience of having to use batteries for the storage of the electrical energy produced. Consequently, they can only be used for small scale water production or need to operate in combination with a diesel generating system (Manwell and McGowan, 1994; Carta and González, 2001; Carta et al., 2003), with the resulting problems related to the emission of contaminants into the atmosphere.

The only large scale use of wind powered sea water desalination systems, of which we are aware, has been on the islands of Fuerteventura and Lanzarote in the Canary Archipelago. However, one cannot here strictly speak simply of wind powered desalination systems. These applications have consisted of the installation of custom-designed wind farms by the companies on the islands involved in the supply of potable water which are connected to the conventional power grids on the islands with the aim of selling wind energy to offset the energy costs in the production of potable water (Calero and Carta, 2004; González et al., 2002).

In the available literature there are proposals for the design of wind powered desalination systems on a large scale which have aimed to exploit the modularity of

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Definition</th>
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<tr>
<td>$q_f$</td>
<td>feed sea water flow, m$^3$s$^{-1}$</td>
</tr>
<tr>
<td>$q_p$</td>
<td>flow rate of water through the membrane, m$^3$s$^{-1}$</td>
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<tr>
<td>$q_b$</td>
<td>brine flow, m$^3$s$^{-1}$</td>
</tr>
<tr>
<td>$E_{c,f}$</td>
<td>electrical conductivity of the sea water, μS cm$^{-1}$</td>
</tr>
<tr>
<td>$q_s$</td>
<td>flow rate of salt through the membrane, g s$^{-1}$</td>
</tr>
<tr>
<td>$E_{c,p}$</td>
<td>electrical conductivity of the water produced, μS cm$^{-1}$</td>
</tr>
<tr>
<td>$E_{c,b}$</td>
<td>electrical conductivity of the brine, μS cm$^{-1}$</td>
</tr>
<tr>
<td>$Y$</td>
<td>conversion, %</td>
</tr>
<tr>
<td>$K_w$</td>
<td>parameter of pure water permeability of the membrane, m bar$^{-1}$ s$^{-1}$</td>
</tr>
<tr>
<td>$K_s$</td>
<td>solute mass transfer parameter of the membrane, m s$^{-1}$</td>
</tr>
<tr>
<td>$A$</td>
<td>surface area of the membrane, m$^2$</td>
</tr>
<tr>
<td>$ΔP$</td>
<td>hydraulic pressure differential across membrane, bar</td>
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<tr>
<td>$ΔC$</td>
<td>salt concentration differential across membrane, g m$^{-3}$</td>
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<tr>
<td>$ΔII$</td>
<td>osmotic pressure differential across membrane, bar</td>
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<td>$p_f$</td>
<td>feed water pressure, bar</td>
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<tr>
<td>$p_b$</td>
<td>brine water pressure, bar</td>
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<tr>
<td>$p_w$</td>
<td>product water pressure, bar</td>
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<tr>
<td>$P_f$</td>
<td>osmotic pressure of the feed water, bar</td>
</tr>
<tr>
<td>$P_b$</td>
<td>osmotic pressure of the brine, bar</td>
</tr>
<tr>
<td>$C_f$</td>
<td>concentration of the feed water, g m$^{-3}$</td>
</tr>
<tr>
<td>$C_p$</td>
<td>concentration of the water produced, g m$^{-3}$</td>
</tr>
<tr>
<td>$C_b$</td>
<td>concentration of the brine, g m$^{-3}$</td>
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2. Description of the system

This paper presents an operational analysis of the prototype of the system that has been developed. The system consists of a wind farm, made up of two wind turbines and a flywheel, which operates in isolation from the conventional power grids and which supplies the energy needs of a group of eight RO plants throughout the complete desalination process (from the pumping of sea water to the storage of the product water), as well as the energy requirements of the control subsystems. The analysis of the electrical and hydraulic results obtained from this prototype, installed on the island of Gran Canaria in the Canarian Archipelago, shows the technical feasibility of the system design and the automatic operational strategy programmed for it. Amongst other tasks, the automatic operational strategy controls the number of RO plants that have to be connected or disconnected at any given moment in order to match the variable wind energy supply. The results obtained thus far have not revealed any significant variation in the level of quality or average volume of the product water, nor any physical deterioration to the main components of the system as a result of the plant start-ups and shut-downs caused by the variations in the wind energy supply or by oscillations of the electrical parameters of voltage and frequency. In conclusion, the system under analysis can be applied in sea water desalination, both on a small and large scale, in coastal regions with a scarcity of water for domestic and/or agricultural use but with wind energy resources.

2.1. Electrical generation subsystem

This subsystem consists of:

- A wind farm made up of two model E-30 wind turbines (Fig. 4), manufactured by Enercon GmbH, each with a nominal power of 230 kW (adjustable), a three-bladed rotor and variable angle of pitch and velocity (20–45 rpm) and a multipolar synchronous type generator, which enables the elimination of the standard use of a multiplier in wind turbines. These turbines use electronic devices (rectifiers and power inverters) to convert the wind energy into electrical energy that can be fed into a grid. There were several technical reasons for the establishment of a nominal power of 460 kW: the non-availability in the market of wind turbines with a nominal power lower than 230 kW and with the required technical characteristics, the participation of Enercon in the SDAWES project and the need to test at least two wind turbines to investigate the problems associated with the control of stand-alone wind farms.

- Equipment consisting of: (a) a synchronous type motor (SM) (with a nominal power of 100 kW) which is mechanically coupled to a flywheel (inertia of 677.5 kg m²); and (b) an asynchronous motor (AM) (with a nominal power of 22 kW) whose shaft is connected, via a power transmission belt (1:1.17 speed ratio), to the flywheel rotation shaft (Fig. 1) and supplies the necessary torque for its start-up. Though this equipment has been classified as part of the electrical generation subsystem, it could be included under a regulation and control subsystem as its uses are: (a) to serve as a grid frequency and voltage reference, (b) to maintain dynamic stability in the face of disturbances at the moments of connection and disconnection of loads and (c) to serve as a temporary energy storage system.

- An uninterrupted power system (UPS) unit with 10 kW of power. This unit, which supplies energy exclusively to the control systems (Fig. 1), consists of batteries (which provide a three day energy autonomy) and AC/DC converters.

In the following sections a description is given of the components of the system, and the reasons which have led to the establishment of a given relation between the installed wind potential and the desalination capacity of the system are explained.

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1 Three synchronised regulating systems with individual blade adjustment.
2.2. Load subsystem

The load system consists of:

- Eight RO modules for sea water desalination (Fig. 2). Each single-stage module, without energy recovery devices (Goubeau and Guinard, 1985; Mallevalle et al., 1996; Kundig, 1988, 1990; Geisler et al., 2001), has a production capacity of 25 m$^3$ day$^{-1}$ of potable water at an average electrical consumption 2 of 6.9 kWh per m$^3$ of water produced. Each module was designed for operation with a conversion rate (relation between product water flow and feed water flow) of 33%, a feed pressure of 62 bar and a feed water temperature of 25 °C. 3 A diagram with the main instruments and components of each module are shown in Fig. 3. In addition to protective measures to avoid irreparable damage and gauges for the most important parameters, each module has a motorised solenoid valve at the high pressure pump outlet 4 which enables a gradual increase of membrane pressure during the start-up periods, a solenoid valve fitted at the cartridge filter inlet for the automatic hydraulic connection/disconnection of the RO plants and a pressure limiting valve fitted after the latter solenoid. Additionally, there is a set of sensors to periodically (every 2 s) take and store operating parameters such as, for example: flows (product and brine); pressures (pressure drop across the sand-anthracite filter, suction pressure at the high pressure pump inlet, feed pressure to the pressure vessels, pressure in the brine line); pH (product); conductivity (product).

2 The driving energy operates at an electrical frequency of 50 Hz.
3 An increase of approximately 4% in product water can be obtained for each increase of 1° centigrade of the feed water temperature.
4 This is a positive displacement pump.
Carta and Calero (1993), using a theoretical model, arrived at the conclusion that from an economic point of view, for each nominal power of a wind farm, particular type of wind turbine and particular wind regime, there is an optimum number of RO modules and an optimum nominal desalination capacity for each of them. For the nominal wind power installed (460 kW), and the wind regime at the installation site (an average annual wind speed of 7.9 m s\(^{-1}\) at 10 m above ground level), and according to the model developed, 11 RO modules should be installed with a nominal production capacity of 100 m\(^3\) day\(^{-1}\). However, for financial reasons the decision was taken to use eight RO plants with a nominal water production capacity of 25 m\(^3\) day\(^{-1}\). This decision, as pointed out by Carta and Calero (1995), meant that the cost per cubic metre of water produced would be higher than the optimum cost, that the percentage of operating hours would be higher and that the frequency of the connection/disconnection of the RO plants in the event of low wind speeds would also be greater.

- A pumping station, consisting of two motor pump sets, each with a nominal power of 13 kW (at 50 Hz) and capable of providing a flow rate of 40 m\(^3\) h\(^{-1}\), operating alternately every 30 min.
2.3 Control subsystem

The control subsystem consists of a network of two industrial PC type computers and six programmable logic controllers (PLC) (González et al., 1997). The control software, especially designed for this project, is installed in one of the computers and not only controls the system but also enables the visualisation in real time of the system operation. The other computer is used to store the information (instantaneous data every 2 s) which comes from the sensors installed in the components of the various subsystems and which is channelled through the PLC network.

Fig. 4 is a panoramic view showing the location of the wind turbines, the flywheel housing and the domes containing the RO modules and the central control subsystem (CCS). The produced water storage tank and the building where the pumps are housed are located closer to the coastline, 100 m from the domes. The prototype has been installed on a site which is part of the facilities of the Instituto Tecnológico de Canarias (Spanish initials: ITC), a company belonging to the Board of Industry of the Autonomous Canarian Government, in Pozo Izquierdo, a coastal area located in the south-east of the island of Gran Canaria.

3. System operation

The system start-up process consists of two main stages: the creation of the electrical grid and the later connection of the various loads in a particular given order.

3.1 Creation of the isolated electrical grid

For the initiation of the electrical grid an average wind speed needs to be detected by the anemometer located on the wind turbine gondola of at least 4 m s⁻¹ for a period of 3 min. The start-up process commences with one of the wind turbines, for example number 1. Since switch \(a1\) is closed and switches \(b1, b2, a2, c\) and \(d\) open (Fig. 1), all the initial electrical energy generated by this wind turbine is employed in accelerating, with the 22 kW asynchronous motor (through the frequency converter), the synchronous machine which turns integral with the flywheel. Once the flywheel has reached the established speed \(^5\) of 1440 rpm (41 Hz for the asynchronous motor) the local control subsystem (LCS-1) connects switch \(c\), \(^6\) and then opens switch \(a1\), disconnecting the frequency converter (the asynchronous machine is switched off) and closes switch \(d\) (exciting the synchronous machine). The flywheel transfers energy making the synchronous machine work as a generator which builds a 3X400 V three-phase grid. Simultaneously, the LCS-1 closes switch \(b1\), and the wind turbine 1 attempts to synchronise its inverter with the three-phase grid created. Once synchronism has been achieved, the wind turbine 1 feeds energy into the synchronous machine (which now works as a motor) to accelerate the flywheel and reach the frequency of 52 Hz (maximum operating frequency of the system). Before reaching the frequency of 52 Hz, specifically at 51.5 Hz, the LCS-2 orders the rotation of the blades of the wind turbine in order to reduce gradually the power which the wind turbine feeds into the grid.

Once the reference grid has been created, the second \(^7\) wind turbine can be connected, closing switch \(b2\).

The procedure described above of the start-up is shown in Fig. 5. It can be seen how (Fig. 5a) one wind turbine, through the asynchronous motor, increases the frequency of the flywheel from 0 to 48 Hz (1440 rpm). During this period, the drops in the power generated by the wind turbine as a result of decreases in the wind speed, cause decelerations of the flywheel. It can also be seen how the frequency of the flywheel falls (on transferring energy) during the period of time (marked by a circle in Fig. 5a) in which the wind turbine is connected to the reference grid through its inverter (AC/DC). Fig. 5b shows the variation in speed of the wind turbine rotor throughout the process, particularly the drop in speed

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\(^5\) This speed is detected by an 8 pulse sensor located on the flywheel shaft.

\(^6\) The transformer is connected before run-up and before the excitation for the synchronous machine is connected, to avoid unacceptably high making currents.

\(^7\) Or remaining turbines, should this be the case, by the simultaneous closure of the corresponding \(b\) switches.
during the synchronism search period. It can also be seen in Fig. 5a how, when the flywheel reaches the frequency of 51.5 Hz, although the wind is blowing at a speed greater than 6 m s\(^{-1}\) and the wind turbine is therefore in a condition to provide higher power (available power, Fig. 5b), the power generated by it begins to decrease. From the moment the frequency of 52 Hz is reached, the wind turbine provides an average instantaneous power of 11 kW (instantaneous power consumption of the flywheel because of aerodynamic and mechanical friction losses in the transformer).

3.2. Load connection procedure

After the creation process of the electrical grid has concluded and provided all the necessary conditions are met, the central control subsystem will commence with the staggered connection of the loads.

The necessary condition for the CCS to proceed with the connection of a load is its verification of the ability of the wind farm to provide, by modifying the pitch angle of the blades (Hau, 2000), the power required by that load. For this verification the CCS works with the characteristic power-wind speed curve of the wind turbine (Hau, 2000). This has been obtained from tests carried out connecting the wind turbines to the conventional island power grid and can be seen in Fig. 6. As can be seen, the power-wind speed characteristic curve of the manufacturer shows a good match to the most optimistic values, although there is a high probability that, for a given wind speed, powers lower than those envisaged by this curve will be produced. This is due to the fact that the manufacturer uses a standardised characteristic curve (IEC, 1988), obtained employing data from a weather tower situated at a certain distance from the wind turbine. However, the wind data used in this study come from an anemometer located on the wind turbine gondola and are subject to the turbulence generated by the wind turbine’s rotor. From the point of view of the CCS it is important to know the power-wind speed curve which ensures, with a high degree of probability, that powers lower than those indicated are not
produced. With the application of adjustment techniques the power-wind speed curve of Eq. (1) has been adopted, the parameters of which are shown in Table 1. This curve has a correlation coefficient of 0.9988 with the minimum values recorded.

$$P(v) = e + f/\{1 + \exp[-(v - g \ln(2^{1/i} - 1) - h)/g]\}^i$$

(1)

The first load to be connected, provided the condition of available power as stated above is satisfied, is the pump coupled to the water circuit which supplies the feed water to the RO modules. This pump takes the water from a well near the sea and drives it through the main feed pipe to the RO modules (Fig. 7).

The hydraulic circuit that has been designed has a solenoid valve 3, controlled by the CCS, which when completely open and when the RO modules have not been connected (the solenoid valve 2 are fully closed), enables all the pumped water to return to the sea through an underwater outlet pipe.

If the CCS verifies, by calculating the difference between the available power given by Eq. (1) and the power of the loads already connected, the ability of the wind farm to provide sufficient power to connect an RO module, it proceeds to do so employing the following procedure. From the information that the pressure sensor 5 provides, the CCS regulates the throttling of the solenoid valve 3 of the main feed pipe raising the pressure in it; then it orders the opening of the solenoid valve 2 of the RO module which is going to be connected and the start-up of its high pressure pump.

While the CCS detects the ability of the wind farm to generate sufficient power, it will proceed gradually with the connection of the RO modules following the procedure described above in such a way that the power of the loads adapts in a staggered (discrete) way to the available supply of wind power.

Any excess wind energy that cannot be consumed by the loads, either because all loads have been connected or because there is not sufficient excess energy to connect a new load, tends to increase the frequency of the system. To control these energy imbalances the system operates in two ways: changing the pitch of the wind turbine blades so that they capture less energy and accelerating the flywheel to store energy in it.

If the control subsystem detects a drop in the wind energy supply it acts in three ways to balance consumption with supply and avoid the frequency of the system falling below 48 Hz (established lower working limit of the isolated electrical grid): it changes the pitch of the wind turbine blades so that they capture more energy, it decelerates the flywheel to transfer more energy to the loads and, if these measures are not possible or insufficient, it undertakes a gradual disconnection of the loads.

3.3. Strategies in the connection–disconnection order of the RO modules

The RO membrane manufacturers guarantee a working life of around 5 years if they are operating under conventional operating conditions, in other words using energy sources with constant operating parameters (voltage and frequency) and long periods of continuous operation (infrequent start-ups and show-downs).

The cost of a cubic metre of water produced using RO technology is extremely sensitive to the cost of membrane replacement; so much so that if the replacements are very frequent the project will not be economically viable.

In order to analyse the optimum order of connection and disconnection of the RO modules from an economic and technical point of view, the CCS software has been programmed to carry out two different operating strategies.

- Base strategy, where the order in which the RO plants are disconnected is inverse to the order in which they were connected. In other words, the first RO plant to be connected will be the last to be disconnected, and so on successively. The purpose of this strategy is to determine the influence of the start-ups and shut-downs on the working life of the components of the RO plants and on the quality and quantity of water that they produce, as the plants that are connected first will undergo less connections/disconnections than the plants that are connected last.
• Ring strategy, where the order in which the plants are disconnected is identical to the order in which they were connected. In other words, the first RO plant to be connected will also be the first to be disconnected, and so on successively. The purpose of this strategy is to uniformize the number of start-ups and shut-downs of all the RO plants.

4. Analysis of results

This section presents the results obtained, in order to show the technical feasibility of the system and relating some of the lessons that have been learnt.

Fig. 5 shows the various stages in the creation process of the isolated electrical grid, starting from a situation in which the flywheel is motionless up to the moment when the frequency of the system reaches 52 Hz. The time required depends on the wind speed; in the case of Fig. 5, with an average wind speed of 5.3 m s\(^{-1}\), approximately 26 min were needed to reach the frequency of 52 Hz. With respect to the time invested by the system from when the synchronous machine is excited to when the wind turbine detects the synchronism speed (note the drop in rotation speed of the rotor in Fig. 5b), this is around 35 s. Once the system reaches the frequency of 52 Hz, it attempts to maintain that speed by altering the pitch angle of the blades.

The results obtained from the numerous tests and the consequent adjustments and corrections that were carried out have been satisfactory, demonstrating the capacity of the wind farm to operate in isolation from the conventional grid, without the need for load connection or back-up diesel generator sets as has been the case in most systems that have been implemented beforehand (Carta and González, 2001; Carta et al., 2003).

Before analysing the load connection procedure, it should be pointed out that only tests employing the base strategy defined above have been carried out though, from the point of view of the technical feasibility of the system in the short term, there should be no significant difference in the results were the ring strategy to be used.

Fig. 8 shows the connection sequence of the various loads on a day with high wind speeds (average wind speed of 14.3 m s\(^{-1}\)). The first load to be connected is a pump set, which has a higher power demand (13%) than if it were operating at a constant frequency of 50 Hz. For most of the time this pump set shows minimum oscillations, though in the connection process power demand peaks are generated: at the moment of connection and when the CCS throttles the solenoid valve 3 (Fig. 7) to raise the pressure in the main feed pipe. Fig. 8 also reveals a sharp power demand peak from the pump set; this last peak, which appears periodically (every 30 min), occurs during the motor pump changeover when, for a short period of time (21 s) both are working in parallel. Fig. 8 also shows the posterior staggered connection of the first RO modules (1, 2 and 3) and their power demands. These are approximately 8% higher than an operation at a conventional frequency of 50 Hz.
Also seen in Fig. 8 are the small falls in pressure in the main sea water feed pipe, with the highest falls coinciding with the pump changeover and the connection or disconnection of the RO modules. These could then be avoided by modifying the software control programming.

Fig. 9 shows the variation in pressure in the RO modules and the main feed pipe in the connection process. A rapid increase (approximately 6 s) of the feed pressure in the RO modules can be observed, as well as a gradual increase (approximately 60 s) in the high work pressure of the high pressure pumps and brine pressure until the nominal values are reached, thanks to the intervention of the motorised solenoid valve (Fig. 3). It can be seen how the hydraulic losses caused by the connection of each RO module slightly lower the pressure (approximately 0.16 bar) in the main feed pipe.

Fig. 10 shows the mass flows \( q \) and electrical conductivities \( E_c \) of the water that enters (feed) and leaves (product and brine) the RO modules in the connection process. The RO modules designed require an average time of 38 s from the moment the CCS gives the connection order to the moment the water produced \( (q_p) \) reaches its nominal flow. However, an average time of 900 s is required before the quality of the product water \( (E_{cp}) \) goes from 946 \( \mu S \) cm\(^{-1} \), in the first seconds of production, to the nominal figure of 648 \( \mu S \) cm\(^{-1} \). Once \( q_p \) and \( E_{cp} \) have stabilised, if there are no variations in the electrical parameters (frequency and voltage), they remain constant.

Due to the fact that the RO modules employed (Fig. 3) do not have devices for the measurement of the feed flows \( q_f \) \(^8\) and the brine flow conductivities \( E_{cb} \), Eq. (2) of flow conservation and Eq. (3) of solute conservation have been used to determine them. Eq. (4) has also been used to calculate the conversion \( Y \).

\[
q_f = q_p + q_b
\]

\[
q_i E_{ci} = q_p E_{cp} + q_b E_{cb} \rightarrow E_{cb} = (q_i E_{ci} - q_p E_{cp})/q_b
\]

\[
Y = 100(q_p/q_i)
\]

\(^8\) The conductivity \( E_{ci} \) of the sea water is measured in sensor 4 of Fig. 7.
The product water flows and conductivities are affected by the variations in frequency of the electrical grid. As can be seen in Fig. 11, the significant falls in frequency of the electrical grid (Fig. 11c) modify the operating parameters of the high pressure motor-pump set of an RO module, decreasing the sea water flow which feeds the membranes \( (q_f) \), as well as the feed \( (p_f) \) and brine \( (p_b) \) pressure (Fig. 11b). The falls in pressure are translated into decreases in the product flow \( (q_p) \) (Fig. 11a), since this is controlled by the pressure (convection), as can be deduced from the diffusion solution model, Eq. (5) (Lonsdale et al., 1965).

\[
q_p = K_w A (\Delta P - \Delta \Pi) \\
= K_w A [(p_f + p_b)/2 - p_p] - [(\Pi_f + \Pi_b)/2 - \Pi_p]
\]

where \( K_w \) is the parameter of pure water permeability of the membrane, \( A \) is the surface area of the membrane, \( p_p \) is the product water pressure and \( \Pi_f, \Pi_b, \Pi_p \) are the osmotic pressures of the feed water, brine water and product water, respectively.

Since the solute flow \( (q_s) \) which crosses the membrane does not vary significantly with the pressure, as can be seen from Eq. (6), \( 10 \) the concentration of the product water \( (C_p) \), \( 11 \) increases, as can be seen in Fig. 11a and is justified by Eq. (7).

\[
q_s = K_s A \Delta C = K_s A [(C_f + C_b)/2 - C_p]
\]

\[
E_{cp} \propto C_p = q_s/q_p
\]

However, due to the fact that the variations in the electrical frequency affect the product flows \( (q_p) \) more than the feed flows \( (q_f) \) the conversions do not increase, Eq. (4), and the membranes are not subject to salt deposits for this reason. Furthermore, the daily average conductivities are practically unaffected for two reasons: (a) the acceptable decreases in electrical frequency (52–48 Hz) do not produce large increases in the conductivity of the water produced (approximately 28 \( \mu \text{S cm}^{-1} \)); (b) the significant falls in electrical frequency only occur

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9 Not shown in the figure, but as it is a positive displacement pump the capacity decreases with the rotation speed.

10 The solute mass transfer parameter, \( K_s \), can be affected by the pressure variations (Kimura and Sourirajan, 1967; Sikar and Rao, 1981; McCutchan and Goel, 1974).

11 The salt concentration in the product stream is, approximately, directly proportional to its electrical conductivity.
in the moments prior to the disconnection process of the RO modules, in other words when the system is not able \(^{12}\) to provide the power required by the RO modules connected for operation under nominal working conditions; therefore, once these are being disconnected the electrical frequency is re-established and with it the quality of the product water.

Also, during the periods in which the electrical frequency undergoes significant decreases the flows of produced water fall by approximately 10%.

Fig. 12 shows the staggered connection process of all \(^{13}\) the RO modules, the initiation of which was shown in Fig. 8. Dealing with a period of high wind speeds (Fig. 12b), the wind farm is able to increase the power generated (Fig. 12a), modifying the pitch angle of the blades (Fig. 12b), as the power demanded by the loads increases (Fig. 12a). The narrow margin of variation can also be seen for voltage and frequency (Fig. 12c), as well as the contribution of the flywheel to the dynamic power balance (Fig. 12a).

Fig. 13 shows a period in which the wind variability (Fig. 13b) gives rise to a situation in which the CCS, during a period of approximately one hour, proceeds with the connection and disconnection of RO modules attempting to balance the system output (Fig. 13a). During the first minutes shown in Fig. 13 it can be seen how the control system takes the pitch angle of the blades to minimum values (Fig. 13b), attempting to capture the maximum wind power. However, as the power demands of the loads which are connected are

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12 As the pitch angle of the blades is at its limit.
13 With the exception of the RO module number 8 which the CCS did not connect as at that moment it was under maintenance.
higher than the power that the system is capable of generating (Fig. 13a) significant oscillations are produced in the electrical frequency, though less in the voltage (Fig. 13c), affecting the quality and flow of the product water, as shown above (Fig. 11). To decrease these oscillations the CCS proceeds with the sequential disconnection of the RO modules (Fig. 13a). It can be seen how, as the wind speed increases again (Fig. 13b) the CCS proceeds once more with the sequential connection of the RO modules (Fig. 13a).

Fig. 14 shows the behaviour of the system on a day with very low wind speeds and with only one wind turbine in operation (the other undergoing maintenance work). The first section of Fig. 14a shows the creation process of the electrical grid, similar to that described in Fig. 5, and the sequential connection of a pump set and an RO module. However, as the wind turbine is unable to capture more wind energy (its pitch angle is at the minimum value, Fig. 14b) the flywheel transfers energy and lowers significantly the frequency of the system, at which the CCS responds by disconnecting the RO module and the pump set (Fig. 14a). This enables the system to restabilise the electrical frequency (Fig. 14a) and voltage (Fig. 14c). When the wind availability increases the CCS proceeds once more with the connection of a pump set and its disconnection if there is another fall in frequency. It can even be seen in the final section of Fig. 14a how, as the frequency falls below 48 Hz, the turbine is disconnected (the pitch angle reaches 90°, Fig. 14b). Again, it can be seen how the creation process of the isolated electrical grid is initiated later as the wind speed rises. This intermittent unproductive process of connections/disconnections is characteristic of days with average wind speeds lower than 4.5 m s⁻¹ (Fig. 14c). Therefore, to reduce long unproductive operating periods of the system, establishment must be made in the

Fig. 13. Connection–disconnection period of RO modules.

14 The time required for the creation of the isolated grid is in this case much less, as the flywheel has kinetic energy.
control software of the appropriate speed threshold for the system start-up which will be in function of the wind regime at the location and the characteristics of the system design. The optimisation of the system start-up initiation should be based on prediction models of the wind speed (Brown et al., 1984; Nfaoui et al., 1996).

5. Conclusions

This paper has analysed the operation of an innovative autonomous wind powered prototype desalination system. The results obtained confirm that it is technically feasible to exploit the modularity of the RO plants connecting and disconnecting modules in function of the wind availability, as stated in the hypotheses established in theoretical models (Carta and Calero, 1993, 1995).

The configuration of the prototype, the creation process of the isolated electrical grid and its operating strategy permit its extrapolation to large scale wind powered water production without the back up support of fossil fuel energy sources.

The conclusion is also reached that the average daily product water flow and concentration are barely affected by the variations in frequency of the electrical grid. Furthermore, due to the fact that these variations have more effect on the product flow than on the feed flow the conversions are not increased and so the membranes are not subject to salt deposits for this reason.
The installation of a motorised valve in the RO modules avoids pressure spikes on the membranes at the moments of connection, and no deterioration has thus far been noted in any of the main components due to the start-ups and shut-downs caused by the variability of the wind energy.

In order to reduce the lengthy periods of unproductive operation of the system when the wind speeds are very low, the appropriate threshold speed for the system start-up has to be established in the control software, which will be in function of the wind regime at the location and the characteristics of the system design. The optimisation of the initiation moment of the system start-up should be based on wind speed prediction models.

Based on the fact that the working life of RO membranes under conventional working conditions is approximately 5 years, a number of years more of similar testing will be required for each of the two connection strategies proposed in order to establish more definitive conclusions concerning their relative effects on the membrane working life.

Finally, it should be pointed out that the operation of the system at frequencies higher than 50 Hz leads to a higher electrical consumption of the various loads.

References


