The SDAWES project: an ambitious R&D prototype for wind-powered desalination

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Abstract

This paper describes the design and operational strategies of an ambitious prototype for a desalination system powered exclusively by wind energy. The system, installed on the island of Gran Canaria, was designed with several objectives in mind: (a) to determine experimentally the feasibility of the stand-alone operation of wind farms isolated from the conventional power grids and supplying energy for a number of desalination techniques (reverse osmosis, electrodialysis reversal and vacuum vapor compression; (b) to verify the operational feasibility of the various desalination techniques when the energy source driving the system is an intermittent one; and (c) to analyze the influence that a variety of operational strategies have on the volume and quality of the desalinated water produced and on the useful working life of the main components of the desalination plants. The first of these three questions has been resolved with the feasibility of such stand-alone systems now clearly demonstrated. As for the second question, initial tests would seem so far to indicate that the reverse osmosis technique is the most suitable for use in stand-alone wind-powered desalination systems. The results that are still to come from the remaining studies will be of vital importance for regions like the Canary Islands, which suffer from a scarcity of potable water, lack conventional energy sources, but do have at their disposal wind energy resources.

Keywords: Wind energy; Desalination; Canary Islands; Reverse osmosis; Electrodialysis reversal; Vacuum vapor compression

1. Introduction

The hydraulic situation in the Canarian Archipelago (made up of seven small-sized islands constituting one of the outermost regions of the European Union) is closely bound to the general lack of rain. Indeed, the average yearly rainfall of just 332 mm for all the Archipelago puts the Canaries on a pluviometrical par with desert regions and temperate zones. The scarcity
and irregularity of rainfall have resulted in an absence of rivers or, indeed, any permanent river flows, and the need to construct a significant number of reservoirs (116 in 1991), wells (2,751 in operation in 1997) and galleries (1,159 in operation in 1997), while searching for alternative methods of water production and treatment.

Seawater desalination was first used on the islands in a limited and expensive way as a means of alleviating the water scarcity on the easternmost islands (Lanzarote and Fuerteventura). However, the rapid rise in population density, which in the last years of the 20th century was more than three times higher than the national average for Spain, a progressive increase in the number of tourists visiting the islands (nearly 12 million in 2002), and the maintenance of crops which require a high consumption of water, have led to the implementation of a significant number of desalination plants throughout the Archipelago [1,2].

Water and energy production is the third largest industrial subsector in the Archipelago. In this respect, it should be pointed out that 10% of the Canary Islands’ primary energy demand is spent on the production of water for human and agricultural consumption from seawater. The existing desalination plants, some of which remain in production despite having exceeded their theoretical operational life, employ all types of desalination techniques and, at the end of 2001, had a total approximate production capacity of 331,800 m³/d [2].

From an energy-related point of view, the Canary Islands present a series of very particular circumstances, the most notable of which are as follows: its geographical isolation, which makes interconnection with the major energy supply sources of the mainland territories enormously difficult; the lack of conventional energy sources, forcing the obligatory importation and practically absolute dependence on oil; and the availability of a high wind energy potential [3] which could satisfy the potable water demands of the Archipelago [4].

In this context, measures have been taken to promote the installation of wind farms connected to the islands’ various power grids, and some of these farms have been employed by potable water producing companies with the aim of reducing the high conventional energy costs associated with such production [5].

However, the need to use reliable electrical generation systems in isolation from the conventional power grids is vitally important for the Canary Islands because the high wind energy potential that is available cannot be fully taken advantage of as a result of the saturation of the islands’ electrical systems [6]. Such stand-alone systems could take advantage of the water–energy binomial, in other words the combination of the lack of potable water and the availability of a non-contaminating and abundant renewable energy source in the Canary Islands, namely wind [7].

In this respect, two important projects have been developed in the Canary Islands in which wind has been the only energy source used for water desalination [5]. The first of these projects consists of a wind–diesel system installed in a fishing village on the island of Fuerteventura where the operational strategies of the system were designed so that all potable water requirements could be supplied exclusively from wind energy sources [8,9]. The other project, named SDAWES (Seawater Desalination with an Autonomous Wind Energy System), is an ambitious R&D prototype for wind-powered desalination set up on the island of Gran Canaria for the purpose of validating the technical and economical hypotheses established in the theoretical models that had been drawn up beforehand [10]. The SDAWES project, with a budget of more than €1.2 M (co-financed by the JOULE III Programme of the European Union), was designed with various objectives in mind: (a) to
determine experimentally the feasibility of the stand-alone operation of wind farms isolated from the conventional power grids and supplying energy for a number of desalination techniques (reverse osmosis, electrodialysis reversal and vacuum vapor compression; (b) to verify the operational feasibility of the various desalination techniques when the energy source driving the system is an intermittent one; and (c) to analyze the influence that various operational strategies have on the volume and quality of the desalinated water produced and on the useful working life of the main components of the desalination plants in order to provide reliable estimates of the cost per m$^3$ of water produced using these systems.

The first of these three questions has been resolved, with the feasibility of such stand-alone systems now clearly demonstrated. As for the second question, initial tests would seem so far to indicate that the reverse osmosis technique is the most suitable for use in stand-alone wind-powered desalination systems. These conclusions — and those that are awaited from the remaining studies to be carried out — will be of vital importance for regions like the Canary Islands (and other potential markets [11–18]), which suffer from a scarcity of potable water, lack conventional energy sources, but do have at their disposal exploitable wind energy resources.

2. Prior basis

Prior to the actual design of the SDAWES project, carried out by the Canarian Technological Institute (Spanish initials: ITC), the Las Palmas de Gran Canaria University (Spanish initials: ULPGC) and four other partners described by the European Commission [19], the following decisions were taken concerning the particular objectives for each of the desalination technologies involved:

- Electrodialysis reversal technology (EDR). The aim was to analyze the technical feasibility of this technology applied to brackish water (salinity below 10,000 ppm TDS) when the operating parameters (voltage and intensity) vary, with the objective of adapting electrical consumption to the variable wind energy supply. The simulations that were carried out led to the selection of a plant with two membrane stacks (four hydraulic stages per stack and two electrical stages per stack) and a maximum capacity of 192 m$^3$/d. The plant that was chosen (Model Aquamite V-II, Ionics) [20] was modified so that its electrical consumption would adapt to the variations in wind energy [21,22].

- Vacuum vapor compression technology (VVC). The aim was to study the technical feasibility of this technology when the speed of the compressor varies, again with the objective of adapting its electrical consumption to the variable wind energy supply. The technical and economical studies that were carried out beforehand led to the selection of a plant (Model VVC50, Alfa-Laval) [23] with a compressor of a nominal power of 30 kW and electrical resistance of 20 kW (for the start-up) and 10 kW (to maintain the temperature when operating under a stationary regime). The plant, with a nominal capacity of 50 m$^3$/d, was modified to enable it to operate under a range of compressor speeds between 8,000 rpm and 12,000 rpm [24].

- Reverse osmosis technology (RO). The aim was to investigate the technical and economic feasibility of RO technology when there is variation in production capacity (the number of desalination plants), but maintenance of practically constant operating parameters (flow and pressure), with the objective of adapting the electrical consumption of the RO desalination system to the variable energy supply provided by a wind farm. The results obtained from the theoretical technical-economical models were conclusive: for a
given wind farm installed capacity (with a particular type of wind-turbine) and a given wind regime, there exists, from an economics point of view, an optimum number of plants and an optimum nominal production capacity for each plant [7,10,25]. In this context, a wind farm with a nominal power of 460 kW and a wind regime (in the area of Pozo Izquierdo, proposed for its installation in Gran Canaria) with an annual average speed of 7.9 m s\(^{-1}\) 10 m above ground level, would give rise to an optimum number of RO plants of 11, each with a capacity of 100 m\(^3\)/d. However, for technical and economical reasons the decision was made to use eight RO plants, each with a capacity of 25 m\(^3\)/d. The technical reasons were, on one hand, the absence of the market at the time of wind turbines with a nominal power lower than 230 kW and with the required technical characteristics and, on the other, the need to test at least two wind machines in order to be able to investigate the problems associated with the control of off-grid wind farms. The economic reasons represented much higher investment costs which plants with a capacity of 100 m\(^3\)/d would require.

3. Technical description of the project

Fig. 1 shows the general electrical and control layout with the subsystems of the project (electrical generation, control and load subsystems) and their main components.

3.1. Electrical generation subsystem

One of the characteristics of the SDAWES project, which differentiates it from proposed or implemented desalination projects which are solar powered [26–35] or wind powered [8,9,28, 34–38], is that the wind generation system behaves like a small mini-power station capable of generating a grid similar to conventional ones without the need to use diesel sets, or batteries to store the energy generated, or for the loads (desalinators, pumps, etc.) to be connected to be able to operate.

The subsystem consists of:

- A wind farm made up of two wind turbines, manufactured by Enercon [39], each with a nominal (adjustable) power of 230 kW, a three-bladed rotor with variable speed and pitch angle, and a synchronous-type electrical energy generator. These turbines use electronic devices (rectifiers and power inverters) to convert the wind energy into electrical energy that can be fed into a grid.
- An electric synchronous machine with a nominal power of 100 kW mechanically coupled to a flywheel with an inertia of 677.5 kg m\(^2\) (Fig. 1). The functions of this equipment are various: (a) for use as a grid frequency reference, (b) to maintain dynamic stability against disturbances when the loads are being connected or disconnected and (c) for use as a temporary energy storage system.
- An uninterrupted power system unit (UPS), permanently connected to the electrical grid. This unit, which supplies energy exclusively to the control systems (Fig. 1), consists of batteries (which provide an autonomous energy supply for 3 days) and DC/AC converters.

3.2. Load subsystem

As can be seen in Fig. 1, the load subsystem is made up of desalination plants which employ the various technologies investigated in this project. They are connected with their corresponding feed pumps through independent water circuits.

The fundamental characteristics of the EDR and VVC plants are outlined in Section 2 above. More detailed information on these plants and their feed pumps is available [20–22] and [23,24], respectively.
The RO system consists of eight independent single-stage desalination plants, each with a nominal capacity of 25 m³/d. The basic design characteristics are shown in Table 1 and a flow diagram with the instrumentation and main components of each plant is shown in Fig. 2. Essentially, these RO plants have a similar design to standard models with this production capacity, but with some modifications aimed at improving performance in the automatic start-ups and shut downs. In this respect, apart from protection systems against irreparable damage and indicators of the most important parameters, there is also a motorized solenoid valve at the outlet of the high-pressure pump 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 valve. Additionally, there is a set of sensors to periodically (every 3 s) take and store operating parameters such as, e.g., flows (product and brine), pressures (pressure drop across the sand-

<table>
<thead>
<tr>
<th>Table 1: Design characteristics of an RO plant</th>
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<tbody>
<tr>
<td>No. of pressure vessels</td>
</tr>
<tr>
<td>No. membranes per vessel</td>
</tr>
<tr>
<td>Membrane type</td>
</tr>
<tr>
<td>Membrane configuration</td>
</tr>
<tr>
<td>Conversion, %</td>
</tr>
<tr>
<td>High-pressure pump</td>
</tr>
<tr>
<td>Specific consumption, kWh/m³</td>
</tr>
<tr>
<td>Feed pressure, MPa</td>
</tr>
<tr>
<td>Sea water TDS, ppm</td>
</tr>
<tr>
<td>Fresh water TDS, ppm</td>
</tr>
</tbody>
</table>

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).

For the supply of seawater to the RO plant there is a pumping station consisting of two motor pump groups (each of 40 m³/h), which operate alternately every 30 min.
3.3. Control subsystem

The control subsystem consists of a network of two computers and seven programmable logic controllers (PLC) [40]. The control software, especially designed for this project, is in one of the computers, while the other is used to store the information which comes from the sensors installed in the components of the various subsystems and which is channeled through the PLC network.
The project facilities are located on land made available to the ITC (company belonging to the Board of Industry of the Autonomous Canarian Government) in Pozo Izquierdo, an area in the southeast of the island of Gran Canaria. Fig. 3 shows the exact location of each subsystem.

4. 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.

4.1. Creation of the isolated electrical grid

If the wind speed at the height of the wind turbine rotor hub maintains for 5 min an intensity equal to or higher than 6 m s\(^{-1}\), one of the wind turbines starts up with a consequent generation of electricity. The initial electrical energy that is generated by this turbine is used entirely to accelerate the flywheel until it reaches a frequency of 52 Hz (maximum operating frequency of the system), thereby creating the isolated electrical grid. From this moment onwards, the connection process, in parallel, of the second wind turbine gets underway. Once this process has been concluded and the necessary conditions have been met, the control subsystem will commence with the staggered connection of the loads.

4.2. Load connection

The facilities and control subsystem were designed to enable the simultaneous operation of the three desalination techniques coupled to the wind farm working in isolation from the main grid. However, the operating strategies that have thus far been carried out have centered on the coupling of just one type of desalination technology for each test performed.

Irrespective of the type of desalination technology being tested, the necessary conditions for the control subsystem to proceed with the connection of a load remains the same. It examines whether the wind farm is able to provide sufficient energy to cover the energy consumption required by a particular load. The first load to be connected, provided this condition is satisfied, is the pump coupled to the water circuit which supplies the feed water to the desalination plants of the particular technique being tested.

In the case of the RO technology (Fig. 4 shows a plan of the water circuit that exclusively feeds the RO plants and which has been designed to operate under a dynamic regime [41]), once a feed pump has been started up, this takes the water from a well near the sea and drives it through the main feed pipe to the RO plants. However, when the solenoid valves 2 are fully closed and the solenoid valve 11 fully open, all the pumped water returns to the sea through an underwater outlet pipe. This system differs from those used in other demonstration prototypes [33,34] where the feed water is stored in tanks before passing to the high-pressure pumps of the RO plants.

If the control subsystem detects that there is sufficient energy available to connect an RO plant, it will carry out the necessary operations to make the connection. These operations involve regulating the throttling of solenoid valve 11 of the main feed pipe to raise the pressure in that pipe and stop temporary pressures, which arise when solenoid valve 2 of the RO plant which is going to be connected is opened, generating values lower than 0.2 MPa at the high-pressure pump inlet of that plant (or of other plants to be connected after the first connection has been made). To carry out this action, the control subsystem is assisted by the information it receives from pressure sensors 12 and 13 and pressure limiters 3, which prevent pressures...
higher than 0.3 MPa at the high-pressure pump inlet of the connected RO plants.

As the control subsystem continues to detect energy availability, it gradually proceeds with the connection of the RO plants, following the process described above in such a way that energy consumption is staggered discretely in accordance with wind availability.

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 (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 pass on more energy to the loads and, if these measures are not possible or insufficient, it undertakes a gradual disconnection of the loads.

In the case of the VVC and EDR techniques, the water circuits are simpler as there is only one plant of each type. As the plants which employ these two desalination techniques have been modified to adapt, within a given range, to the available energy via a continuous control system of consumption (though this means departing from the nominal working point of the plant and increasing specific consumption), if the control subsystem verifies that the wind farm is supplying sufficient energy for these plants to operate at minimum consumption, it will proceed with connection of the plants.

Increase in the energy supply from the wind farm can be initially balanced by modifying the operating parameters of these technologies within

![Fig. 4. Water circuit layout for RO technology.](image-url)
the acceptable range limits. If the energy consumption, when these technologies are operating at the upper limit of the acceptable range, is lower than the wind energy supply, the system acts in an identical way to that described for the RO technology.

5. Test methodology and procedure

The methodology that was developed to achieve the three objectives proposed in the SDAWES project is shown in Fig. 5. It can be seen how the first task assignment proposed with the aim of achieving objective (a) is carried out at the same time as the first task assignment defined for objective (b). In other words, parallel to the determination of the operational feasibility or otherwise of the wind farm operating in stand-alone mode (start-up process and operating stability without loads for different wind intensities), the operational tests are undertaken of the EDR and VVC plants, connected to the conventional power grid.

The results obtained from the first assignment task defined for objective (a) are of fundamental importance since the further continuation of the project depends on them. The group of tests proposed as the first task assignment for objective (b) has various aims:

![Fig. 5. Outline of the test methodology.](image)
to establish experimentally the operating ranges for each parameter
• to obtain the set of optimum operating points
• to determine the problems that the VVC and EDR techniques might present when their operating parameters vary and to analyse the repercussions that such operating conditions could have on the system when these plants are connected to the wind farm
• to estimate the technical feasibility of the EDR and VVC techniques being able to operate when following the operational strategies drawn up for the RO technique. In other words, connecting and disconnecting plants in function of a variable energy supply.

As can be seen in Fig. 5, the hypothetical problems that arise from the first task assignment of objective (b) can lead, depending on their extent, to the rejection of the desalination technique that creates such problems or to the proposal of modifications to lessen their effects.

If the results obtained from the first task assignment of objective (a) are positive, the second task assignment for objective (a) is undertaken. That is, the determination of the feasibility or otherwise of the automatic connection/disconnection of each of the desalination techniques to the isolated electrical grid. These tests are to be carried out independently for each of the desalination techniques which have had positive results in the first task assignment of objective (b) and for the RO desalination technique. In these tests an analysis is made of questions that are basically related to aspects of control, system stability, electrical frequency range, signal sampling frequency, time required between connections, harmonics, etc.

If the results obtained for objective (a) are positive, the second task assignment defined for objective (c) are undertaken. That is, the determination of the influence which the operating strategies have on the volume and quality of water produced and on the working life of the main components of the desalination plants.

With respect to this final objective, it should be pointed out that for the RO desalination technique, the order of connection and disconnection of the eight plants was designed to follow different strategies in order to analyze the optimum order from a technical and economical point of view. The following two operational strategies were established:

1. 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.

2. 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 was to uniformize the number of start-ups and shut-downs of all the RO plants.
6. First results

The tests carried out under the task assignment 1 of objective (a) were completely satisfactory, demonstrating the operational capacity of the wind farm under a totally isolated regime without loads. In Fig. 6 it can be seen how, once the start-up process has concluded, the frequency of the system remains within the established range without the need for battery or dump load intervention. It can also be seen in Fig. 6 how the frequency remains practically unvaried after the connection of a seawater feed pump.

With respect to task assignment 1 for objective (b), the following results are of particular significance:

EDR technology: From the various tests made with the modified EDR unit, which were presented by Veza et al. [21,22], it should be pointed out that, besides variable consumption, this technology permits rapid start-ups. However, it also currently has the drawback of generating electrical harmonic distortions. As can be seen in Fig. 7, the current signal presents a clear harmonic distortion at low frequency, which is typical of six pulse rectifier-type electronic converters with thyristors. As a consequence of this distortion, considerable consumption of reactive energy is generated, with a phase lag angle between the voltage and current at the fundamental frequency on the order of 70°. This gives rise to power factors (cos φ) of 0.3, which in turn cause the flow of large reactive currents through the feed lines to the EDR plant, with corresponding losses and overloads in the electrical system.

In isolated electrical systems these harmonic currents will cause voltage harmonics in a more prominent way than in the grid used for the test. The presence can be seen in Fig. 8 of a notable harmonic voltage component at 250 Hz (fifth harmonic) and another at 350 Hz (seventh harmonic) with reverse and direct flow, respectively, producing noise and losses through heating and antagonistic pairs in the rotating electrical machines, fundamentally in the induction motors which would be connected to the same system.

In the case of stand-alone operation, the flow of reactive currents from the wind farm to the EDR unit could only be mitigated by the use of filters which would make the system more expensive [5]. Among the known disadvantages
Fig. 8. Percentages of voltage and current harmonics in the EDR plant.

of this technology [42], special mention should be given to its restricted field of application (brackish waters) and the significant specific energy consumption (if used to desalinate seawater) when compared with that produced by the RO technology.

VVC technique: The results of the tests carried out on the modified VVC unit showed that despite adapting to variable energy consumption, as predicted by Salomon [43], there are currently a number of drawbacks to the system which were detected during the tests. These include the slowness of the start-up (Fig. 9), with approximately 60 min needed for the creation of the necessary conditions for the evaporation of the seawater (in the case of the unit tested: 20 kPa and 60°C), and a further 30 min for the heating and acceleration of the compressor. Another drawback was the problem of calcareous deposits which occurred after long periods when the unit was not operating (over 24 h). These deposits resulted in laborious maintenance work, as it was necessary to open the plant room, remove the plates and carry out an acid cleaning of each plate. In terms of the generation of harmonics, as a result of the operation of the speed changers in the VVC plant, although these were present, they were of a lower magnitude than those produced by the EDR plant (speed changers and AC/DC conversion). Since this technology also requires greater investment costs and higher specific consumption than RO systems of equal capacity, its use is not recommended in systems which work in stand-alone mode where frequent start-ups and shut-downs are required and where there are numerous periods of inactivity as a result of low wind speeds. This non-recommendation would not be so definite if the VVC plant were to be used as a base load subject to sporadic start-ups and shut-downs, with very short periods of inactivity, and if only very low concentrations of water product were required.

RO technique: Though testing the RO plants under variable operation (variation in pressure and flow) was not one of the original objectives of the SDAWES project and, therefore, was not included in the methodology described above, a model of such operation has been made [44,45] and some tests have been carried out [46]. The results obtained contradict those obtained by Bindner and Lundsager [47] who stated that RO technology does not accept a variable energy input. If results obtained over the long term do not differ from those obtained thus far, then RO technology could operate varying its capacity (the number of RO plants) and simultaneously varying its operating parameters (pressure and flow), in which case it would be better able to adapt to the energy supply of the wind farm.

As a consequence of the results obtained in task assignment 1 of objective (b) (see the comparative results in Table 2), task assignment 2 of objective (a) was undertaken, fundamentally with the RO technique.

The problems that arose during this stage were of a varied nature. On one hand, the amount of information flowing through the control networks (2×6 = 12 signals from the wind farm, 8×8 = 64 signals from the RO plants; five signals from the seawater pumping system) and the sampling
First start-up (IS)

0 Time (s)

@ Connection @ Disconnection resistance 1 @ Connection resistance 2 and connection resistance 1 to 12000 rpm

@ Connection of product @ Operation under nominal conditions

@ Plant shut down. Ventilator operation

Fig. 9. Start-up of the VVC plant (operation at 12,000 rpm).

Table 2
Comparison of results of the three desalination techniques

<table>
<thead>
<tr>
<th>Desalination technique</th>
<th>Start-up time (min)</th>
<th>Harmonics (%)</th>
<th>Effects of shut-downs</th>
<th>Specific investment (m³/y)</th>
<th>Product water salinity (ppm)</th>
<th>Specific consumption (kWh/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RO</td>
<td>1</td>
<td>None</td>
<td>Normal</td>
<td>3.96</td>
<td>495</td>
<td>7.5</td>
</tr>
<tr>
<td>VVC</td>
<td>90</td>
<td>Low</td>
<td>Serious problems with scale deposits of CaCO₃</td>
<td>15.62</td>
<td>2</td>
<td>14.4</td>
</tr>
<tr>
<td>EDR</td>
<td>5</td>
<td>Very high</td>
<td>Normal</td>
<td>2.44</td>
<td>250</td>
<td>2.4</td>
</tr>
</tbody>
</table>

period that had been initially set (0.5 s) blocked the control system. On the other hand, there were non-optimized control program sequences which slowed down the control system producing, in some instances, out-of-phase orders which even caused communication failures between the central control system and the wind farm. Furthermore, the serial connection of the RO plants, although within very short time period intervals, provoked stability conflicts in the system.

A large number of tests were carried out, with various modifications and adjustments being made, primarily to the control software (incorrectly programmed line debugging, increase of the sampling period to 2 s, establishment of a waiting time between the connection of RO plants of 300 s); and the results obtained were
entirely satisfactory, demonstrating the ability of the wind farm to operate in total isolation from the conventional power grid and connecting and disconnecting the RO plants.

Fig. 10 shows various operating stages. One stage is where the wind speed permits the sequential connection of seven RO plants, one where the seven RO plants are operating in parallel, and one stage where there are connections/disconnections of the RO plants as a result of variations in the wind speed. It can also be seen in Fig. 10 how every 30 min and for a few instants, the pump set produces power consumption peaks. These peaks are due to the operation in parallel of the seawater pumps before the operational interchange of the two motor pump sets.

With respect to the results obtained from task assignment 2 of objective (b), special mention should be given to the following: the first tests that were carried out showed the short period of time (1 min) that elapsed between the control subsystem activating the start-up of an RO plant and the moment in which it began to produce potable water. Moreover, the tests that have thus far been carried out in the base mode have not revealed any difference in the quality or quantity of water produced by the various RO plants, despite frequency and voltage fluctuations in the electrical power driving the plants. The average specific energy consumption has been approximately 7.5 kWh/m³, though this could be reduced if energy recovery devices, as described by McBride et al. [36], Maurel [38], or similar ones, were to be installed in the RO plants.

From the results obtained thus far, it can be deduced that although, as previously pointed out [11], all energy forms can be used to power conventional desalination plants, there is one type of desalination technology whose operational characteristics are better suited to an intermittent energy source, such as wind energy. Also, of the two renewable energy sources most frequently proposed for use in powering desalination plants, namely solar-photovoltaic (PV) and wind energy, it can be stated that the technical and economic advantages of systems like SDAWES for large potable water production are at the present time much greater than those of PV-powered systems. This conclusion is based on the battery requirements for energy storage in PV systems, on the high investments costs involved in photovoltaic panels and on a comparison of the results thus far obtained in the SDAWES project with those obtained by the ITC for a RO plant powered by a PV system installed on the same site as the SDAWES project [31,48].

7. Conclusions

This paper describes the design and operational strategies of a desalination system prototype specifically intended to be powered exclusively by wind energy. It is an innovative project which differs fundamentally from other
proposed or implemented desalination projects which are solar powered or wind powered in that the wind generation system behaves like a small mini-power station capable of generating a grid similar to conventional ones, without the need to use diesel sets or batteries to store the energy generated or for the loads (desalinators, pumps, etc.) to be connected to be able to operate. Other differentiating characteristics of this project are the size of the installed power, which with the design and control system that has been developed could easily be extrapolated, and the number of desalination technologies being investigated.

The tests carried out confirmed one of the hypotheses that were established in the prior theoretical studies, namely the feasibility of the automatic operation of wind farms, isolated from conventional power grids and connected to different desalination technologies (RO, EDR and VVC).

As for the second objective of the SDAWES project, testing the operational feasibility of the various desalination techniques when the energy that feeds them is intermittent, the following conclusions have been drawn:

- VVC technology, despite the fact that it could be adapted to variable energy consumption, currently presents problems related to the slowness of the start-ups and the appearance of scale accumulation which requires frequent and time-consuming maintenance. Its use is therefore not recommended in systems which work in stand-alone mode where the wind speed profile subjects the VVC plants to frequent start-ups and shut-downs and where there are numerous periods of extended inactivity.

- The EDR unit which was used with the modifications that were performed presented the following positive characteristics: its ability to operate within a range of variable energy consumption to adapt to the variation in energy produced by the wind farm, and the rapid start-ups and shut-downs. However, this technology generates electrical harmonic disturbances as a result of the AC/DC conversion, which causes a considerable consumption of reactive energy in the EDR unit.

- RO technology seems to be the most suitable for coupling to a wind farm isolated from a conventional power grid, if it is operated with variation in capacity (number of desalination plants), but maintaining practically constant the operating parameters (pressure and flow). This conclusion is based on the short periods of time required for start-ups and shut-downs and on the fact that so far no variations in the quantity or quality of the water product have been detected.

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