Electrodialysis desalination designed for off-grid wind energy

José M. Vezaa*, Baltasar Peñateb, Fernando Castellanoa

aProcess Engineering Department, University of Las Palmas de Gran Canaria, Spain
Fax +34 (928) 458975; email: jveza@dip.ulpgc.es
bTechnical Direction, Technological Institute of the Canary Islands, Gran Canaria, Spain
Tel +34 (928) 727503; Fax +34 (928) 727517; email: baltasarp@itccanarias.org

Received 19 November 2002; accepted 11 June 2003

Abstract

An electrodialysis desalination plant has been set up and tested to treat brackish water while driven from an off-grid wind energy system. The tests were carried out in the framework of a wider scope project, located on Gran Canaria Island (Spain). The main goal of this project was to test and identify the most suitable desalination systems for connection to the above-mentioned medium-scale off-grid wind farm. After having previously analysed the behaviour of the system on-grid, the following stage was to develop an operational envelope for the electrodialysis reversal (EDR) unit while operating off-grid, i.e., only coupled to the wind farm. The unit included power converters for the membrane stacks (DC-drivers) and variable frequency drivers (VFD) for the feed pumps. The tests were carried out to establish the power intervals for the EDR unit depending on the product flow rate specified as well as water quality. Product flow rate between 3 and 8.5 m³/h, power requirements between 4 and 19 kW, while product water conductivity ranged between 200 and 500 μS/cm were recorded. The desalination unit showed good flexibility, adapting smoothly to variations in wind power, even when sudden drops or rises occurred. The control system, slightly modified from a standard design, can cope with such sudden variations. Good agreement between performance predicted with software and the actual operating performance was observed. The presence of harmonics in the electric system due to DC drivers and VFD became harmful for the control and electric system, and care must be taken through appropriate mitigating measures.

Keywords: Electrodialysis; Brackish water; Wind energy; Off-grid; Brackish; Power fluctuation

1. Introduction

In areas where the scarcity of water resources goes in parallel with the availability of renewable energy, a common strategy is to enlist local energy resources in order to provide fresh water. Wind energy is a typical example. This is the framework for a historical problem in the archipelago of the Canary Islands where the increase in population (i.e., high population density) and the low rainfall are increasing concerns about water supplies.
In addition, the amount of wind-driven electricity that can be injected to the grid is limited in order to avoid disturbances in the grid. Therefore, stand-alone desalination is an interesting way of using this remaining energy resource.

A research project known as SDAWES was developed to analyse the coupling between desalination units and wind energy. The project pursues the use of a natural renewable source — wind energy — to produce a natural, scarce resource: water. It consists in a connection of three types of desalination systems — reverse osmosis (RO), vacuum vapour compression (VVC) and electrodialysis reversal (EDR) — to an off-grid wind farm to produce fresh water on a significant scale [1].

The general objective of the project is to apply wind energy to desalt seawater on a large scale in systems isolated from the electrical distribution grid. The particulars of the seawater desalination plants coupled to autonomous wind farms imply that the latter must be closely controlled when the wind force provides more power than required at the desalination plant. On the contrary, when the wind power available is not enough to provide for nominal freshwater production, the desalination plant must also adapt to this situation, modulating the production according to the power available.

So far, most tests on desalination using renewable energies have been carried out with RO systems or vapour compression distillation [2–5]. Little field data have been reported for the electrodialysis process. This paper reports on the tests carried out in an off-grid mode (isolated from the grid) in an EDR unit together with the operating and control framework, calling for a high degree of autonomy and self-operation in the unit.

Prior to these off-grid tests, the EDR unit was tested when connected to the grid (on-grid tests) in order to establish the “operating envelope” for the system. A number of operating points were identified and characterised. The characterisation consists of determining some parameters or operating conditions including: feed water quality; product water quality vs. applied voltage, and product water flow rate. All parameters were recorded in a database. These tests have been reported elsewhere [6]. The outcome from that stage came in the form of limiting values for the variables, i.e., an operating envelope.

Any variation in these parameters has direct effects on variations in the power to be supplied by the wind farm. It follows the relevance of knowing at all times the required power, in order to find out whether the wind farm can provide the energy demanded for a given operating point at any time (current wind velocity, wind velocity database). It is also most relevant to be able to predict whether the unit must shift to another operating point if so required. The operation and control system will compare the available power as provided by the wind farm and the power required by the desalination unit, and later will set the operating point for it, based on pre-set criteria of quantity and quality for the product water.

2. Experimental

The test platform consists of two wind turbines (230 kW each), eight RO units (25 m³/d production capacity each), a VVC unit (50 m³/d). Also included is an EDR desalination unit with a production capacity ranging from 192 m³/d down to 72 m³/d. The latter is designed to treat brackish water, as opposed to RO and VC, which desalt seawater. Details for the platform are described elsewhere [7–10], and Fig. 1 shows a general view of the wind turbines and buildings.

2.1. Equipment

The EDR unit was designed to use brackish water as feed, treating it for use as drinking water. The purpose of treatment is to improve
water quality by removing suspended and dissolved solids including ions in solution. Fig. 2 shows the EDR flow diagram.

The EDR unit is a modified design from a standard module (Aquamite V-II, by Ionics) to account for the non-stationary input from the wind. Hence, the design includes DC drivers for each electrical stage in the membranes stacks in order to regulate the DC current applied to remove ionic compounds. Specifically, the electrical stacks are provided with drivers capable for 38 kW (0–170 VDC) for stage E1 and 19 kW (0–170 VDC) for stage E2.

The feed pump (3.5 kW max) and brine recycling pump (2.5 kW max) are both operated via variable frequency drivers (VFD) which can modify the motor speed in order to control feed pressure and the stack inlet differential pressure, respectively. Fig. 3 shows the electrical layout for the system.

Other components include the electrode clean in place (CIP) system using hydrochloric acid (HCl). Other features of the unit are as follows [11]: full load current 140 A, total connected load 93 kVA, number of EDR stacks is two, each one with two hydraulic stages and two electrical stages. Number of cell pairs is 340, with improved brine spacers (so-called “third generation”) to increase efficiency. Maximum
Fig. 3. Electrical layout.
Fig. 4. View of the EDR unit.

production capacity 204 m³/d, specific consumption (for 8 m³/h product) ranging from 1.22 to 2.32 kWh/m³. Fig. 4 shows a picture of the EDR stacks.

2.2. Control system

The control system consists of a general control unit and local controls for each of the desalination units in place. The general control system, via the power management routine, will send the available power for the EDR plant. This power is a fraction of the total power available from the wind farm.

The EDR plant is controlled by its own programmable logic controller PLC (Allen-Bradley SLC 500), which is responsible for the operating mode and the transferring of data about plant variables to the data acquisition computer. Thus, the PLC will set all the controls of the plant to adapt its power consumption to the fraction of assigned available power. Available power data, start/stop commands and request for data are the only communication items that the plant would receive from the general control system [12]. The control system for EDR presents a significant difference from the standard in its conceptual design. All the operational data of the plant (power required, flow rates, voltages and water quality) are stored in a control matrix. The plant would read the power available from the general control system, and then its own unit control would set all the drivers to match the desired power consumption.

The control system was developed in Visual Basic (Labview by National Instruments) and, as regards the EDR plant, the control system is capable of:

- starting up and shutting down the EDR unit
- calculating and modifying (both manual and automatically) the operating mode as a function of the available power
- resetting alarms and starting up the unit again in case of non-critical alarms
- logging data for the main variables in the system (spreadsheets).

3. Off-grid tests

Once the grid-connected tests were completed, the wind-EDR system was run off-grid, adjusting the output (product water) to the wind power available (input), for a number of pre-set parameters (product conductivity, feed flow). The response of the system was analysed, as well as the incidents occurred during the tests.

We looked for correlations between parameters in order to model the operation in other conditions other than those stored in the database obtained when operating on-grid. In addition, the adjustment between the previously modelled performance and the actual operation conditions was analysed.

The main goal of the off-grid tests was to estimate the power requirement by the plant at each operating condition. With the data acquired, we expected to obtain empirical correlations between power requirement, product flow rate and applied voltage. Relying on these equations we would be able to control plant operation at all
times, always depending on the wind energy, which converts into available power. Thus the unit, controlled by the PLC system, could self-regulate automatically, adjusting to wind conditions at all times, and therefore keeping operation within the basic concept of the project.

The second objective of the tests was aimed at finding out the response of the system to the following operating conditions that can arise in an off-grid unit:

- **Sudden decay in wind velocity**: reduction from a high wind velocity to no-wind in a short period (shorter than a minute). The system must shift from a certain operating point to another, much lower in power demand, in a short while, and even stop when the power decreases below a minimum.
- **Slow reduction in wind velocity**: reduction from a peak value in wind velocity to a zero or minimum value in a moderate time interval (shorter than 5 min). The unit may be stepped down to operating points with lower energy demand. In this case it is most relevant to know the response time: how long does it take for the unit to adapt to the new operating point?
- **Sudden increase in wind velocity**: shifting from a low wind regime to a peak value in a short time interval (shorter than 1 min). Can the unit adapt without major constraints when shifting from a low energy condition (single stack) to a maximum energy operating point? What is the response time?
- **Slow increase in wind velocity**: shifting from a low wind condition to a peak value within a moderate time interval (shorter than 5 min), as opposed to slow reduction. The unit would step up to operating points with higher power demand.
- **Limiting operating point with a single ED stack (4.4 m³/h)**: It is relevant to find out how the unit responds when only one stack is operating at its upper limit.

### 4. Results and discussion

Previous on-grid tests were carried out in a stepwise configuration, which allows the operator to scan all the operating point stored in the matrix, thus making the plant operate in the whole interval of power and product water flow rate. On the other hand, the off-grid tests were carried out in any operating condition, set by the control system, as long as it remained within the contour intervals as shown in Table 1.

The system was operated in three different operating modes, given the system flexibility, being able to adapt to almost any wind condition. The operating mode can be set for any certain period of time. The various modes were defined as follows:

1. **Constant quality for the product water**: the system will calculate and modify the operating points while keeping the product water conductivity constant at the preset level. These conductivity levels range between 200 to 500 µS/cm as contour values.
2. **Constant product flow rate**: the system will calculate and modify the operating points while keeping the product water flow rate as a constant (ranging between 3 to 4.4 m³/h and 6 to 8.5 m³/h) and aiming to the lowest product conductivity.
3. **Variable operation**: the system in this case will calculate and modify the operating points, shifting from minimum to maximum power demand, depending on the available energy. The product flow rate and conductivity will vary accordingly, in a random manner.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Limiting operating parameters for the off-grid tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed water conductivity, µS/cm</td>
<td>5000</td>
</tr>
<tr>
<td>Product water flow, m³/h</td>
<td>3–8.5</td>
</tr>
<tr>
<td>Product conductivities, µS/cm</td>
<td>200–500</td>
</tr>
<tr>
<td>Power interval, kW</td>
<td>4–19</td>
</tr>
</tbody>
</table>
The tests were designed to take into account the power demands obtained as output from the projections by proprietary software (WATSYS, Ionics Iberica) and corrected as a function of the desired product water conductivity. As an example of mode (1), Fig. 5 shows the operating points for a specific test run off-grid. Different operating points were allowed so as to keep product water quality to 200 µS/cm. The grey area in the graph shows the disallowed operating points where the system shifts from using a single membrane stack to connect both stacks. The response of the system in this area produces alarm indications due to the low feed water flow rate.

The graph shows the plant performance for each polarity time interval (response mode, response time, product conductivities). The data obtained provide information about the use of the energy supplied to the desalination plant even when a polarity reversal happens. Most likely, the plant will demand less energy in each polarity reversal, and therefore the unit must be able to follow those changes in demand. Similar tests were performed for product water qualities at 300, 400, and 500 µS/cm and variable feed water conductivity.

Table 2 shows operating data obtained from an experiment when setting product quality at 200 mg/L (368 µS/cm). These data were loaded into the database of off-grid plant operation points. E refers to the electrical stage into the stack (two electrical stages per stack in our EDR plant), and P refers to the order number of the stack (two stacks), whereas subscripts 1 and 2 refer to the stack number. Similar tables were derived for other product salinities, between 300 to 500 mg/L TDS.

One major fact obtained from the tests shows that the EDR unit is capable of adapting smoothly to variations in the available energy. It takes some 20 s to adapt to new operating conditions provided the change does not include shifting from one to two membrane stacks (or vice versa) and between 40 and 45 s when a change in the number of stacks is involved. There were doubts about the plant response when the unit, operating at maximum product flow rate, would have to step down to a minimum. However, the tests revealed that the adjustment to new operating conditions, even on the contour, would not affect the operation.

Another interesting observation is that the power requirement calculated with the software differs only by ±5% from the actual power demanded by the plant when operating off-grid.
Table 2
Operating conditions for 200 mg/L TDS product water

<table>
<thead>
<tr>
<th>Available power, kW</th>
<th>Product flow, m³/h</th>
<th>Voltage El-P1</th>
<th>Voltage E2-P1</th>
<th>Voltage El-P2</th>
<th>Voltage E2-P2</th>
<th>Off specification product OSP, µS/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.8</td>
<td>3</td>
<td>95</td>
<td>54</td>
<td>0</td>
<td>0</td>
<td>750</td>
</tr>
<tr>
<td>9.0</td>
<td>4</td>
<td>125</td>
<td>70</td>
<td>0</td>
<td>0</td>
<td>750</td>
</tr>
<tr>
<td>10.6</td>
<td>6</td>
<td>95</td>
<td>54</td>
<td>95</td>
<td>54</td>
<td>750</td>
</tr>
<tr>
<td>11.8</td>
<td>6.5</td>
<td>100</td>
<td>60</td>
<td>100</td>
<td>60</td>
<td>750</td>
</tr>
<tr>
<td>13.7</td>
<td>7</td>
<td>105</td>
<td>66</td>
<td>105</td>
<td>66</td>
<td>750</td>
</tr>
<tr>
<td>15.0</td>
<td>7.5</td>
<td>108</td>
<td>65</td>
<td>108</td>
<td>65</td>
<td>750</td>
</tr>
<tr>
<td>17.0</td>
<td>8</td>
<td>120</td>
<td>70</td>
<td>120</td>
<td>70</td>
<td>750</td>
</tr>
<tr>
<td>18.7</td>
<td>8.5</td>
<td>128</td>
<td>74</td>
<td>128</td>
<td>74</td>
<td>750</td>
</tr>
</tbody>
</table>

Table 3
Experimental equations for various product qualities

<table>
<thead>
<tr>
<th>Product salinity (TDS, mg/L)</th>
<th>Product flow rate (m³/h)</th>
<th>P vs Qp</th>
<th>Qp vs V (E1)</th>
<th>Qp vs V (E2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>3–4</td>
<td>P = (Q - 1.89)/0.23</td>
<td>V = 25 Q + 20</td>
<td>V = 16 Q + 6</td>
</tr>
<tr>
<td></td>
<td>6–8.5</td>
<td>P = (Q - 3.12)/0.27</td>
<td>V = 2.5 Q² + 4.57 Q - 100</td>
<td>V = -3 Q² + 50 Q - 138</td>
</tr>
<tr>
<td>300</td>
<td>3–4</td>
<td>P = (Q - 1.43)/0.29</td>
<td>V = 32 Q - 13</td>
<td>V = 19 Q - 11</td>
</tr>
<tr>
<td></td>
<td>6–8.5</td>
<td>P = (Q - 3.54)/0.26</td>
<td>V = 16 Q - 12.67</td>
<td>V = -2.5 Q² + 44.5 Q - 131</td>
</tr>
<tr>
<td>400</td>
<td>3–4</td>
<td>P = (Q - 1.53)/0.23</td>
<td>V = 35 Q - 30</td>
<td>V = 16 Q - 4</td>
</tr>
<tr>
<td></td>
<td>6–8.5</td>
<td>P = (Q - 2.83)/0.25</td>
<td>V = 2.5 Q² - 17.5 Q + 90</td>
<td>V = -3 Q² + 50 Q - 148</td>
</tr>
<tr>
<td>500</td>
<td>3–4</td>
<td>P = (Q - 1.5)/0.31</td>
<td>V = 30 Q - 20</td>
<td>V = 18 Q - 12</td>
</tr>
<tr>
<td></td>
<td>6–8.5</td>
<td>P = (Q - 3.42)/0.31</td>
<td>V = 5 Q² - 55 Q + 220</td>
<td>V = 4 Q² - 47 Q + 180</td>
</tr>
</tbody>
</table>

On the other hand, we tried to develop experimental correlations between the available energy with the flow rate and the voltage to be applied for the reference operating points which had been logged in the previous on-grid tests. Figs. 6a and 6b show examples of graphs where data for 200 mg/L have been plotted. Those data were used to develop correlations as listed in Table 3 for several product conductivities where \( P, Q_p \) and \( V \) apply to available power (kW), product flow rate (m³/h) and voltage applied (V) for the first (E1) or second (E2) electrical stages in each stack.

The results are explained by the fact that the unit can operate with one single stack or two stacks. Each stack carries two electrical stages (voltages denoted as E1 and E2). In both cases, the flow rates for each stack are similar, around 4 m³/h. Therefore, flow rates of 4 and 8 m³/h are associated to operating one or two stacks, respectively.

An attempt was also made to correlate product conductivity and available power, but unfortunately such a relationship was not found. Had that correlation been derived, it would have allowed testing the plant at any desired conductivity, not only those preset in the database.
Equation Product Flow vs Voltage E1 (product 200 ppm)

\[ y = 25x + 20 \]
\[ y = -2.5x^2 + 47.5x - 100 \]

Fig. 6a. Correlation voltage-product flow rate for product water 200 mg/L (first electrical stage E1).

Equation Product Flow vs Voltage E2 (product 200 ppm)

\[ y = 18x - 12 \]
\[ y = 4x^2 - 47x + 180 \]

Fig. 6b. Correlation voltage-product flow rate for product water 200 mg/L (second electrical stage E2).

The correlations obtained were also loaded into the general control program for SDAWES. The software would then estimate, according to criteria which will be described below, the operating point for the plant, dependent on the available wind power, and it would also send to the PLC the input values for product flow rate and stack applied voltage. The control system would then shift to the new operating point and would remain there until a new set of operating parameters was set by the control program, always depending on the available wind power. The control system always tries to keep the operating conditions stationary, available energy permitting, or will otherwise improve the conditions, according to the preset criteria.

In addition, the control system includes timing devices which will manage how long the plant stays in a certain condition in case of sudden variations in wind velocity by using the energy storage in the flywheel. The stored energy is applied when it is required to counterbalance significant decreases in the available power, and even a complete shut down in case of zero power. The flywheel can provide up to 160 kJ (available energy in the flywheel considering friction), which means enough stored energy for the plant to operate during 1 min and 20 s in a standard shut down for rinsing off.

Behaviour of the electrical power signal: The EDR unit uses power converters for electricity supply to the membrane stacks (the DC- drivers) and frequency drivers in the pumps to control the plant flow rate (VFD). These devices introduce disturbances in the electrical system in the form of current harmonics. The disturbances generate a serious problem affecting not only the electrical devices in the EDR unit but also damaging the isolated grid used by other desalination units. Some of the consequences might be:

- vibrations and noise in the transformers, coils and pump motors, due to mechanic pulsating pairs produced by harmonic spinning fields
- losses due to heating in the wiring, transformers and motors (isolation wear-off) due to an increase in the current harmonics
- overheating of the neutral wire in the grid
- overheating of condensers due to an increase in the reactive energy produced
- disturbances on the command lines
- disturbances on the control devices (thyristor commuting conditions)

The magnitude and variations of the harmonic distortions were measured during the off-grid tests for the various operating points at the EDR unit. After data treatment the total harmonic
distortion (THD) and the power factor were worked out in each case. The data recorded show values of THD in current ranging from 30 to 60%. On the other hand, the power factor ranges from 70 to 20%. Hence, both THD and the power factor in the system lie far from the generally accepted rates (below 10% and over 95%, respectively), showing poor electrical performance.

Both parameters increase as the regime in the power converters diminishes. However, the high THD and power factor values at high power regimes are a cause of concern because at these high regimes, more damage can be done to the internal network. Particular attention must be paid to the fifth and seventh harmonic in current.

A more detailed investigation must be carried out in order to assess the effect on the local grid, hence designing an effective harmonic filtering system, appropriate for the installed rectifiers.

5. Conclusions

This paper describes a number of tests and results obtained in an EDR brackish water desalination unit, while operating off-grid with energy from wind turbines. The plant shows good flexibility and adapts smoothly to modifications in operational modes in the same way as a plant connected to the grid would do. When receiving feed water around 5000 μS/cm, the unit will demand between 4.8 and 19 kW. Product water quality may range between 200 and 500 μS/cm.

We have derived correlations that allow testing at different conditions and have acquired new data, other than those previously tested on-grid. Experimental data differ from those estimated by the software application by a maximum of 2%.

A control system has been developed for automatic management and optimisation of plant operation, both for on-grid and off-grid modes. The control system is capable of setting the optimum operating condition, based on the available power and the criteria predefined by the plant operator.

During the tests carried out, the control system, supported by the flywheel, was capable of shutting down the plant in case of zero-energy, even performing the final wash out, which indicates a high quality in the control. This particular issue was a main cause of concern beforehand, but the test unit responded satisfactorily.

The presence of harmonics in the systems has produced disturbances, which might be a drawback to the operation of the off-grid system due to the DC-driver (rectifiers) and the frequency converters (VFC). A detailed assessment must be made in order to analyse the effect of the plant to the electricity network, and set up the appropriate filtering equipment to fit plant requirements so that the unit may work in the widest range of operating conditions.

Acknowledgments

The European Commission (DG Research, Joule III) and Instituto Tecnológico de Canarias SA (ITC) have funded the project. Their support is gratefully acknowledged. The authors also wish to thank the cooperation provided by other members of the research team: R. Calero, V. Subiela, J.A. Carta, A. Menéndez, R. Vega and J. González. The engineering staff from IONICS Iberica also cooperated in the development of the process control.

References


