Gonzalez-Vogel, Alvaro; Rojas, Orlando J.

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Alvaro Gonzalez-Vogel\textsuperscript{1,2,a) and Orlando J. Rojas\textsuperscript{2}}

AFFILIATIONS
\textsuperscript{1}Bioforest S. A., Camino Coronel Km 15, VIII Region, Chile
\textsuperscript{2}Department of Bioproducts and Biosystems, School of Chemical Engineering, Aalto University, Finland

\textsuperscript{a)Corresponding Author; Electronic mail: alvaro.gonzalez.v@arauco.com}

ABSTRACT
New strategies for the intensification of industrial electromembrane processes are needed, especially to reduce equipment size and operational costs. To intensify those processes and to decrease fouling and scale occurrence in such systems, we propose operation with very short asymmetric pulses (order of microseconds) of alternating polarity. Hence, a custom made Asymmetric Bipolar Switch was designed and built, operating with pulse widths in the $10^{-5}$-10$^{-2}$ s range. Compared to traditional systems, we demonstrate the possibility of applying pulses with high intensities, up to three times higher than normal operation, using a frequency range between 0 (continuous operation) and 10$^2$ Hz. The proposed device was coupled to an electrodialysis cell for desalting a brine solution. When switching in desalination, a Back Electrochemical Force was identified, which could affect the integrity of the electronic systems due to spikes of reverse voltage. Hence, mitigation strategies were applied by changing the switching logic and incorporating new elements in the circuitry, similar to those in breaking methods in electrical motors. While desalting in electrodialysis, the experiments showed a limited power loss, up to 0.6% of the total power applied, attributed mainly to electrical disturbance (conduction and switching losses in the electronic components were minor at this scale). No significant variation in the desalination performance was observed at low current densities. The designed Asymmetric Bipolar Switch opens new possibilities for the operation with electromembranes and other electrochemical processes.

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I. INTRODUCTION
Generally, electromembrane processes are based on ion exchange membranes and electrodes, driven by an electrochemical potential. These processes include electrodialysis (ED), electrodialysis reversal (EDR), reverse electrodialysis (RED), bipolar membrane electrodialysis (BPED), capacitive electrodialysis (CDI), Microbial Fuel Cells (MFC), among others.\textsuperscript{1,2}

At industrial scale ED, alternating cation and anion exchange membranes (pairs) are stacked up to 600 times, and used to process feed solutions that are pumped into the system. If an electrical potential is applied in the electrodes, the overall result is the dialysis of the solution and concentration of salts in alternated hydraulic streams. Thus, the main application of conventional ED is the desalination of water and pre-concentration of ions for salt production.\textsuperscript{1}

Reversing the polarity was one of the first attempts for intensification of electrodialysis, in a process called electrodialysis reversal (EDR). In this operation, by reversing the polarity of the electrodes, colloidal material is released from the surface of the membranes and inorganic scales can be re-dissolved, decreasing or even eliminating the need for cleaning and anti-scale treatments.\textsuperscript{3} This operation requires automatic three-way or four-way valves that invert the hydraulic flow. Unfortunately, this leads to production losses due to stream mixing, e.g., when changing the hydraulic polarity. Nevertheless, EDR with polarity changes is widely used in desalination of brackish water allowing a long and useful life of the membranes, typically operating with a change of cycles between 15 and 30 minutes.\textsuperscript{4} Although a high frequency is expected to improve the performance of the process, a cycle shorter than 15 minutes is not practical due to product mixing and time spent in reversing hydraulic flows.\textsuperscript{5}
Other reported intensification method of ED is through the application of a Pulsed Electric Fields (PEF). Here, alternating pauses (pulse-relaxation) are performed in order to control the concentration polarization phenomenon and to decrease fouling. This pulsed mode includes the use of a direct current during a given time, followed by a pause, in the absence of any current. This alternative is attractive because it does not require a special anode as electrode, but compared to EDR, does not involve an effective self-cleaning. Even more, the application of pauses means that more membrane area or cells are required to perform the same work, increasing capital and operational costs.

In this study we propose a novel intensification strategy by the application of very short, intense and asymmetric pulses of reverse polarity, herein termed Asymmetrically Pulsed Electrodialysis (APED). For this, an Asymmetric Bipolar Switch (ABS) was specifically designed and placed between a power supply and an electrodialysis cell. This power electronic device controls the direction, time, and intensity of the current flow when changing the polarity.

We analyze the effect of asymmetric pulses of reverse polarity in electrodialysis and other related electromembrane processes, including the design considerations of the device circuitry and the desalination performance. Furthermore, different operational modes are considered along with an evaluation of the reduction of membrane fouling and scaling. The electronic device and its coupling to an electrodialysis system is reported. Details about the circuitry employed to perform desalination, protection strategies of the electrical system, and power loss in the process are discussed in the following sections. The intensification of electrodialysis and mitigation of fouling and scaling will be presented in accompanying reports.

II. DESIGN OF AN ASYMMETRIC BIPOLAR SWITCH

An electronic device was designed to apply bipolar, continuous, and rectangular pulses at various intensities, frequencies, and pulse widths. The device was then coupled to an electrodialysis cell for analyzing the performance of the device. An H-Bridge was used as Asymmetric Bipolar Switch for reversing the cell polarity. A device was constructed using Insulated Gate Bipolar Transistors (IGBTs) to work up to 600VDC and 50A when driving the process at low frequencies (<1 kHz), based on the power requirements of electrodialysis at laboratory and pilot scales. If higher frequencies are required, a better design should include Metal-Oxide Semiconductor Field-Effect Transistors (MOSFETs) as switching elements. The driver IR2104 was employed with a bootstrap capacitor for controlling high-side switches. In conventional switching applications it becomes necessary a Pulse Width Modulation (PWM) signaling to charge a bootstrap capacitor after each cycle. For this application with electrodialysis, a continuous mode (without pulses) or very low frequencies were strictly necessary for the operation. Thus, a charge pump using ICM7555 was integrated to refill continuously the bootstrap capacitor.

Compared with a conventional H-Bridges, a new configuration was employed to adapt the technology for electrodialysis (Fig. 1). The described charge pump and a variable/second power supply were added to work in a continuous mode and to change the intensity of the reversal polarity pulses, respectively. This configuration was used for research purposes, controlling the direction of the current for defined times, frequencies, and intensities. Conventional H-Bridges utilize PWM to drive motors or inverters, whereas asymmetric pulses with defined times and intensities cannot be finely tuned. A control panel was included as well, for a simple
configuration of experimental variables. ATmega328P-AU was used as microcontroller for its simplicity, although any other microcontroller can do the same work. Si8429, a 2-channel digital isolator, was used to isolate the signal generated by the microcontroller (A1 and A2), and to protect the microcontroller from noise and voltage spikes (up to 2.5 kV of isolation), derived from industrial operation of electrochemical processes.

III. CHARACTERISTICS AND LIMITATIONS OF THE DEVICE

The driver IR2104 integrates functions to control the high side and low side switching of IGBT/MOSFETs. The high side channel must keep a potential, given by the floating feed in Vs, to activate the ON state of the switch Q₁ or Q₃. This potential is supplied by an isolated power supply or by a bootstrap circuit (note: it cannot be used above 600VDC due to the isolation of IR2104 in between the high side and low side channels).

Each IR2104 independently controls one high side component of the full bridge. The isolated voltages, supplied by the bootstrap capacitors (CBOOT), are charged through bootstrap diodes (DBOOT) at 12-15V, when Q₁ is OFF and Q₂ is ON. Nevertheless, due to technical characteristics of APED, it is necessary to keep ON the high side Q₁ and low side Q₄, in continuous forward polarity operation, or high side Q₃ and low side Q₂ when continuously working at polarity reversal mode. To achieve this, a charge pump circuitry was added using the timer ICM7555, necessary to provide the low current required by IR2104. By this way, when Q₁ or Q₃ is ON, CBOOT keeps the 12-15V reference voltage, filtered by the 10 nF capacitor after the square signal generated in the timer. The diodes 1N4148 keep this voltage constant during the operation time. On the other hand, the Zener diode regulates the potential needed for the operation of ICM7555, which must be kept below 18V.

IV. ASYMMETRIC BIPOLAR PULSES

Conventional H-Bridges are commonly used in motors for velocity adjustment using PWM, and adjustment of the motor direction by reversing the polarity. However, in electrochemical systems, more elaborated pulse functions could be advantageous. For this propose, an asymmetric H-Bridge was designed and constructed, as mentioned. It is defined as asymmetric because the bipolar pulses could vary intensity, frequency, and pulse width for given applications, without strictly using PWM techniques.

The device is limited by its components (for instance, it only works up to 600VDC), although new driving circuitry and switching elements can be replaced to fulfill industrial requirements. In the case of electromembrane cells, independently of the device limitations, the intensity can not be increased more than 3-times the working voltage, considering around 1.2V of voltage drop per membrane. The reason behind this is the evolution of ozone above 3V per membrane, which can irreversibly produce their damage.

To check the versality of the device and asymmetry of the pulses, a resistive load was connected to the constructed device, using two power supplies for adjustment of the applied voltages (Fig. 2). Power supply 1 was kept fixed at 12V, while power supply 2 was adjusted for changing the intensity of the pulses. Pulse width and frequency were configured using the integrated control panel.

As observed in Fig. 2, it is possible to control the intensity (by regulating the reverse voltage from power supply 2), frequency, and pulse width parameters. It is even possible to turn off the power supply 2 to pause the system (0 RV), simulating a PEF operation. The modification of all these parameters introduces some degree of freedom, to configure different operational modes in electrochemical processes, including electromembranes. Moreover, automation and dynamic adjustment of the parameter could boost the performance of the respective processes, by an adequate feedback and processing, based on the operation data obtained in real time.

**FIG. 2.** (a) System configuration for application of asymmetric pulses of reverse polarity. (b) Frequency (Hz), forward voltage (FV), reverse voltage (RV) and pulse width (PW) were modified to obtain different operational modes. The signals were tested using an oscilloscope.
V. COUPLING THE DEVICE TO AN ELECTRODIALYSIS UNIT

The employed commercial ED system consist of a power supply for feeding the cell, automatic valves, pumps, sensors, and the electrodialysis cell. Five pairs of ion exchange membranes were included, giving a total surface area of 640 cm$^2$ (membrane area of 64 cm$^2$ each). The flow rate was fixed at 0.67 L/min with a linear velocity of 2.8 cm/s. The rinsing compartment had a solution of 0.25 M Na$_2$SO$_4$ operated with a flow of 1.6 L/min. A data acquisition unit with a set of sensors allowed recording the values of conductivity, voltage drop, current consumption, flowrate, pH, and temperature.

Even though two power supplies can be coupled to the device, only one was used at the beginning, to study the effect of pulses in upstream connections (Fig. 3). A copper connection between the inputs (Fig. 1b) allowed the utilization of only one power supply, although no variation of pulse intensity occurred using this configuration.

As mentioned, a voltage drop of 1.2V was considered for each membrane as part of the cell, and 3V for both electrodes. Thus, a fixed working voltage of 15V (potentiostatic mode) was utilized in the desalination experiments. The current through the systems depended mainly on the area of the membrane and the conductivity (or salinity) of the medium. In the experiments, a current of ca. 0.5A was measured in the initial conditions, equivalent to a current density of 7.8 mA/cm$^2$ considering 64 cm$^2$ of effective membrane area. Using Ohm’s law, an equivalent resistance of 30Ω is determined, consuming 0.5A at 15V.

No noise was measured when coupling a resistance of 30Ω instead of the ED cell, using a probe (Fig. 3a, P$_1$) and ground as reference. However, electrical behavior of electromembrane cells are quite more complex than a resistor. Thus, an experimental approach was simply used, connecting directly the ED cell to the ABS device. Voltage spikes were detected when using the ED cell as load, described as Back Electrochemical Force.

VI. BACK ELECTROCHEMICAL FORCE

When fresh and salty water is fed into the electrodialysis cell, the saline gradient generates electrical power in a process called Reverse Electrodialysis (RED). Then, in a desalination process, voltage spikes would be expected when reversing polarity, analogous to the discharging of a capacitor. Thus, the chemical gradient could generate a Back Electrochemical Force (BECF), pushing the current back through the device into the power supply, which can be harmful to the electrical systems. BECF can be calculated using Eq. (1).

$$E = \alpha_{CEM} \frac{RT}{zF} \ln \left( \frac{a_i^+}{a_j^+} \right)$$

where E is the potential generated between the concentrate (c) and the diluate (d) compartments of the desalination process. Equation 1 gives the potential across a cation exchange membrane, using the activities of the moving cations ($\alpha_i^+$ and $\alpha_j^+$). $\alpha_{CEM}$ refers to the selectivity of the membrane. The same equation can be used to calculate the potential across an anion exchange membrane.

Depending on the concentration difference between the compartments and the number of cell pairs employed to run a given process, the operation could turn critical. At industrial scale, the concentrate stream is recirculated, increasing the concentration difference between the compartments. Additionally, the number of membrane pairs that are potentially stacked (up to 600), increases the chances for problems related with BECF. Therefore, BECF must be considered when scaling the technology.

For reducing BECF into the electrical system, a dead-time was applied in between the pulses. Thus, electrochemical energy is dissipated in the freewheeling diodes of the asymmetric H-Bridge. This was achieved by controlling the switching logic, closing both low side IGBTs ($Q_2$ and $Q_3$) and opening both high side IGBTs ($Q_1$ and $Q_4$) for 1 μs. This strategy has been used in motors to decrease the Back Electromotive Force from inductive loads when collapsing the magnetic field of the motor coils after breaking.

![Fig. 3](image-url)
Additionally, small smoothing capacitors (10 μF) were placed in parallel with the power supply outputs to mitigate BECF effect (C1 and C2, Fig. 1), protecting the electrical system. The value of this capacitor was based on the capacity needed to absorb the released energy. Voltage cannot change instantaneously across a capacitor, smoothing the voltage peaks. An oscilloscope was used in between the power supply and ABS to detect this BECF effect. Voltage spikes and the effect of both mitigation strategies are shown in Fig. 4.

Voltage spikes of 0.63 V were detected when pulsing the system. This value is in accordance with the calculated potential (Eq. (1)), considering a concentration of 0.2 M of sodium chloride in the concentrate compartment and 20 mM in the diluate compartment. This is equivalent to 0.059 V per membrane or 0.65 V in the whole cell. Since the concentrate is recirculated in industrial cells, and membranes are stacked up to 600 pairs, voltage peaks of at least 100 V are expected in large scale systems. Therefore, mitigation strategies are compulsory to avoid such problems at industrial scale.

VII. POWER LOSS DURING DESALINATION

The electrodialysis performance was calculated in desalination using Eq. (2),21 and normalized by the volume of the processed brine.

\[ E = \int \frac{UIdt}{V} \]  

(2)

where \( V \) is the volume of treated water in m\(^3\). The time \( t \) was obtained when reaching a defined water quality in terms of electrical conductivity.

Power is consumed in the electrodialysis cell when desalting. However, if the Asymmetric Bipolar Switch is coupled to electrodialysis, the current will flow through the electronic elements and some power will be lost as heat. Power loss in transistors occurs when conducting current or switching. Thus, the total power lost as heat is obtained by calculating the conduction and switching losses of the IGBT elements, and adding the freewheeling diode losses, as shown in Eq. (3),22 and normalized with the demineralized water volume expressed in Eq. (4).

\[ P_{\text{Avg}} = (P_{\text{Cond}} + P_{\text{sw}} + P_{\text{Diode}}) \times 2 \]  

(3)

\[ E_{\text{heat}} = \int \frac{P_{\text{Avg}}dt}{V} \]  

(4)

where \( P_{\text{Cond}} \) is the power loss when the IGBT elements are fully closed, \( P_{\text{sw}} \) is the switching loss when the IGBT elements are turned ON and OFF, \( P_{\text{Diode}} \) is the power loss as heat in the freewheeling diodes, and \( P_{\text{Avg}} \) is the average power loss. Considering that conducting IGBTs are 2 in series in the H-Bridge, then Eq. (3) is multiplied by 2. \( E_{\text{heat}} \) is the energy loss as heat in the electronic components when running a desalination process, calculated as kWh/m\(^3\).

Power loss when desalting can be empirically measured and calculated based on \( P_{\text{Avg}} \), this value will change based on both, switching element characteristics and ED operation. Accordingly, a dialysis of a brackish solution was performed by feeding an electrodialysis cell with direct current, connected directly to the power supply or with the current flow passing though ABS (Fig. 5). Thus, these experimental results were compared to the calculated losses.

The power dissipated as heat was calculated using Eq. (4), and compared with a desalination process without using the Asymmetric Bipolar Switch. When dialyzing at a (low) switching frequency (10 Hz), ca. 0.59 to 1.89% of the energy is lost in the IGBT elements. This measured power loss depends on the frequency of polarity reversal, the velocity of opening and closure of switching elements, and the selected measuring point of current (ammeter A1 or A2). Some differences were found depending on the measuring point, while 0.59% of energy loss was obtained by measuring at A1, 1.89% of power loss was obtained when using the ammeter A2. These differences are explained by the current flowing through the system when closing Q2 and Q1 and opening Q1 and Q3 in the application of dead time in between pulses. As observed in Fig. 5, the current BECF peaks distort experimental measurements when measuring at point A1, and should be considered if ABS is coupled to other electrochemical processes. On the other hand, the calculated power loss was 0.26% in the switching devices, mainly due to conduction losses. Switching losses were calculated to be 1.8 x 10^{-7} kWh at 10 Hz and 850 s of operation, negligible at this low operation frequency.

The characteristics of the asymmetric pulses and their application frequency must be defined based on operational parameters of the studied electrochemical process. In the case of electrodialysis, Duty Cycle, Limiting Current Density, Desalination Efficiency,
and Fouling and/or Scaling occurrence could be considered. Therefore, for each specific process power loss should be independently determined, considering a common (ground) measurement point of current for decreasing disturbances.

VIII. CONCLUSIONS

The electronic design of an Asymmetric Bipolar Switch was reported and the possible disturbances when using an electrodialysis unit as electrical load were discussed. Voltage spikes were identified when pulsing the system, which could damage the connected power supplies. Two mitigation strategies were described for protecting the electronics, being effective for absorbing the released energy coming from the electrodialysis cell as Back Electrochemical Force. ABS allows the modulation of frequency, pulse width, intensity of the pulses, and application of pauses, differing from PWM techniques. This flexibility permits its utilization as instrument for improving the operation of a variety of electrochemical systems. Moreover, high power applications can be achieved by replacing the electric components, according with the requirements of the electrochemical processes. Automation is also possible for a dynamic application of asymmetric pulses, although no studied at this point. Finally, energy loss as heat in the bipolar switch was calculated and measured when switching and conducting current from a desalination process. The energy loss obtained in the experiments was 0.59 to 1.89% of the total applied energy, depending on the measurement point, while around 0.26% of the energy was calculated as lost in the electronic elements using a frequency of 10Hz.

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