Journal of Solar Energy Research 22 (2017) 13-18

Journal of Solar Energy Research (JSER)

Journal homepage: www.jser.ut.ac.ir

Application of PV and Solar Energy in Water Desalination System

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ARTICLE INFO

Received: 2 April 2017
Received in revised form: 30 April 2017
Accepted: 5 May 2017

Keywords:
water desalination process, solar energy distillation, electrodialysis, reverse osmosis, capacitive deionization

A B S T R A C T

Nowadays, shortage of the water resources is a global issue. Water desalination is a solution that can be used to solve the water shortage problem. Several methods have been proposed for water desalination and are categorized to membrane and non-membrane procedures. The most popular membrane processes are electrodialysis (ED) and reverse osmosis (RO); in contrast, the most popular non- membrane processes are capacitive deionization (CDI) and distillation. All water desalination procedures need energy supplies. The solar and Photovoltaic (PV) energy is potentially a desirable green energy supply for water desalination especially for non-residential areas where the grid is not available. In areas such as deserts and offshore stations, the PV solar energy is a practical and cost effective solution for water desalination systems. Where the grid connection is available, the PV and solar desalination systems produce fewer emissions. The PV energy needs to be processed through power electronic power conditioning systems. This paper proposes the application of PV power and solar energy to supply the water desalination systems.

1. Introduction

One of the most abundant resources on earth is the water whereas three-fourth of the earth's surface is occupied by water. The geography science indicates that about 97% of earth's water is saltwater in the oceans and only 3% is freshwater which is existed in the poles (in the form of ice), ground water, lakes, and rivers. Unfortunately, 70% of this small 3% is inaccessible due to glaciers and permanent snow cover. Also, 30% of the entire freshwater is underground and just a little more than 0.25% of freshwater is in human access which is comprised of lakes and rivers. Nowadays, due to population growth, incorrect water usage, and management problems of the usable water resources for humans are significantly limited. Water scarcity defines as a lack of sufficient water resources [1]. According to united nation (UN) research, one seventh of world's population do not access to clean drinking water. One way to overcome, or at least reduce, this problem is desalination of brackish water and seawater.

Desalination processes require energy for separation of salt from brackish water or seawater. The intense rising of desalination systems consume lots of energy which cause environmental pollution due to the use of fossil fuels. Renewable systems are a desirable selection to replace with fossil fuels energy base systems for preventing harmful effluent and environmental problems. As of today, less than 1% of the installed desalination systems are supplied with renewable energy. This is predominantly caused by the high capital and maintenance costs used by renewable energy. Solar desalination plants connected with common desalination systems have been installed in diverse locations around the world [2, 3]. The majority of these desalination plants are pilot systems for technology research and demonstration. Fresh water production using desalination technologies driven by renewable energy systems is a reasonable solution to the water scarcity in remote areas marked by the lack of potable waters and conventional energy resources such as a heat and electricity. The desalination systems divided into two general processes which are called membrane and non-membrane process. The principle method of membrane processes is reverse osmosis

(RO) and electrodialysis (ED). The two major method of non-membrane processes is capacitive deionization (CDI) and distillation.

In this paper, special attention is paid to PV and solar energy systems. The application of PV energy in various water desalination systems will be evaluated. Solar energy can be used for brackish water desalination by producing either thermal energy required to drive distillation processes or the electricity required to drive membrane processes such as RO and ED and non-membrane procedure such as CDI. Considering the aforementioned processes, solar desalination systems can be classified into two categories: direct and indirect systems. These categories will be discussed in the next sections.

2. Solar desalination systems

2.1. Direct desalination system

Direct solar desalination systems use solar energy to distillate seawater directly. This method does not require a complicated technology and can be operated by an unskilled worker. Fig. 1 shows a typical solar still that uses greenhouse effect to evaporate salty water. It includes a basin in which a constant amount of seawater is enclosed in an inverted V-shape glass envelope. The blackened bottom of the basin absorbs the sun rays that pass from the transparent roof. These rays cause water to be heated. After the water reaches the boiling point, it starts to evaporate. The resultant evaporated water is then condensed in the underside of the roof and runs down into troughs, which

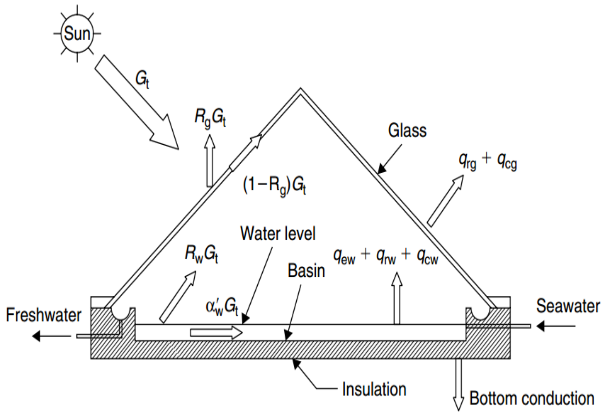

Fig. 1. Schematic of a direct solar system which known as a solar still

conduct the distilled water to the reservoir. The roof encloses the vapor, prevents losses, and keeps the wind out of the salty water to make it cool [4]. The design issue with solar still can encounter as brine depth, vapor tightness of the enclosure, distillate leakage, material, cover slope shape, and thermal insulation. Several attempts have been applied to solar still to utilize it economically by using of plastic material, however, the short lifetime is another problem in this procedure [5, 6]. The performance of solar still is reported in [7]. Accordingly, the hourly evaporation per square meter achieved from a solar still q_{ew} , and it can be formalized by

$$q_{ew} = 0.0163 h_{cw} (P_w - P_g) \tag{1}$$

Where h_{cw} is convective heat transfer coefficient from the water surface to glass, P_w is partial vapor pressure at water temperature and P_g is partial vapor pressure at glass temperature.

2.2. Indirect desalination system

The principle of indirect solar water desalination systems can be summarized into two subsystems:

1) Solar energy collection system (solar collector and photovoltaic cell)
2) Plant for transforming the collected energy to fresh water

The plant subsystem includes various processes that are categorized to the membrane and non-membrane processes that are mentioned in the introduction. The popular distillation processes are multi-stage flash (MSF), Multiple-effect boiling (MEB) and Vapor Compression (VC).

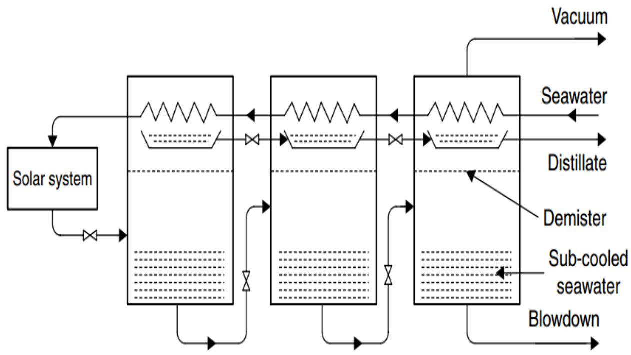

Fig. 2. MSF plant driven by a solar system

2.2.1. Multi-Stage Flash (MSF)

The simple MSF process plant along with solar collector system is shown in Fig. 2. The plant has a series of spaces called stages, each containing a heat exchanger and a condensate collector. The sequence of the plant has a cold end and a hot end while intermediate stages have intermediate temperatures. The pressure in each stage is adjusted according to the required process. There is a container after the hot end, which is called the solar collector array. The fed water at the cold inlet temperature is pumped through the heat exchanger and warms up to raise its temperature in every stage. Then, the water enters the solar collector array to raise its temperature to nearly the saturation temperature at the maximum system pressure. The produced vapor passes through a wire mesh (demister) to remove any entrained brine droplets and then goes into the heat exchanger; where, it is condensed and drips into a distillate tray in each stage. This process is repeated through the plant because both brine and distillate streams flash as they enter subsequent stages that are at successively lower pressures. In the final stage, the brine water reduces its temperature and the condensate water has a temperature near the inlet temperature. Then the brine and condensate water are pumped out from the low pressure in the stage to the ambient pressure. By increasing the number of stages, the terminal temperature becomes cooler; hence, less heat transferring area is required [8]. MSF should operate at the precise pressure level in the different stages. Therefore, a transient time is required to establish the normal running operation of the plant. This feature makes the MSF relatively unsuitable for solar energy applications unless a storage tank is used for thermal buffering. The mass rate of distillate is given by [9]:

$$M_d = \frac{M_f}{\frac{L_v}{c\Delta F} + \frac{N-1}{2N}} \quad (2)$$

Where M_f is the mass rate of feed, L_v is the average latent heat of vaporization, c is mean specific heat under constant pressure for all liquid streams, N is the total number of stages or effects.

The flashing temperature range, ΔF, can be written as below

$$\Delta F = T_h - T_{bN} = (T_{b1} - T_{bN})\frac{N}{N-1} \quad (3)$$

Where T_h is top brine temperature, T_{b1} is the temperature of brine in the first effect and T_{bN} is the temperature of brine in the last effect.

2.2.2. Multiple-Effect Boiling (MEB)

An MEB process is comprised number of elements that are called effect. It is an apparatus for efficiently using the heat from steam to evaporate the water which is illustrated in Fig. 3. The feed water is boiled in a sequence of effects, each held at a lower pressure than the last. Because the boiling temperature of water decreases as pressure decreases, the vapor boiled off in one effect can be used to heat the next and only the first effect (at the highest pressure) requires an external source of heat. In this procedure, the vapor is made by flashing and by boiling, but the majority of the distillate is produced by boiling. This process is repeated all the way through (down) the plant. The distillate also passes down the plant. Both the brine and distillate boil as they travel down the plant due to a progressive reduction in pressure. The MEB process conventionally operates as a once-through system without a large mass of brine recirculation around the plant that is different from MSF process [10]. The MEB is the most appropriate process for solar energy applications that the noticeable points are its stable operation between virtually 0 and 100% output, even when sudden changes are made, and its ability to follow a varying steam supply without upset.

The mass rate of distillate for the MEB system is calculated for this process as:

$$M_d = \frac{M_f}{\frac{\sum_1^N f_n}{M_d}\frac{L_v}{cN\Delta t_n} + \frac{N-1}{2N}} \quad (4)$$

Where $f_n, \Delta t_n$ are the mass rate of distillate obtained by flashing per stage temperature drop between two effects consisting of the heat transfer and temperature difference and an augmented boiling point elevation respectively.

2.2.3. The Vapor Compression (VC)

In a VC plant, heat recovery is based on raising the pressure of the steam from a stage by means of a compressor that is shown in Fig. 4. The condensation temperature is increased and the steam can be used to provide energy to the

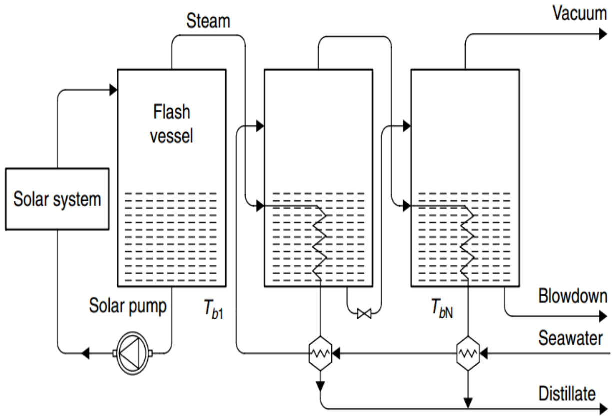

Fig. 3. Principle operation of MEB plant driven by a solar system

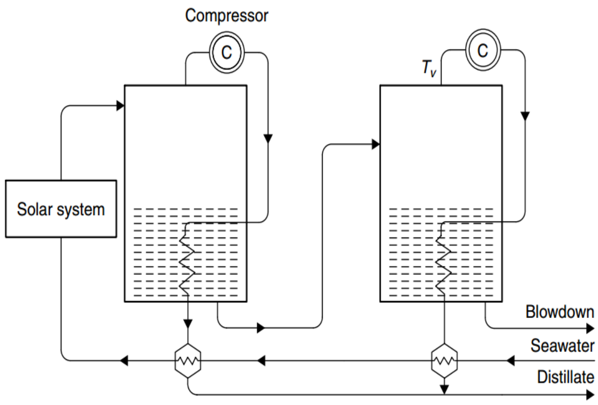

Fig. 4. A TVC plant that uses vapor produced by a solar system

the same stage it came from or to other stages. Unlike conventional MEB system, in VC vapor produced in the last effect is passed to the vapor compressor, where it is compressed and its saturation temperature is raised before it is returned to the first effect. The cost considerations and procedure designs issue have been carried out and represent that this type of process is not individually convenient unless it is incorporated with an MEB system. Moreover, it comes into sight that the mechanical energy requirements have to be supplied with a primary drive, such as a diesel engine, and cooling the radiator of such an engine provides more than enough heat for the thermal requirements of the process, making the solar collector system redundant [11, 12]. Therefore, the VC system can be got along with an MEB system and operated at periods of low solar radiation or overnight. It should be considered that VC is divided into two system: mechanical vapor compression (MVC) and thermal vapor compression (TVC) systems. MVC systems utilize a mechanical compressor to compress the vapor, while TVC applies a steam jet compressor for vapor compressing.

In the case of VC process, the mass rate of distillate can be calculated as:

$$M_d = \frac{\sum Q}{\frac{M_f}{M_d} c(T_v - T_o) + L_v} \quad (5)$$

Where Q is total thermal load per unit product obtained by adding all loads, T_v is the temperature of vapor entering the compressor, T_o is environmental temperature.

2.2.4. Reverse Osmosis (RO)

The RO system is a membrane process that pertains to the properties of semipermeable membranes which used to separate water from a salt solution and allow fresh water to pass into the brine compartment under the influence of osmotic pressure. Theoretically, the only energy requirement is to pump the feedwater at a pressure above the osmotic pressure. However, in a practical process, higher pressures must be used, conventionally 50–80 atm, to have a sufficient amount of water pass through a unit area of the membrane [13]. Fig.5 illustrate principle operation of an RO process conjunction with a solar energy. In larger plants, it is economically viable to recover the rejected brine energy with a suitable brine turbine. Such systems are called energy recovery reverse osmosis(ER-RO) systems. Solar energy can be used with RO systems as a prime mover source driving the pumps with the direct production of electricity through the use of photovoltaic panels [14, 15]. By considering the fluctuations of energy in PV panel due to climate changes, it is sensible to utilize an energy storage system for facing with these climate changes. Because the unit cost of the electricity produced from photovoltaic cells is high, photovoltaic-powered RO plants are equipped with energy-recovery turbines. In [16], a system analyzed using an RO desalination unit driven by PV panels or from a solar thermal plant. According to results, due to the high cost of the solar equipment, the cost of freshwater is about the same as with an RO system operated from the main power supply.

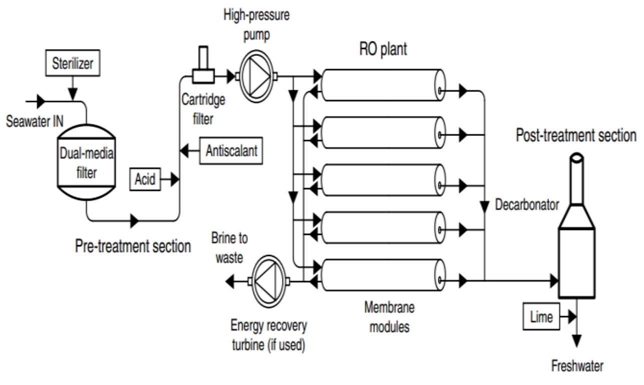

Fig. 5. A complete process of an RO system

2.2.5. Electrodialysis (ED)

ED is a membrane process which is utilized to move salt ions from one solution through ion-exchange membranes to another solution under the influence of an applied electric potential difference. The process uses a DC voltage or DC current to remove salt ions in the brackish water. Saline feedwater comprises dissolved salts separated into positively charged sodium and negatively charged chlorine ions. These ions transport toward a reversely charged electrode plunged in the solution, i.e., positive ions (cations) relocate to the negative electrode (cathode) and negative ions (anions) to the positive electrode (anode). If particular membranes, alternatively cation permeable and anion permeable, separate the electrodes, the center gap between these membranes is gradually eroded of salts. In a practical process, a large number of alternating cation and anion membranes are cascaded together, divided by plastic flow spacers that let the flow of water [17]. Because the energy requirements of the system are proportional to the water's salinity, ED is more sensible when the salinity of the feedwater is no more than about 6000 ppm of dissolved solids. Similarly, due to the low conductivity, which increases the energy requirements of very pure water, the process is not suitable for water of less than about 400 ppm of dissolved solids. Since the process operates with DC power, solar energy can be applied with electrodialysis by directly producing the voltage difference required with photovoltaic panels. Also, a storage system can be coupled with ED photovoltaic supply process to ensure stable operation of the system.

2.2.6. Capacitive Deionization (CDI)

Capacitive deionization (CDI) is a non-membrane process that uses electricity to remove ions from the water. An electric field will be provided that attract positive and negative electric chargers inside the solution by applying an electrical potential difference on the plate (electrode) of the CDI's cell. The ions which are contained in salty water will separate and attract to the plate by passing the flow of water between the electrodes. In comparison with other desalination technologies, CDI process is popular method due to high energy efficiency operation. The reason of notable energy efficiency benefit is that in CDI the energy can be recovered. CDI by nature is a supercapacitor and can store energy. Therefore, energy can recover in this system. CDI operation consists of two stages. As the first stage starts, the DC voltage is applied to CDI electrode for removing the ions. This stage continues up to the ions saturation of the plates and is called purification stage. The second stage starts by shorting the electrodes or transferring the stored energy from the CDI. The feeding water flows between the electrodes to purify them. This stage is called purging stage. As Fig. 6 depicts, A CDI plant can consist of two CDI cell or one CDI cell and one supercapacitor (for saving the energy). A solar system which is comprised of photovoltaic cells generates electricity for supplying the plant. Maximum power point tracker (MPPT) block take maximum available power from the solar system. On the other hand, it improves the efficiency of power production [18, 19]. The output power of MPPT feeds storage system and main system that contains CDI cells. The storage system is considered for stable operation of the plant during all day long. The aforementioned systems are constituted energy supply section which is operated as an input energy feeder. By using this energy section, the initial energy of the main system is provided through the power electronic converter for feeding the CDI_1 in purification stage. At the end of the purification stage, the stored energy in CDI_1 needs to transfer to other CDI_2 through the converter to start the purification stage in that cell for purifying the salty water while the CDI_1 begins to clean the electrodes in purging stage. Then, the initial energy continues to move up between two cells and the energy supply section only compensates the system's losses [20-24]. Due to the high efficiency of CDI system, a PV system can be a desirable selection for energy supply especially in a remote area that the electricity network is not available. Also, the requirement of potable water on boats and ships are another example.

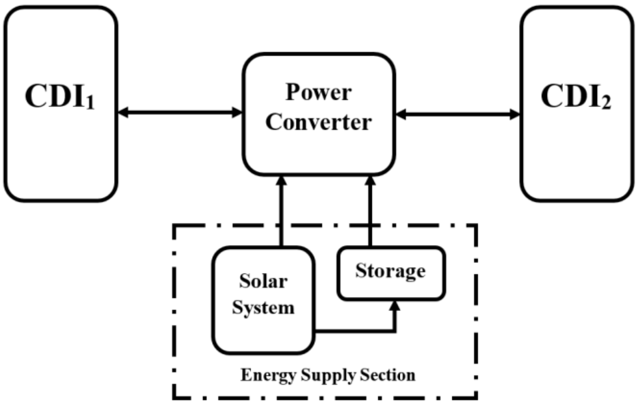

Fig. 6. Block diagram of a CDI system that utilizes a solar system as an energy supply section

3. Conclusion

It can be considered that the solar energy is best and most cheaply harnessed with solar collection (thermal energy) systems. Therefore, the two systems that could be utilized are the MSF, the TVC, and the MEB plants. With comparing these processes, it becomes clear that the MEB process needs less energy, is cheaper, and has a very simple seawater treatment. Therefore, it is a desirable selection in conjunction with a solar collection system. However, if thermal energy is attainable somewhere like in a nuclear station or a power station, it can be applied directly to drive a distillation process, such as MSF, MEB, or TVC. TVC also has lower performance than MEB and MSF. If the accessible energy resources can generate electrical energy or mechanical power (shaft power), RO, ED, or MVC are preferred. Fluctuations in feeding energy would damage the RO plant. Therefore, an energy storage system is needed, but it would grow the capital costs and add a maintenance service. Although MVC requires more energy than RO system, it exhibits fewer problems than RO due to more stable operation in the situation of energy fluctuations. MVC systems are more suitable for inaccessible grid network area since they are well-conditioned and need less skilled workers and fewer chemicals treatment than RO systems.

In remote areas, CDI and ED are most suitable for brackish water desalination, because they are more robust and their operation and maintenance are simpler than RO systems. In addition, the ED and CDI processes can adapt to changes of available energy input so that, a photovoltaic cell can connect to them for supplying energy input. Furthermore, CDI process needs no membrane replacement and offer a better quality product than ED. CDI system also consumes less energy than ED and it can operate with different water salinity. Moreover, the use of power converter in CDI can provide a prime control to monitor the operation of the system, such as controlling the duration of energy transfer and converter efficiency. Therefore, both brackish water and seawater can be a feedwater for such a system.

References

[1] Delyannis, E., 2003. Historic background of desalination and renewable energies. Sol. Energy 75 (5), 357–366.

[2] S. A. Kalogirou, "Chapter eight - Solar Desalination Systems," *Solar Energy Engineering*, S. A. Kalogirou, ed., pp. 421-468, Boston: Academic Press, 2009.

[3] Kalogirou, S., 2005. Seawater desalination using renewable energy sources. Prog. in Energy Combus. Sci. 31 (3), 242–281.

[4] J. A. Eibling, S. G. Talbert, and G. O. G. Löf, “Solar stills for community use—digest of technology,” *Solar Energy*, vol. 13, no. 2, pp. 263-276, 5//, 1971.

[5] Kreider, J.F., Kreith, F., 1981. Sol. Energy Handbook. McGraw-Hill, New York.

[6] Tleimat, B.W., 1978. Solar distillation: The state of the art, Technology for solar energy utilization. United Nations, New York, pp. 113–118.

[7] Tiwari, G.N., Singh, H.N., Tripathi, R., 2003. Present status of solar distillation. Sol. Energy 75 (5), 367–373.

[8] Morris, R.M., Hanbury, W.T., 1991. Renewable energy and desalination—A review. In: Proceedings of the New Technologies for the Use of Renewable Energy Sources in Water Desalination, Sec. I, Athens, Greece, pp. 30–50.

[9] El-Sayed, Y.M., Silver, R.S., 1980. Fundamentals of distillation. In: Spiegler, K.S., Laird, A.D.K. (Eds.) Principles of Desalination, Part A, second ed. Academic Press, New York, pp. 55–109.

[10] Kalogirou, S., 1997b. Survey of solar desalination systems and system selection. Energy—The Intern. J. 22 (1), 69–81

[11] Mustacchi, C., Cena, V., 1978. Solar water distillation, technology for solar energy utilization. United Nations, New York, pp. 119–124.

[12] Eggers-Lura, A., 1979. Sol. energy in developing countries. Pergamon Press, Oxford, UK pp. 35–40.

[13] Dresner, L., Johnson, J., 1980. Hyperfiltration (Revere Osmosis). In: Spiegler, K.S., Laird, A.D.K. (Eds.) Principles of Desalination, Part B, second ed. Academic Press, New York, pp. 401–560.

[14] Luft, W., 1982. Five solar energy desalination systems. Int. J. Sol. Energy 1 (21).

[15] Grutcher, J., 1983. Desalination a PV oasis. Photovoltaics Intern. (June/July), 24.

[16] Tabor, H., 1990. Solar energy technologies for the alleviation of fresh-water shortages in the Mediterranean basin, Euro-Med solar. In: Proceedings of the Mediterranean Business Seminar on Solar Energy Technologies, Nicosia, Cyprus, pp.152–158.

[17] Shaffer, L.H., Mintz, M.S., 1980. Electrodialysis. In: Spiegler, K.S., Laird, A.D.K. (Eds.) Principles of Desalination, Part A, second ed. Academic Press, New York, pp. 257–357.

[18] B. S. Shankar, K. P. Pranav, and R. K. Raj, "Capacitive deionization based water desalination system using an MPPT based solar charge controller." pp. 277-282.

[19] Y. Oren, “Capacitive deionization (CDI) for desalination and water treatment -past, present and future (a review),” *Desalination*, vol. 228, no. 1–3, pp. 10-29, 8/15/, 2008.

[20] A. M. Pernia, F. J. Alvarez-Gonzalez, M. A. J. Prieto *et al.*, “New Control Strategy of an Up&Down Converter for Energy Recovery in a CDI Desalination System,” *Power Electronics, IEEE Transactions on*, vol. 29, no. 7, pp. 3573-3581, 2014.

[21] A. M. Pernia, M. J. Prieto, F. Nuno *et al.*, "Improving energy recovery in CDI systems." pp. 1-8.

[22] Perni, A. M. a, J. G. Norniella *et al.*, “Up&Down Converter for Energy Recovery in a CDI Desalination System,” *Power Electronics, IEEE Transactions on,* vol. 27, no. 7, pp. 3257-3265, 2012.

[23] M. Alkuran, M. Orabi, and N. Scheinberg, "Highly efficient Capacitive De-Ionization (CDI) water purification system using a buck-boost converter." pp. 1926-1930.

[24] M. Alkuran, and M. Orabi, "Utilization of a buck boost converter and the method of segmented capacitors in a CDI water purification system." pp. 470-474.