Capacitive Deionization based Water Desalination System using an MPPT based Solar Charge Controller

Sai Shankar B[1], K P Pranav[2], Kiran Raj R[3]
Electrical and Electronics Engineering
Sri Sai Ram Engineering College
Chennai, India
SaiShankar.B.IN@ieee.org[1], Pranav.K.P@ieee.org[2], kiran.1994.r@ieee.org[3]

***Abstract*—This paper focuses on addressing the issue of potable water scarcity, prevalent in various parts of the world. There is a need to employ various expensive techniques to transform the brackish water to standard potable water. The traditional methods of brackish water desalination deployed, namely the Reverse Osmosis Technique (RO) and Distillation processes are expensive in implementation and operation. Capacitive Deionization is an energy efficient technology that provides an ideal alternative solution to this problem. It is a novel technique which removes salt ions from brackish water instead of removing pure water from brackish water like in the conventional reverse osmosis system. Thin film composite membranes of AEM Type-I and CEM Type-I are employed for collecting the respective ions which are separated by means of application of a low value of dc voltage. It requires the usage of significantly less direct current energy for operation. This proposed system is enhanced by the utilization of Solar Energy so as to incorporate the most abundant renewable energy source available. This paper proposes a model which exhibits extreme potential of application mainly in remote locations which are devoid of proper access to conventional sources of energy and WHO specified standard potable drinking water.**

***Keywords*—** Capacitive Deionization; carbon aerogel electrodes; AEM and CEM Type Thin Film Composite Membranes; Desalination; Maximum Power Point Tracking;

I. INTRODUCTION

Desalination can be viewed as the process of creation of freshwater by the separation of salt from salt or brackish water supply. Most large-scale desalination processes in the world are based on variations of evaporation and distillation. Multiple Effect Distillation and Multi Stage Flash Desalination form a group of techniques employed [7]. These energy-intensive, thermal processes require heat that is derived from various non conventional sources of energy. Some of the other common methodologies adopted for desalination include Reverse Osmosis and Electro dialysis [8]. Reverse Osmosis is the widely adopted process involving the separation of freshwater from brackish water with the usage of a semi-permeable membrane. The driving force for this process is the application of a very large potential difference between the ends of electrodes employed. Electrodialysis on the other hand involves the separation of ions by forcing them to pass through membranes and hence separating them from the main stream. However all these methods are seen to be less energy efficient and fail to completely remove a majority of the salt content present in brackish as well salt water sources at large. Thus, cost-effective and efficient methods are required due to the rising cost of energy. Hence salt immobilization by Capacitive Deionization is considered as an energy-efficient method for the desalination of brackish water. Capacitive Deionization (CDI) is a promising alternative technology in desalination which is particularly suitable for small scale inland brackish water desalination due to its lower energy demand [10]and less maintenance requirements. CDI involves the removal of the salt ions from saline water, unlike most other technologies that aim to shift water, which accounts for the majority of the brackish water sample [9]. Additionally, CDI requires low energy for operation and also the electrodes used can be easily regenerated. Solar Energy is used to drive the process of Capacitive Deionization, thereby providing a reliable and environment friendly source of power supply.[1] The solar charging process is enhanced by utilizing a digital maximum power point tracking based solar charge controller. In this proposed model of desalination using Capacitive Deionization, an Arduino microcontroller based solar charge controller is designed to charge a dc battery so as to provide the low value of voltage required to drive the Capacitive Deionization unit [5]. Initially, the brackish water is subjected to a series of pre filtration processes. The pre-filtration process substantially treats the highly impure inlet brackish water. In this critical time of energy and power crisis, the adequate usage of renewable sources of energy to provide technological solutions to humanitarian problems faced by the society at large is absolutely essential. The proposed model adheres to this by solely using solar energy to actuate the water desalination mechanism.

II. CAPACITIVE DEIONIZATION

The working principle of Capacitive Deionization is the imposition of a low direct voltage on two parallel electrodes between which the thin film composite membranes are carefully slotted in a stack arrangement.

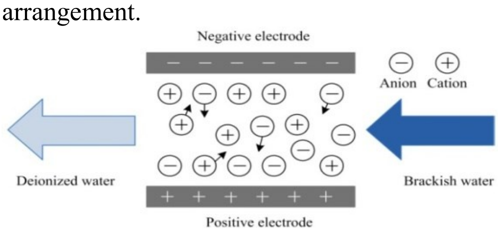

Figure 1. Capacitive Deionization Mechanism

When voltage is applied between the two electrodes, ions get accumulated by the electrosorption process, where cations move into the cathode while anions are electrosorbed in the anode [9]. When the electrodes reach their adsorption capacity, depending upon the cell voltage, a discharge cycle is initiated by reducing or reversing the cell voltage, thereby releasing the salt accumulated as a concentrated stream. Hence no redox occurs and the process can easily be reversed when the electrical field is reversed to get rid of the salt accumulated in the membranes. This salt concentrated water is removed from the system with the help of a back flush system. The utilization of ion exchange membranes in the CDI process results in greater desalination performance compared to CDI implemented without the exchange membranes. In a standard CDI device, the salt removal efficiency is slightly reduced because of co-ion effects (ions of equal polarity as the electrode)[12]. These co-ions are near the electrode but cannot be electro-adsorbed efficiently as a result. To avoid this negative effect, ion-exchange membranes are placed in front of the carbon aerogel electrodes. More specifically, a cation-exchange membrane is placed in front of the electrode that is negatively polarized, and an anion-exchange membrane is placed in front of the positively charged electrode. Counter-ions produced as a result move freely in and out of the electrode while co-ion movement is restricted.

III. PROPOSED SYSTEM.

The proposed system is broadly divided into two subsets namely the Solar Charging module and Capacitive Deionization unit. The CDI unit further contains a pre-filtration system to effectively filtrate the incoming brackish water.

MPPT BASED SOLAR CHARGING MODULE

The objective is to design a digital solar charge controller that implements Maximum Power Point Tracking algorithm for effective and continuous charging of the DC battery which is utilized to drive the CDI process.

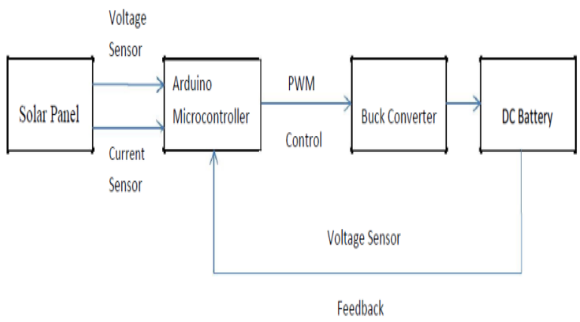

Figure 2.Block diagram of Solar Charging Module

The DC-DC buck converter changes the higher voltage/lower current solar panel input to lower voltage/higher current battery charging power [5]. The Arduino microcontroller controls the conversion ratio of the DC-DC buck converter and does so dynamically and keeps the solar panel operation at its maximum power point. In addition to this, the charge controller also provides protection against overcharging of the battery [4]. Thereby, it provides dual functionality with respect to overcharging protection as well as maximum power point tracking. The solar panel electrical parameters are measured dynamically and feedback is sent to the Arduino microcontroller. The voltage of the solar panel is sensed by using a potential divider circuit. Similarly, voltage of the DC battery is measured using a potential divider. This voltage of the battery is given as feedback to the microcontroller which performs the maximum power point operation according to the algorithm. The current flowing from the solar panel is computed using a hall-effect current sense module. The current sense module used in this module is the ACS712 Hall-Effect based linear current sensor [1]. Thus, at each step, the microcontroller processes these parameters through its analog input pins. The microcontroller is utilized to set the charging state (on, off, bulk and float) by using iterative comparison method of solar panel power and battery power in watts. The microcontroller also sets the pulse width modulation duty cycle on the MOSFET driver IR2104 integrated circuit which is used to switch the MOSFETs. The pulse width modulation is high or one hundred percent when maximum power is to be achieved [2]. In all other cases, it is suitably set to a lesser value which is less than the maximum value, sufficient enough to start charging the battery.

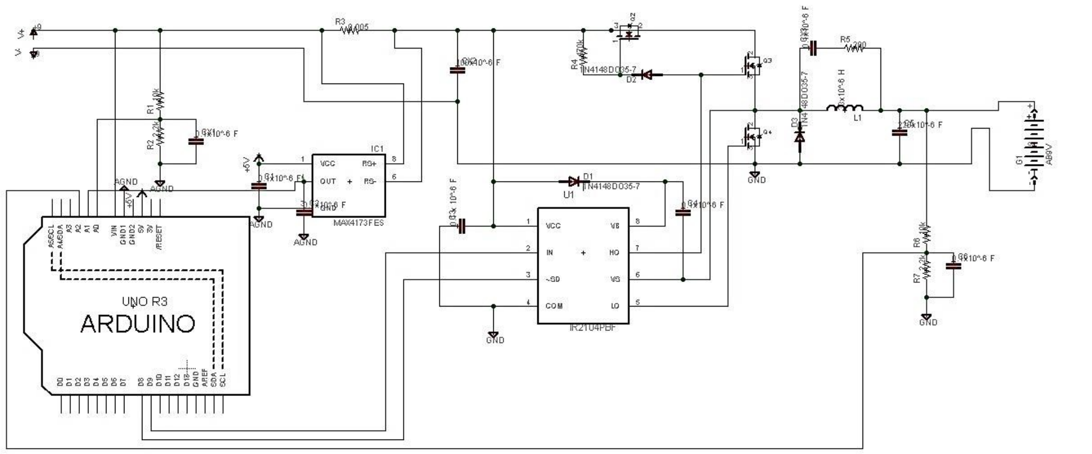

Figure 3.Schematic of Arduino based solar charge controller using EAGLE v6.6.0

The charger circuit is basically a buck converter controlled by the Arduino microcontroller [3]. The microcontroller figures out the voltage of solar panels where the peak or maximum power is produced and controls the buck converter to match the solar panel voltage to the battery voltage. The processor also controls the buck converter by generating a pulse width modulation signal that switches the MOSFET's. The solar panel input voltage is connected to the Vin or raw input to the Arduino microcontroller. The solar panel ground input is connected to the ground of the Arduino microcontroller. The solar panel input voltage is divided down by two resistors and sent to the analog 0 input to be read by the microcontroller. The solar input current is read using a hall-effect current sensor module. This module utilizes the Allegro ACS712 hall-effect based linear current sensor. This is a three pin module with pins as: V_{cc}, Gnd and Out. The module is powered up by connecting the V_{cc} pin to 5 volts pin provided in the Arduino microcontroller. The ground is connected to the common ground of the circuit. The output pin is connected to one of the analog pins, analog 1 of the microcontroller which is used to read the current value. The positive ends of the solar panel and the battery are connected across the current sensor module to form a closed loop for measurement of current. C2 is the input filter capacitor which is used to smoothen the input current pulses. Q1 functions as the blocking MOSFET which keeps the battery power from flowing back into the solar panels. This can be done by using a diode. However, MOSFETs tend to have a lower power dissipation or loss as compared to diodes. The intrinsic MOSFET diode doesn't conduct since Q1 is turned around. Q1 turns on when Q2 is on from voltage through D2. The resistor connected across this MOSFET drains the voltage off the gate of Q1 so it turns off when Q2 turns off.Q2 is the main switching MOSFET for the buck converter and Q3 is the synchronous switching MOSFET. The MOSFETs are driven by an IR2104 MOSFET driver. The IR2104 takes the pulse width modulation signal from the processor digital input pin 9 on pin 2 and uses it to drive the switching MOSFETs employed. The IR2104 MOSFET driver can also be shut down with the control signal from the processor digital pin 9 on pin 3. So the IR2104 uses a charge pump circuit made of a diode and a capacitor to boost the gate drive voltage to turn on the high side MOSFET. This charge pump circuit operates only when the MOSFETs are switching. The software keeps track of the pulse width modulation duty cycle and never allows maximum or hundred percent. It caps the pulse width modulation duty cycle at almost maximum to keep the charge pump working.D1 is a diode that will start conducting current before Q3 turns on. It is aimed at making the converter more efficient. L1 is the main inductor that is used to smoothen the switching current and along with C3 it also smoothens the output voltage.

A snubber circuit is used to eliminate the ringing of the inductor voltage which can otherwise have adverse effects on the overall performance of the charging module.

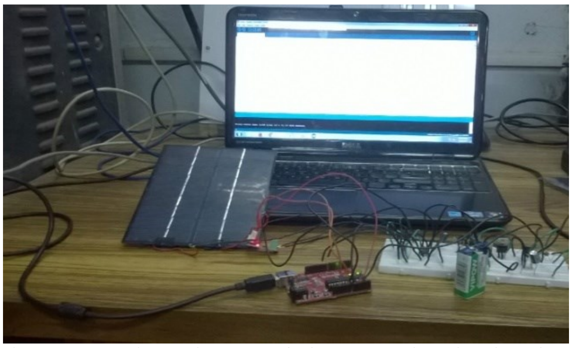

Figure 4.Experimental setup of the MPPT based solar charge controller.

The main purpose of designing this module is to eliminate the unnecessary use of commercially available, high cost maximum power point tracking solar charge controllers. In this solar charge controller, the electrical parameters are monitored dynamically and displayed in the output screen. This establishes a monitoring system. The user will be able to keep track of the overall system functionality based on the output displayed. The monitoring system provides details pertaining to: charge state (on, off, bulk, float), pulse width modulation duty cycle, and the electrical parameters of the solar panel and the battery.

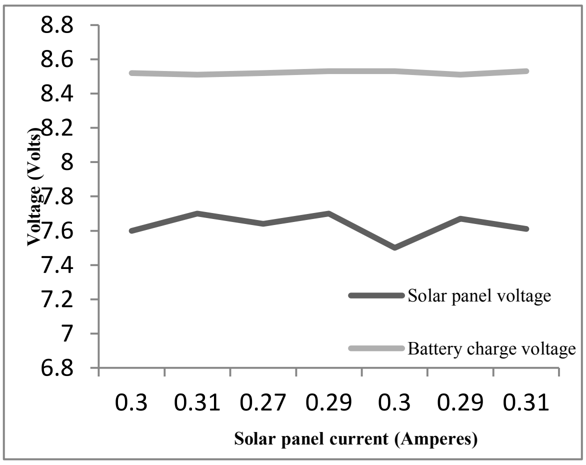

Figure 5.Solar charge controller performance characteristics in float charging state.

CAPACITIVE DEIONIZATION UNIT

The CDI process is preceded by a suitable pre-filtration procedure that treats the inlet water initially. The selection of highly efficient thin film composite membranes is essential in enhancing the performance of the CDI system.

Property	Value	Units
Thickness	125-135	µm
Permselectivity(0.5M NaCl)	92	%
Electrical Resistance(0.5M NaCl)	1.3-2.7	Ω cm^2
Water permeation	6-10	ml/bar.m^2.hr
Burst Strength(Wet)	2.4-2.7	kg/cm^2
pH stability	2-12	-

Table 1. Properties of Thin Film Composite membrane

The thin film composite membranes are arranged in a stack sequence to maximize the efficiency of the process. .

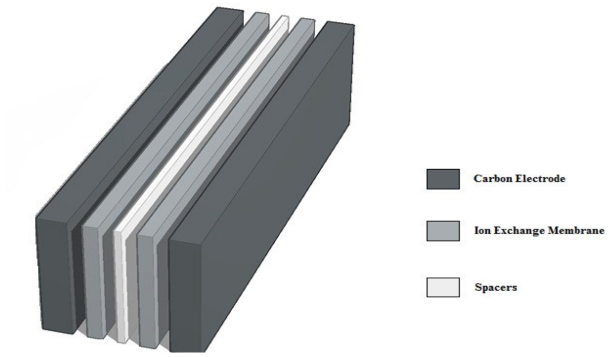

Figure 6. CAD design of TFC membranes arranged in stack sequence.

The CDI unit is comprised of the following two constituents:

1. Pre Filtration System

2. Desalination System

The contaminated water is first treated, to remove impurities by an effective pre-filtration process. The dissolved impurities level is brought to 1000 PPM which is still not potable for human consumption. This necessitates the usage of the Capacitive Deionization process. Water is passed through these stages for a long duration of time till the permissible rates are obtained. A pump rated at 0.5 to 0.7 HP is employed to pump the brackish water supply into the CDI unit for purification. The water supply is subjected to an extensive process of pre filtration with the aid of sand and activated carbon filters. The sand filter helps in the removal of any suspended impurities which may be present in the water. An activated carbon filter aids in the process of removing agents like chlorine, sediment, volatile organic compounds (VOCs), taste and odour from the contaminated water. Such a process of pre filtration is crucial in ensuring that the hardness of the water entering the CDI unit is limited to 1000 PPM. Thin film composite membranes are employed for the desalination process. These are customized membranes based on the new polymer technology in combination with thin substrates. They are optimal in stack configurations and offer a low value of resistance, apart from exhibiting excellent perm selectivity property for salt [8].

The desalination system is implemented in the form of a stack arrangement for effective removal of salt impurities from the water flowing through the system. Carbon Aerogel electrodes [10] are employed due to their high surface area (2.0-5.4x10'ftýlb**)**, low electrical resistivity (< 40 m Ω cm) and controllable pore size distribution (<=50 nm). The output water from the CDI unit is further purified by passing it through a UV filter to kill any bacteria that maybe present in the water sample. An effective back flush system ensures that the concentrated stream of water is driven out of the system. The output produced from the entire unit is potable drinking water in adherence with the defined drinking water standards of World Health Organization of 500 PPM.

IV. CALCULATIONS

1. The total area of carbon electrode sheet required to desalinate a given feed stream (S) can be estimated with the following equation:

$$S= \frac{F(\mathrm{CF} - \mathrm{CP})}{\sigma}\tau \qquad (1)$$

Where

s = total surface area of the electrode
F = volumetric flow rate
CF = concentration of salt in feed stream
CP = concentration of salt in product stream
τ = the breakthrough time
σ =the area-specific electrosorption capacity of the carbon aerogel at CF.

2. The salt removal capacity of the process is given by,

$$(C - C_o) / (58.44\times M) \qquad (2)$$

where M denotes the Molarity of the concentrated stream of water.

3. The salt removal efficiency of the Capacitive Deionization technique is given by the following formula

$$(C - C_o) / C_o \qquad (3)$$

Where,
C_o - Initial concentration (mg/L)
C - Final concentration (mg/L)
These formulae are applied under a working condition of 120 litre/hr. flow rate and at a temperature range of 25^0 to 35^0 C.

V. RESULTS

The various crucial parameters pertaining to the performance of the proposed CDI system are determined and to elucidate the merits of the proposed model, a comparative analysis is carried out in terms of technical operating parameters and economic feasibility. The focus is also on determining the amount of energy required for varying concentrations of brackish water entering the system.

Description		**Unit**	**Proposed CDI Model**
Inlet parameters	Pressure	Kg/m^2	2.0
	Hardness	ppm	1000
Outlet parameters	Flow rate	Litres/hour	120
	Pressure	Kg/m^2	1.2
	Hardness	ppm	175
Maximum operating hours per day		Hours	20
Maximum water produced from the unit		Litres	2000
Operating temperature		Centigrade	4-50

Table 2. Operating Conditions of the CDI Model

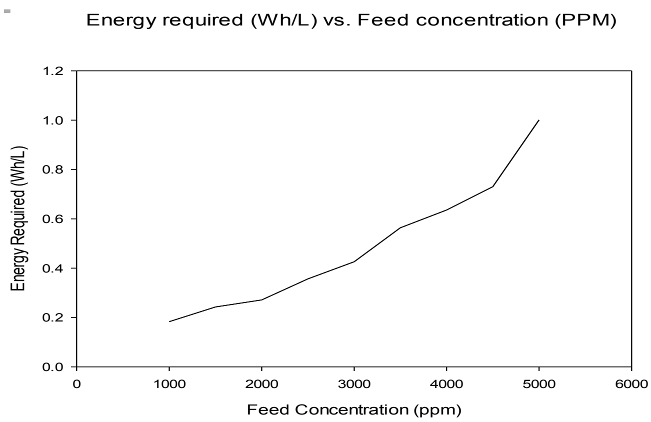

Figure 7. Energy Requirement for various feed concentration under constant flow rate

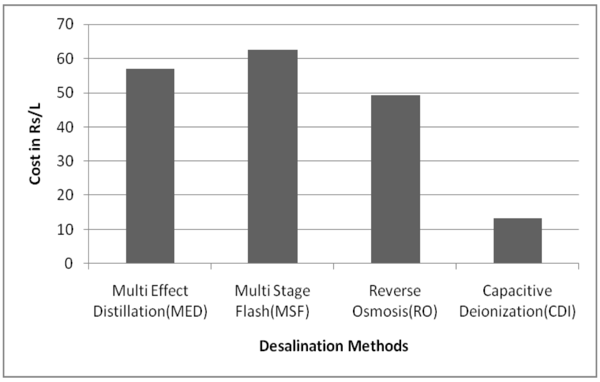

Figure 8.Cost comparison with various desalination methods

PARAMETERS	REVERSE OSMOSIS SYSTEM	CAPACITIVE DEIONIZATION SYSTEM
FEED CONCENTRATION (INLET WATER)	1780 PPM	1780 PPM
PRODUCT CONCENTRATION (OUTLET WATER)	96 PPM	175 PPM
WASTE WATER REJECTION	58%	21 %
POWER CONSUMPTION	0.005 KWh/L	0.002 KWh/L

Table 3.Comparison: RO System and CDI system

V. CONCLUSION

This Capacitive Deionization is an energy efficient technology that is bound to benefit developing countries primarily, since their water problems are more severe as compared to the developed world. Capacitive Deionization is an attractive option for many other low TDS applications such as treating input water for cooling towers, point-of entry related water treatment, and treating produced water from oil, gas mining and other mainstream industrial activities. The proposed model has proved beneficial as compared to other existing desalination methods in terms of system operating parameters and economic feasibility. This model has the additional advantage over the conventional system as it makes use of an efficient MPPT based digital solar charging methodology. This system provides a viable technological solution to the critical humanitarian problem of accessibility to potable water.

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