Desicn and Simulation of A desalination system

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ABSTRACT:

In this work the design, construction and testing of a photovoltaic-powered reverse-osmosis (PV-RO)desalination system is presented using Matlab. The system operates from seawater and requires no batteries, since the rate of production of freshwater varies throughout the day according to the available solar power. Initial testing of the system, with the modest solar resource available in Iraq, provided freshwater at approximately 1.5 m3/day. Nearer to the equator and with a PV array of only 2.4 kWP, a software model of the system predicts production of over 3 m3/day throughout the year. The system employs a Clark pump brine-stream energy recovery mechanism and this, coupled with variable water recovery ratio, achieves a specific energy consumption of less than 4 Three motors and pumps are employed and provide good energy and cost efficiency.

Testing and modelling of the system components in MATLAB-Simulink is presented, together with a discussion of the full system modelling and design procedure, in which the aim was to minimise the cost of water.

1.INTRODUCTION:

1.1 Desalination and Renewable Energy:

The desalination of seawater and brackish groundwater to provide fresh drinking water is an established and thriving industry. The most commonly used technologies are thermal distillation and reverse-osmosis (RO) filtration. Many towns and cities, particularly in the Middle East and the US, already rely heavily on large-scale desalination plants for their municipal water supplies. Small-scale desalination is also well-established, for example on ships. [1]

The energy consumption of desalination also has an environmental impact, in particular the release of carbon dioxide (CO_2) into the atmosphere through the burning of fossil fuels. Prior to the industrial revolution in the 1760's, the concentration of CO_2 in the earth's atmosphere was around or below 280 parts per million (ppm), and had been for hundreds of thousands of years. Since the industrial revolution, mankind has raised this dramatically, as shown in Figure 1.

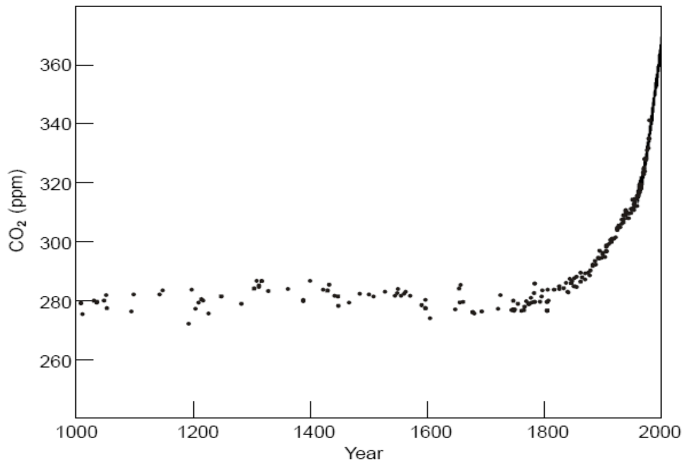

Fig.(1)Atmospheric carbon dioxide over the last 1000 years.

CO2 emissions can be greatly reduced through the application of renewable energy technologies, which are already cost competitive with fossil fuels in many situations.

Good examples include large-scale grid-connected wind turbines, solar water heating and off-grid solar photovoltaics (PV). The use of renewable energy for desalination is, therefore, a very attractive proposition. [1]

1.2 Reverse Osmosis(RO):

Reverse osmosis is a form of filtration, in which the filter is a semi-permeable membrane that allows water to pass through, but not salt. When a membrane of this type has saltwater on one side and freshwater on the other, and in the absence of applied mechanical pressure, water will flow through the membrane towards the saltwater side, evening out the concentrations and reducing the quantity of freshwater. This is the natural process of osmosis, and is widely employed in the cells of all living species. In desalination, of course, the aim is to *increase* the quantity of freshwater and so a pump is employed to make the flow reverse, hence the name: reverse osmosis.

Osmosis is a surprisingly powerful phenomenon; the osmotic pressure of typical seawater is around 26 bar, and this is the pressure that the pump must overcome in order to reverse the flow. (26 bar also equates to the theoretical minimum energy consumption of 0.7 kWh/m3, mentioned earlier.) In practice, a significantly higher pressure is used, typically 50-70 bar, in order to achieve a generous flow of freshwater, which is the *product*, also known as the *permeate*. Of course, as freshwater passes through the membrane, the remaining saltwater becomes more concentrated and, for the process to continue, this *concentrate*, also known as the *brine*, must be continuously replaced by new feed water. To achieve this, the feed water is pumped *across* the membrane as well as through it; hence, RO is a *cross-flow* filtration process as depicted in Figure 2. [2]

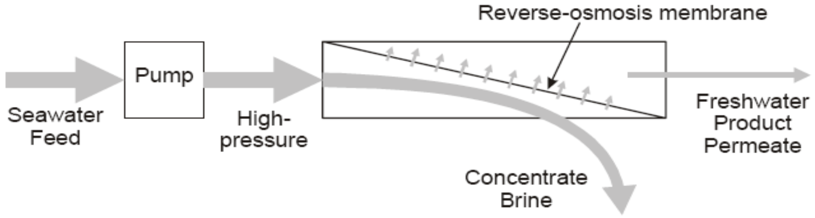

Fig.(2) Schematic of a simple reverse osmosis(RO) system

1.3 Photovoltaics (PV) Batteries:

Photovoltaic panels convert sunlight directly into electricity, and are already widely used in critical applications such as vaccine refrigeration, water pumping and battery charging for lighting and communications. PV is highly reliable and is often chosen because it offers the lowest life-cycle cost, especially for applications requiring less than 10 kW, where grid electricity is not available and where internal-combustion engines are expensive to maintain. PV is a rapidly developing technology with costs falling year on year, and this will soon lead to its broad application in systems requiring larger powers.

Today however, it is clear that PV-RO will initially be most cost-competitive at the small-scale, perhaps for supplying remote villages or small hotels.

Batteries are widely used in PV systems, storing the energy during the day and making it available through the night. Unfortunately, batteries are notoriously problematic in practice, especially in PV systems in hot countries. [3]

Figure(3) shows the picture of a desalination system.

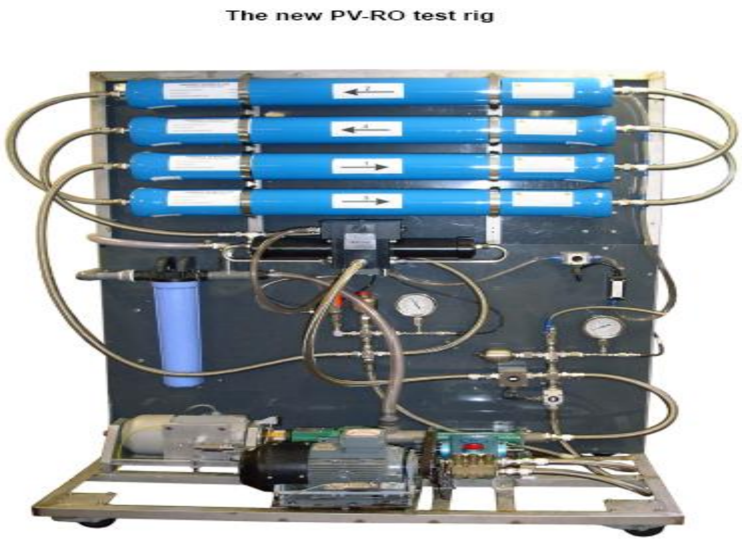

Fig.(3) the new PV-RO test rig

2.DESIGN AND SIMULATION OF DISALINATION SYSTEM:

MATLAB-Simulink is a general-purpose modelling and simulation package that is used throughout science and engineering research and design. MATLAB itself is a text-based programming language that is particularly intended for manipulation of matrixes (hence the name) and mathematical computing in general. Simulink is a graphical programming language that acts as a front-end to MATLAB and allows rapid construction of dynamic simulation models. MATLAB-Simulink was used extensively for the modelling of the PV-RO system. MATLAB (without Simulink) was used for much of the off-line processing of data from LabVIEW.

Simulink models are constructed as interconnected blocks that are structured hierarchically. The programmer has complete control over the structure, and the first challenge is to design an efficient structure for the task in hand. [3]

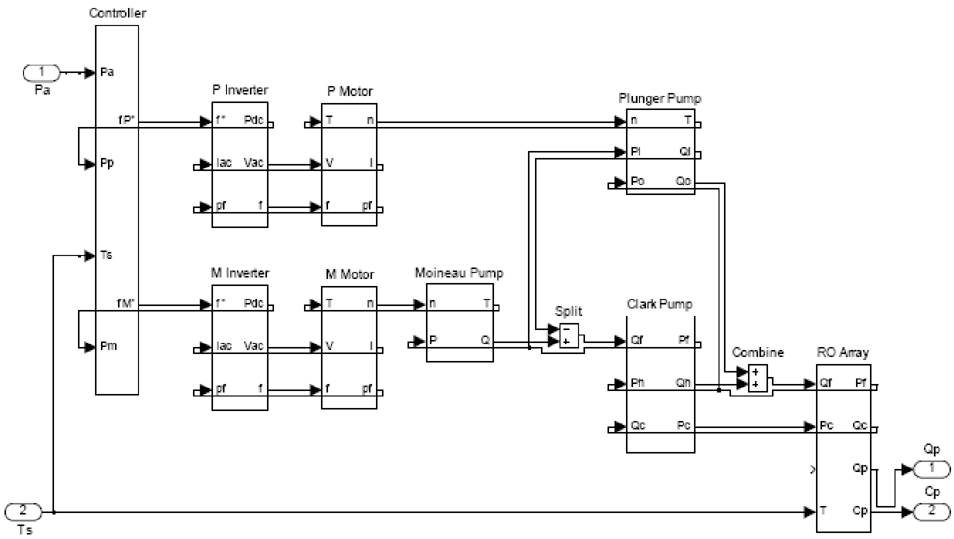

Fig.(4) Simulink model structure

The Simulink model shown in Figure (4) is presented here only to illustrate the general structure and interconnections between the component models.

2.1 PV array:

2.1.1 Two-diode model:

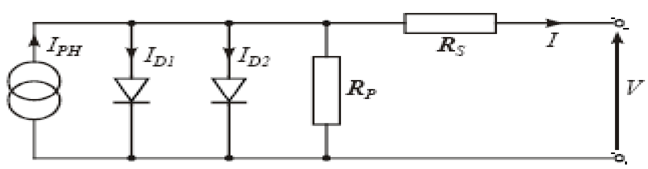

Fig.(5) Two-diode model of a PV cell

The *two-diode model* shown in Figure (5) is commonly used to represent an individual PV cell. *IPH* is the photo current, which is the part we actually want. The other components represent losses within the cell; in particular: *ID1* represents recombination in the bulk material, *ID2* represents recombination in the space charge region, *RP* represents parallel leakage losses and *RS* represents the series resistance. *I* and *V* are the terminal current and voltage respectively.[4]

2.1.2 Simulink model:

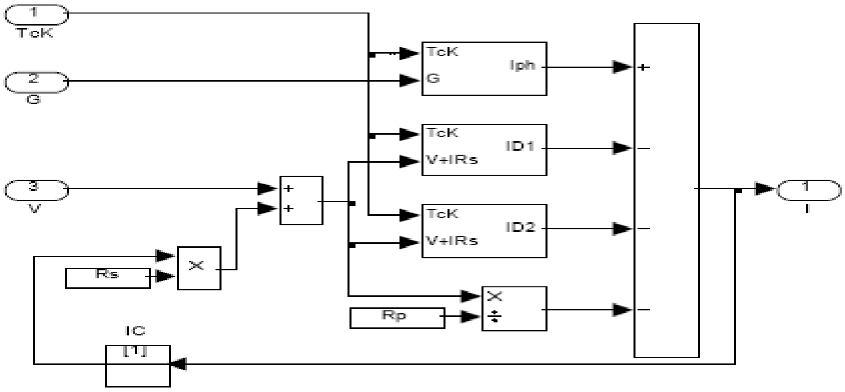

Fig.(6) Two-diode model of a PV cell in Simulink

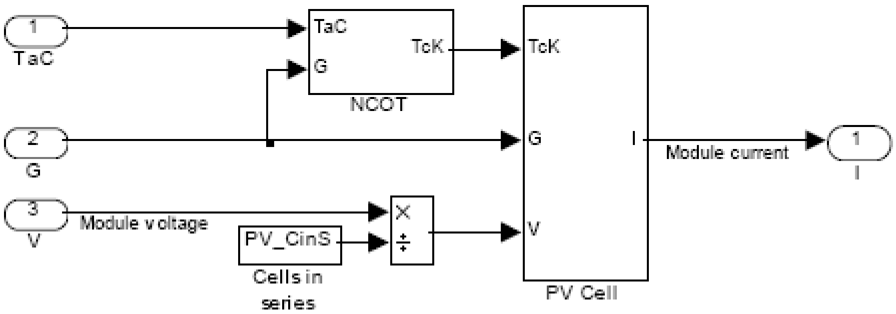

Fig.(7) Simulink model of a PV module

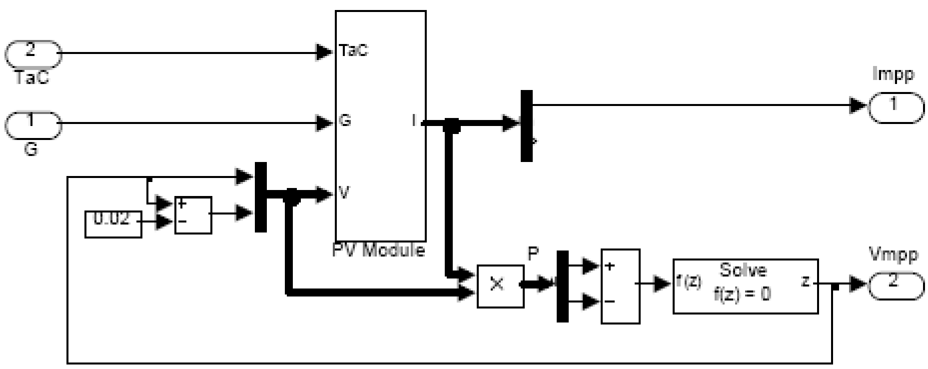

Fig.(8) Simulink programme to locate maximum power point(MPP)

3.CALCULATIONS:

The model first calculates the small pressure drop in the feed/concentrate channel:

$\Delta P = -0.26 + 7.61 Qf / T + 11.3 Qf$ ……………………………………………(1)

2 + 3.36×10-6Cf + 326(T×Pc)-1 – 1.22×105(T×Pc)-2

The pressure of the feed Pf is simply $Pc + \Delta P$, and the average pressure in the feed/concentrate channel is $Pfc = Pc + ½\Delta P$. Where:

Q : the flow , f :the flow and Pc is the pressure at the concentrate channel.

The osmotic pressure is calculated using:

$$\pi_f = \frac{0.002654 \times C \times (T + 273.15)}{1000 - C/1000}$$

…………………………….(2)

In the early Simulink models, the calculation of C included Cc and concentration polarisation, following the DOW equations. But this creates an algebraic loop and it was found better to simply to calculate the osmotic pressure of the feed and to accommodate the concentration increase through extra terms in the product flow calculation. The net driving pressure (neglecting concentration increase) is then given by:

$Pnd = Pfc - \pi f - Pp$. ………………………………………………………..(3)

Where: Pnd the net driving pressure, Pfc :the feed/concentrate channel

The product flow is then given by:

Qp = 0.00307 + 0.000193Pnd – 1.61×10-7Cf + 5.49×10-5T + 2.01×10-5Pnd×T + 2.44×10-5Pnd×Qf×T + 7.9×10-7Cf/T – 3.25×10-10Pnd×T×Cf ……………..(4)

The salt passage through the membrane is the product of the product flow and its concentration and is given by:

Qp×Cp = 5.26 – 7.55×10-5Cf – 0.0209Pnd – 0.422T + 0.00551T 2 + 7.52×10-6Cf×T

+ 0.00163Pnd×T + 5.79Qp/Qf ………………………………………….(5)

Suppose NaCl solution at 32,800 mg/L has an osmotic pressure of 25.8 bar.The testing described here used NaCl solution at 29,000 mg/L: [5]

3.1 power flow and efficiency calculations for desalination system:

Electric motor shaft power = speed x torque

= 864 rpm x 2π rad/sec/60 rpm x 8.7 Nm

= 787 watts

Inverter & motor losses = electrical input power – electric motor shaft power
= 997 w – 787 w

feed power = feed flow x feed pressure
= 0.233 L/s x m^3/1000 L x 58.9 bar x 10^5 Pa/bar
= 1372 watts

Concentrate flow = feed flow – product flow
= 0.233 L/s – 0.022 L/s
= 0.211 L/s

Cross flow loss = concentrate flow x delta pressure
= concentrate flow x (feed pressure – concentrate pressure
= 0.211 L/s x m^3/1000L x (58.9bar-56.4bar)x 10^5Pa/bar
= 53 watts

Concentrate power = concentrate flow x concentrate pressure
= 0211L/s x m^3/1000L x 56.4bar x 10^5Pa/bar

Suppose NaCl solution at 32000 mg/L has an osmotic pressure of 25.8 bar.
The testing described here used NaCl solution at 29000 mg/L.

Osmotic pressure = 25.8 bar x 29000 mg/L/32800 mg/L
= 23 bar

Desalination power = product flow x osmotic pressure
= 0.022 L/s x m^3/1000L x 23bar x 10^5Pa/bar
= 51 watts

Through flow = feed power – crossflow – concentrate power – desalination power
= 1372w – 53w – 1190w - 51w
= 78 watts

Pump shaft power = feed power/pump efficiency
= 1372w / 0.85
= 1614 watts

Pump loss = pump shaft power – feed power
= 1614 w – 1372 w
= 242 watts

Recovered power = pump shaft power – electric motor shaft power
= 1614w – 787 w
= 827 watts

Saving given by energy recovery = recovered power/pump shaft power
= 827w/1614w
=51%

The toothed belt is assumed to have an efficiency of 95%.

Hydraulic motor output power = recovered power/belt efficiency
= 827w/0.95
= 871 watts
Hydraulic motor efficiency = hydraulic motor output power/concentrate power
= 871w/1190w
= 73%
Water-to-water efficiency = hydraulic motor efficiency x belt efficiency x pump efficiency
= 73% x 95% x 85%
= 59% [6]

4.SYSTEM MODELING, OPTIMIZATION AND PERFORMANCE:

4.1 System model structure:

The general strategy for interconnecting the component models within Simulink was discussed in before . Now, the completed model will be discussed, starting with the top layer of the hierarchy shown in Figure (9) below.

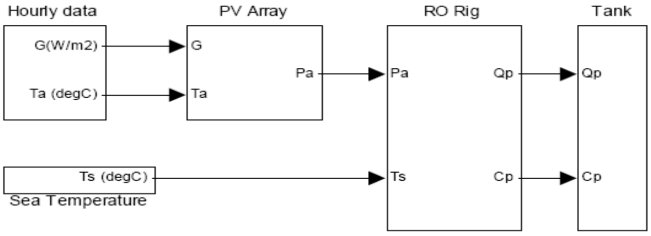

Fig.(9) Simulink model of the complete system

The Controller shares the power available Pa between the two inverter/motor/pumps in order to maximise the water production, as described before. It does this by providing a frequency set point signal f* to each of the two inverters. In return, the inverter models provide signals Pdc that represent the DC power drawn. The controller model ensures that the sum of these two equals the power available: Pp + Pm = Pa. [7]

4.2 Delayed injection-single motor:

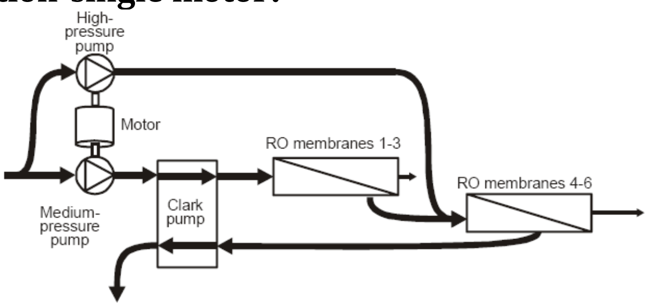

Fig.(10)Delayed injection-single motor

Figure(10) shows the block diagram of the delayed single motor used in the system.

4.3 Two motor-variable recovery ratio:

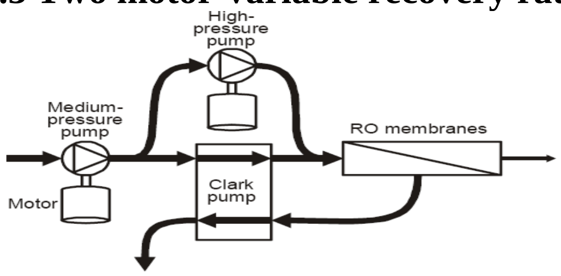

Fig.(11) Two motor-variable recovery ratio

A system using two variable-speed motors is shown in Figure(11) , and this is the general arrangement finally adopted for the PV-RO system. The independent control of the two pump speeds provides control over the water recovery ratio, and this is especially valuable in a batteryless PV-RO system because it enables the water production to be maximised as the available sunlight varies through the day. The next step was to determine how the recovery ratio should be varied in order to achieve this maximum. [7]

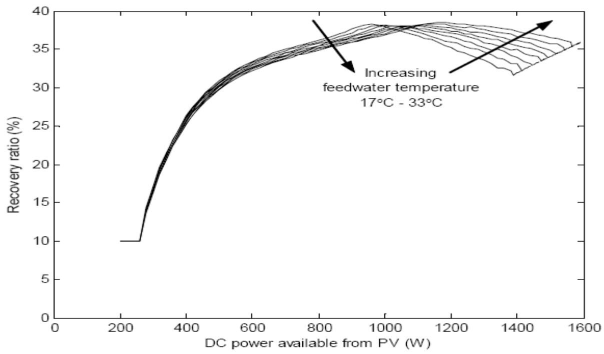

Fig.(12)Optimum recovery ratio versus DC power available from PV

Figure (12) shows how the water recovery ratio must be varied, in order to maximise the product water flow as the available power varies. When the available power is low, 200-300 Watts, the system operates with a low recovery ratio: 10 %. This is achieved by the running only the medium-pressure pump.

4.4 The completed design:

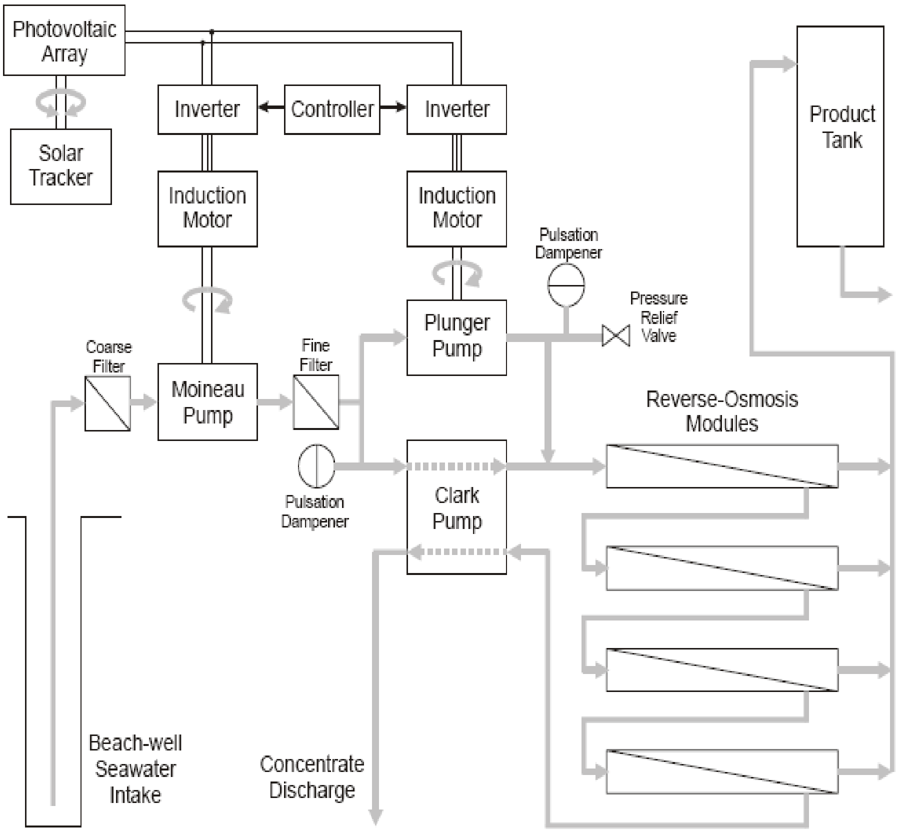

Fig.(13) The completed design of the system

4.4.1 Power usage:

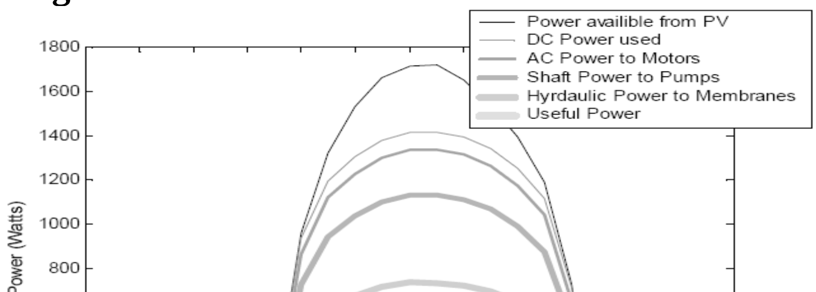

Fig.(14) Predicted analysis of power usage over an average day

Figure (14) illustrates how the power available from the PV array is used throughout an average day. The average is created from hourly values across the whole year.

Thus, the *DC Power used* in Figure (39) is significantly below that available. The *AC Power to Motors* is the sum of that going to the two motors and is below the *DC Power used* because of losses in the two inverters. Likewise, the *Shaft*

Power to Pumps is the sum for the two motor-driven pumps, and is below the *AC Power to Motors* because of the losses in the two motors. [8]

4.5 Maximum power point tracking algorithm:

Connection of a PV array to a standard industrial inverter is common practice – the challenge lies in achieving maximum power point tracking (MPPT) as introduced before. The next section will outline some of common MPPT algorithms used in PV systems, and after that, the implementation of MPPT with standard industrial inverters will be discussed**.**

4.5.1 Constant voltage:

Perhaps the simplest way to get close to the MPP is to control the current drawn from the PV array such that the voltage remains constant.

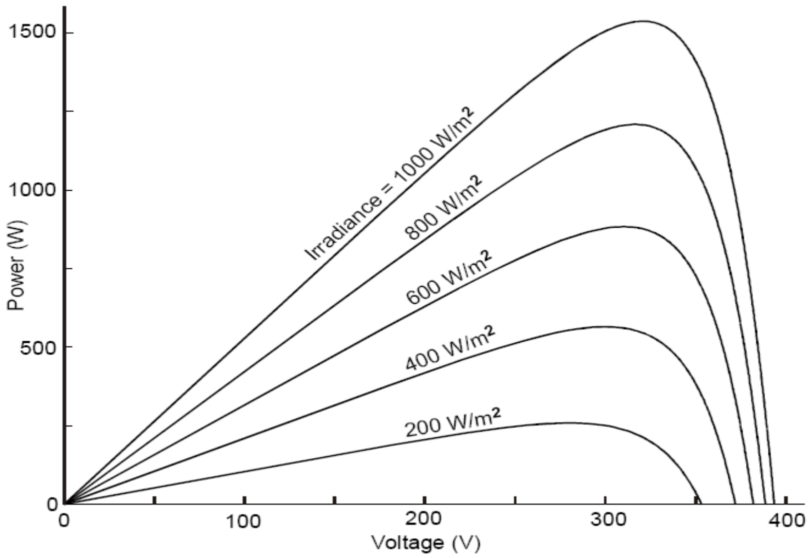

Fig.(15) Indicative power curves for a PV array at 50C

5.PROCEDURE AND RESULTS:

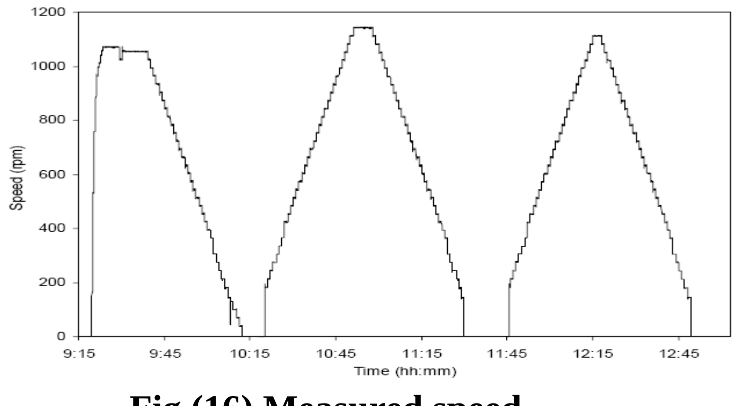

Fig.(16) Measured speed

The measured speed shown in Figure (16) closely matches the set point the irregular steps between 300 and 400 rpm. These are due to a mode change within the inverter software. [9]

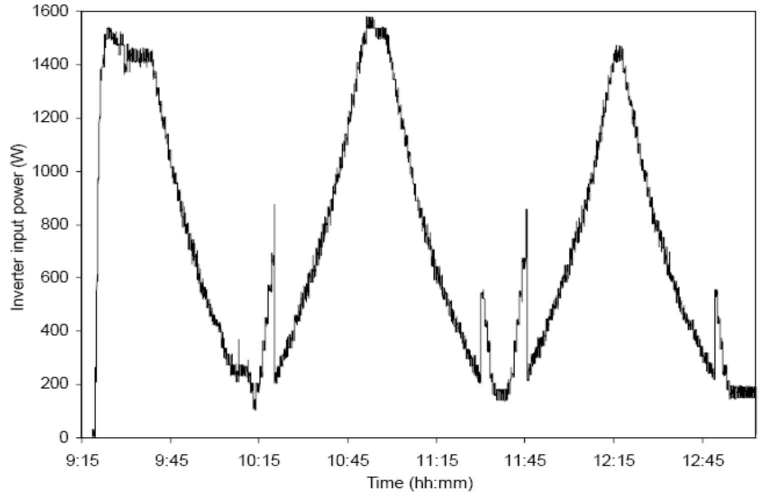

Fig.(17) Measured inverter input power consumption

Figure (17) shows the input power to the inverter, and shows the aforementioned mode change more markedly.

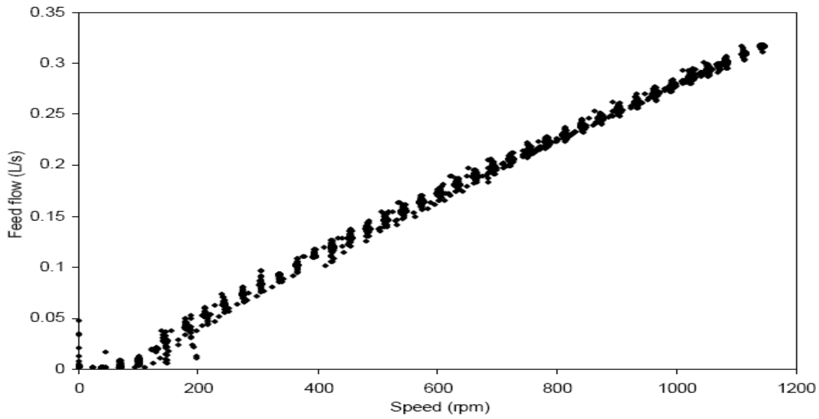

Fig.(18) Measured feed flow versus pump speed

Figure (18) shows that the feed flow through the plunger pump is approximately equal to its shaft speed, as expected with a positive displacement pump. The scatter in the figure is due primarily to the inaccuracy of the turbine flow meter in use at the time.

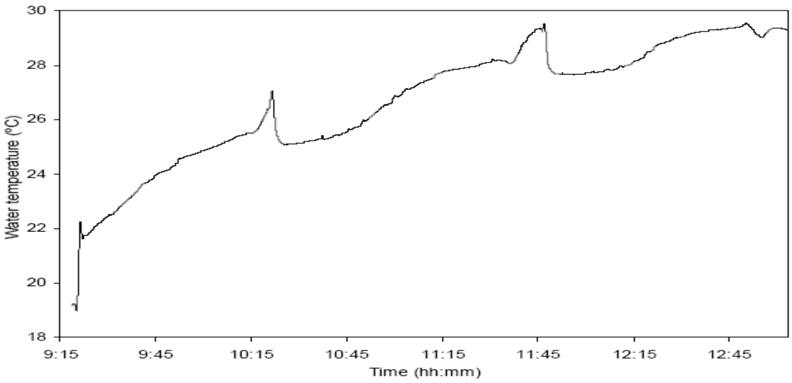

Fig.(19) Measured water temperature

The water for the test rig is circulated through the tank heats up by virtue of the energy introduced by the two pumps. [9]

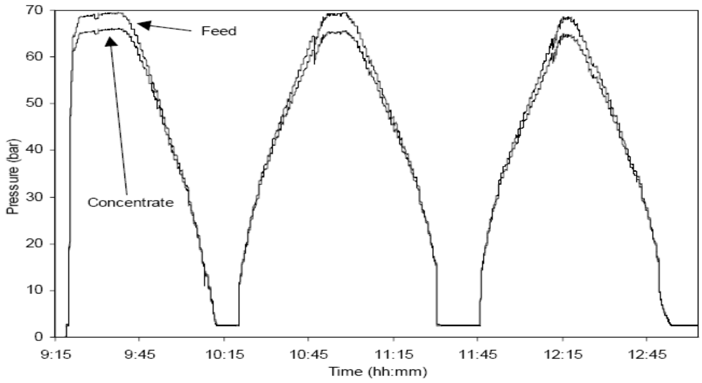

Fig.(20) Measured feed and concentrate pressures

The measured pressures in Figure (20) indicate a delta pressure of up to 4 bar, which is unusually high and was caused partly the poor condition of the membranes and partly because they are small-diameter (2½-inch) membrane elements.

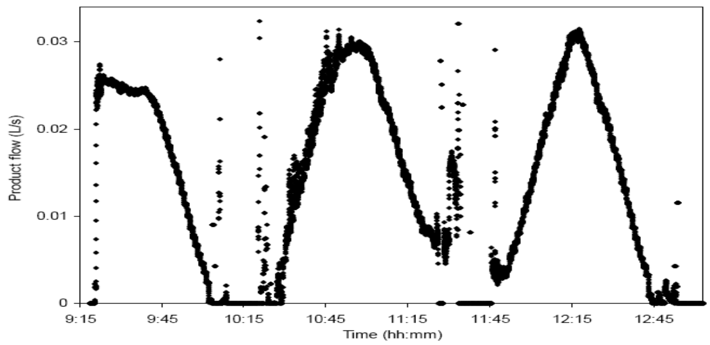

Fig.(21) Measured product flow

The three main peaks, shown in Figure (21) (9:30, 10:55 and 12:15), are progressively higher, due to the rising water temperature.

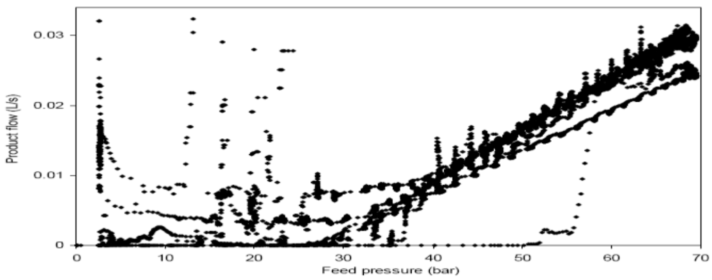

Fig.(22) Measured product flow versus feed pressure

Figure (22) illustrates, as expected, that the product flow is roughly proportional to the net driving pressure (the feed pressure less the osmotic pressure). It is also illustrates, as expected, that the product flow is roughly proportional to the net driving pressure (the feed pressure less the osmotic pressure). [10]

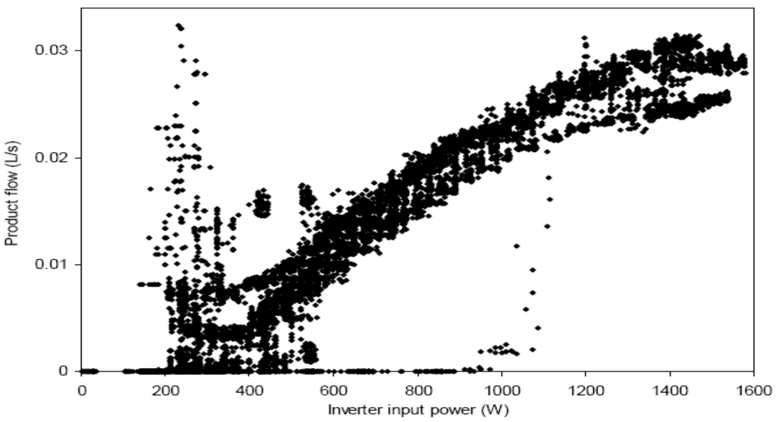

Fig.(23) Measured product flow versus inverter input power consumption

Figure (23) again shows the spurious product flow due to suck-back between 200 and 300 W. Ignoring this, it can be seen that water production starts below 400 W and increases to a maximum of ~0.029 L/s at around 1500 W.

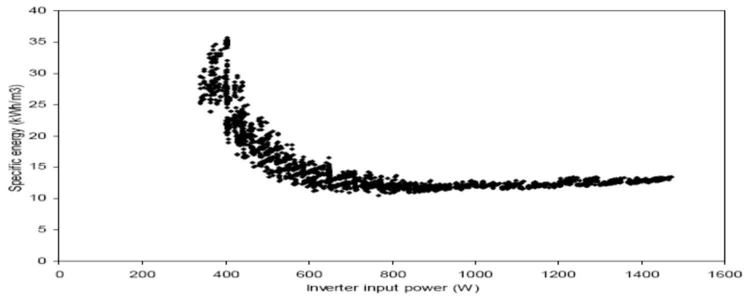

Fig.(24) Specific energy versus inverter input power

$$specific\ energy\ (\mathrm{kWh/m^3}) = \frac{input\ power\ (\mathrm{W})}{product\ flow\ (\mathrm{L/s})\ \times 3600}$$

……………(6)

Figure (24) shows the specific energy consumption during the third ramp-up/rampdown in particular, between 11:50 and 12:43. This data was selected in order to eliminate spurious data caused by the osmotic suck-back described earlier [11]

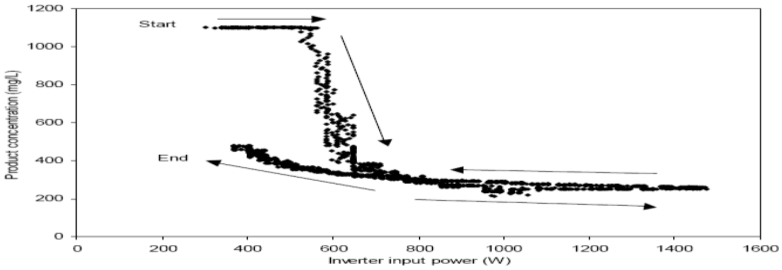

Fig.(25) Measured product concentration versus inverter input power

Figure (25) shows the concentration of the product during the same period: between 11:50 and 12:43. Again this data was selected in order to eliminate spurious data caused by osmotic suck-back; in particular, the concentration sensor was affected by the air introduced. [12]

5. Discussion and conclusion:

It was undertaken the modelling and dynamic simulation of water treatment plant to support the design and development of plant hydraulic behaviour and process and operational controls.

By modelling the controlled flows of water from source of supply through treatment units such as flocculates, filters, chlorinators, intermediate storage vessels and pumps through to treated-water delivery, our simulations can predict the behaviour of continuous and sequence process controls and their effects on water flows, pressures and hold-ups in vessels.

Past simulations have been used to study:

- -Sizing of vessels in the treatment path – to minimize vessel capacities and construction costs while still coping with changing operational and unusual flow conditions, such as plant trips.
- Investigating hydraulic interaction; e.g. between adjacent filters during washing operations.
- Supporting plant commissioning – by providing initial tuning parameters for feedback controllers of flows, levels and pressures, and by revealing to commissioning engineers in advance the significant behaviours to be expected from a new or modified plant.
- Investigating commissioning problems – by comparing actual behaviour with modeled behaviour – to help pinpoint the likely sources of any deviations of actual plant behaviour from design behaviour.

In accordance with our in-house modelling and simulation engineering principles: we use only commercially available, off-the-shelf, general-purpose dynamic simulation software as our modeling environment. This ensures that our models are accessible to the customer and can made available and uadopted readily by the customer for further in-house development, with the assurance of ongoing support from the simulation software supplier.

For our simulation studies we use MATLAB® and Simulink™ – possibly the worlds most popular general-purpose dynamic simulation software environment.

Our models are aimed primarily at simulating the behaviour of pressures, flows and accumulations (in vessels) of water by means of dynamic models of pipe work, valves, pumps, vessels etc. and their associated
manual and automatic feedback and sequence controls.

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الخلاصة:

تم في هذا البحث تصميم وبناء واختبار منظومة تقطير باستخدام برنامج الماتلاب.

تعمل المنظومة على مياه البحر والمياه الجوفية ولا تحتاج الى بطاريات حيث ان انتاج الماء الصالح يعتمد على الطاقة الشمسية المتوفرة. وقد تم اختبار المنظومة بتوليد مياه حلوة بمعدل 1.5 م^3 اليوم.

ولقد وجد انه قرب خط الاستواء وباستخدام منظومة شمسية ذات قدرة 2.4 كيلوواط اظهرت نتائج المحاكاة للمنظومة انتاج 3 م^3 يوميا وخلال ايام السنة. تستخدم المنظومة مضخة نوع كلارك التي تعمل بطاقة البخار وتصل الى نسبة معالجة للمياه اقل من 4. استخدمت ثلاثة محركات ومضخات لتجهيز قدرة جيدة وكفاءة عالية. وامكن الحصول على اعلى قدرة باستخدام برنامج المحاكاة الماتلاب. ومن خلال فحص وبناء مكونات المنظومة باستخدام الماتلاب تم عرض المناقشات لكامل المنظومة وطريقة تصميمها والتي كان غايتها تقليل كلفة المياه