Direct driven (battery-less) photovoltaic/wind turbine reverse osmosis desalination system employing computational intelligence techniques

George Kyriakarakos[1]*, Evangelos Dimitriou[1], Christos Karavas[1], Essam Sh. Mohamed[1], Dimitrios D. Piromalis[2], Anastasios I. Dounis[2], Konstantinos G. Arvanitis[1], George Papadakis[1]
[1]Agricultural University of Athens, Department of Natural Resources and Agricultural Engineering, 75 Iera Odos Street, GR 11855, Athens, Greece,
[2] Technological Education Institute of Piraeus, Department of Automation, 250, P. Ralli&Thivon Str., GR 122 44, Egaleo, Greece
*email: gk@aua.gr

Abstract

This paper presents an innovative reverse osmosis desalination system for sea water capable of covering the needs in potable water for settlements presenting low cost and minimized environmental footprint. The system is powered by PVs and a wind turbine and will be able to produce between 2.5 -5 m^3 per day, capable of covering the needs between 25 and 50 people with an average water consumption of 100-300 l per day. This system features no lead acid batteries. The desalination unit is equipped with an energy recovery subsystem and is able to operate in part load. This system features two main innovations. The first is concerned with two short term energy storage subsystems and the second one is an advanced intelligent energy management system based on computational intelligence allowing the unit to operate in part load and achieving overall greater efficiency. This energy management system also includes advanced algorithms based on grey model theory for the prediction of the produced power from the photovoltaics and the wind turbine. The design of this system aims at lowering the cost of desalinated sea water below 5 €/m^3 for units with nominal water production of up to 5 m^3/day.

Keywords: desalination, hybrid system, computational intelligence

Introduction

One of the most important goods necessary for human survival and development is potable water. At the dawn of the 21st century there are still many areas around the world that do not have access to potable water. It is estimated that more than one billion of people have no access to clean fresh water. In developed countries, potable water is available but usually at high costs because of the transportation cost added to its price. Desalination emerges as a solution to the lack of potable water. Sea water can be turned into high quality drinking water. When the desalination processes are coupled with renewable energy technologies then the systems become environmentally friendly and can aid the development of these areas – areas situated in both the developed and the developing world [1-3].

The energy production of this system is based on an hybrid combination of photovoltaics (PVs) and a windturbine. This combination has been used extensively in the past and can ensure that the system can be deployed in most areas of the world [4]. The traditional approach as far as hybrid systems are concerned includes a battery bank so as to allow constant power flow from the energy production system to the loads. The batteries, though, present specific disadvantages as high cost, low operational lifetimes, high energy losses on a yearly basis and can present environmental risks due to the heavy metals they contain [5, 6].

Reverse Osmosis (RO) desalination units have been used globally for the production of fresh water in areas that are either near to the sea, or have nearby brackish water sources. The combination of hybrid systems for the production of the needed energy and RO units leads to systems that have low energy consumption and reduced maintenance needs [2, 7]. Energy recovery systems have been used and proved to present significant gains in terms of specific energy consumption [8]. Research has taken place in the part load operation of RO desalination units and has been found that part load operation presents higher efficiencies [3, 9, 10].

Since a battery bank is not going to be included in the proposed system, an innovative proprietary energy buffer is being developed and is going to be utilized along with advanced control algorithms. PID control has been found to be inadequate for the control of such energy systems, unless it is coupled with a self-tuning controller for the adjustment of its gains [11]. Fuzzy logic has been proven to work with success in the management of energy systems [12]. Its main drawback is the relatively hard optimization of its parameters, since their number is high. A combined petri nets (PN) – fuzzy cognitive maps (FCM) approach has been developed in order to overcome this problem and has been applied in renewable energy systems successfully [9]. Grey predictors have been used for the forecast of solar irradiation and wind speed for the long term successfully where historical data are absent [13].

The aim of the proposed project is to develop a renewable energy powered reverse osmosis (RO) desalination system with low specific energy consumption. Different configurations are being setup in the laboratory in order to investigate their performance. All systems employ an energy recovery subsystem in order to maximize the utilized energy. Both AC and DC approaches are being investigated coupled with the needed power electronics in order to make the system operational. The heart of the system is the advanced computational intelligence energy management system.

System configuration

The proposed system is an innovative reverse osmosis desalination system for sea water and it is presented in Figure 1. It includes units producing renewable energy power, a wind turbine and a photovoltaic system and energy storage system that consists of hybrid ultra-capacitors and pressure vessels. The energy management of the system is regulated by a controller which includes advanced algorithms.

The components are (Figure 1):

1. PV array: A typical monocrystalline silicon photovoltaic array
2. Wind Turbine: A typical DC wind turbine.
3. Short Term Energy Storage system:
   A proprietary energy buffer has been developed.
4. Desalination unit:
   A reverse osmosis desalination unit with energy recovery
5. Potable Water tank

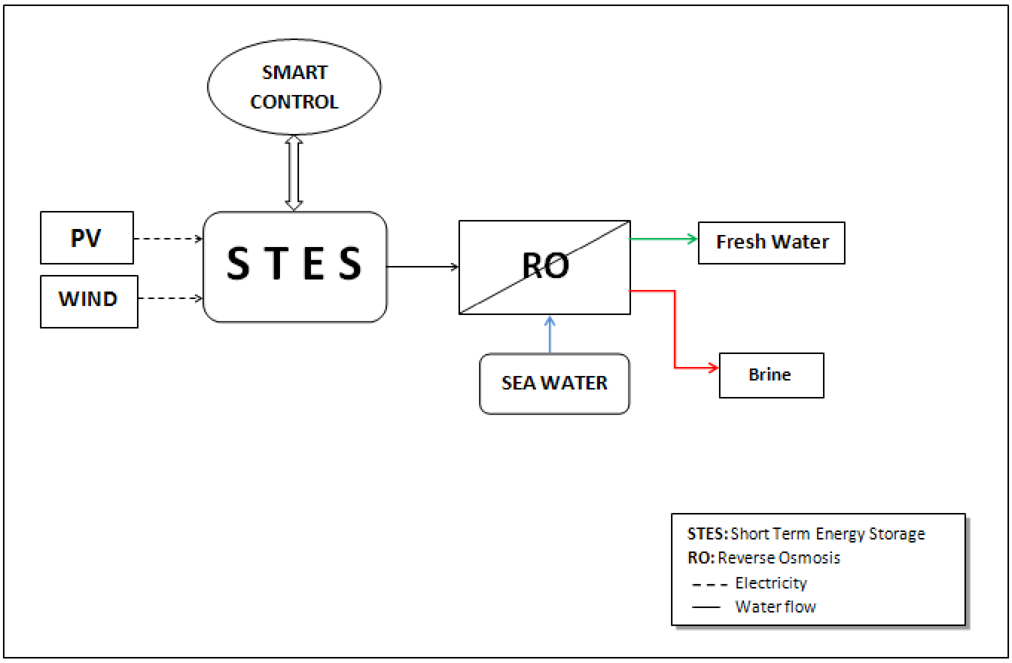

Fig. 1 Schematic presentation of the desalination system

Short term storage units

In order to ensure the existence of potable water in a water tank which is adequate to cover the average water consumption at least, it is required sometimes in the period of the day, a minimum energy power flow to the desalination unit. The continuous changes of the weather and the no produced photovoltaic power during the night, leads to the need of appropriate energy buffers able to power the system for small periods of time (about thirty minutes to one hour). The benefits of the energy buffers in those systems are considerable. When the renewable energy sources produce more power that the system needs, the energy buffer stores this power and uses it when it is necessary. The membranes of the reverse osmosis desalination units take as an input the seawater under pressure. When the solar radiation is reduced or there is not enough produced energy by wind generator, the produced power is dropped and consequently the pump could not keep the needed pressure. As a result, the produced water has higher electrical conductivity than the permissible limits and it is rejected. The energy buffer can in such cases complement the produced energy of the renewables in order to ensure that acceptable salinity water is produced.

One of the two most important innovations of this system is the elimination of the use of batteries. The second is the advanced energy management system, which will be presented in a following section.

System Design – Simulation of the system

Two software packages, TRNSYS and Matlab, were used in order to design and simulate the system. TRNSYS is a dynamic simulation software package which gives the ability to the user to insert subroutines written in FORTRAN. Matlab is a high level language and interactive environment for numerical computation, visualization and programming. All components of the system will be simulated in TRNSYS. The combined Petri Nets and Fuzzy Cognitive Maps energy management system and the Grey Prediction system will be designed and implemented in Matlab. The system design was realized on a software platform consisting of TRNSYS and Matlab software packages (Figure 2).

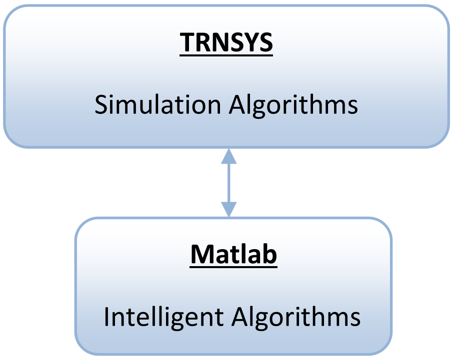

Fig.2. Software structure

Advanced energy management system

The developed supervisory energy management and control unit is based on computational intelligence algorithms. The smart control is built upon a combined Petri Net-Fuzzy Cognitive Maps approach. This combined approach has already proven to be able to complement the weakness of the one with the advantages of the other. Also, a grey prediction system was designed, in order to forecast the produced energy by the photovoltaic array and the wind turbine. The PN is used to decide the operational modes of the system, where the FCMs are used to determine the operational state of the desalination unit. The energy management system takes four inputs; the produced power by the PV array, the produced power of the wind turbine, the equivalent state of charge of the energy buffer and the stored desalinated water in the potable water tank. Then it follows to predict the expected produced power for the next time step of the PV array and the wind turbine. Then the combined Petri Nets – Fuzzy Cognitive Maps energy management system decides the point of operation of the desalination unit. This system is presented in Figure 3. This system was designed and optimized in the software platform presented in Figure 2 and was then ported to the Labview software environment, from where the actual control of the system takes place.

Results – Discussion

The object of the presented work was to develop a very low specific energy consumption desalination unit able to produce between 2.5 -5 m^3 per day. Based on previous work it was decided not to use conventional battery storage in this system. At the same time though, an energy buffer for the short term proves to be beneficial, so a proprietary short term energy storage buffer was developed. In order though to maximize system performance and ensure optimal operation of the desalination unit an advanced energy management system was designed and implemented. This system was based on the combined Petri Nets – Fuzzy Cognitive Maps approach and also Grey predictor algorithms where designed and implemented in order to forecast the production of the PVs and the wind turbine in the short term.

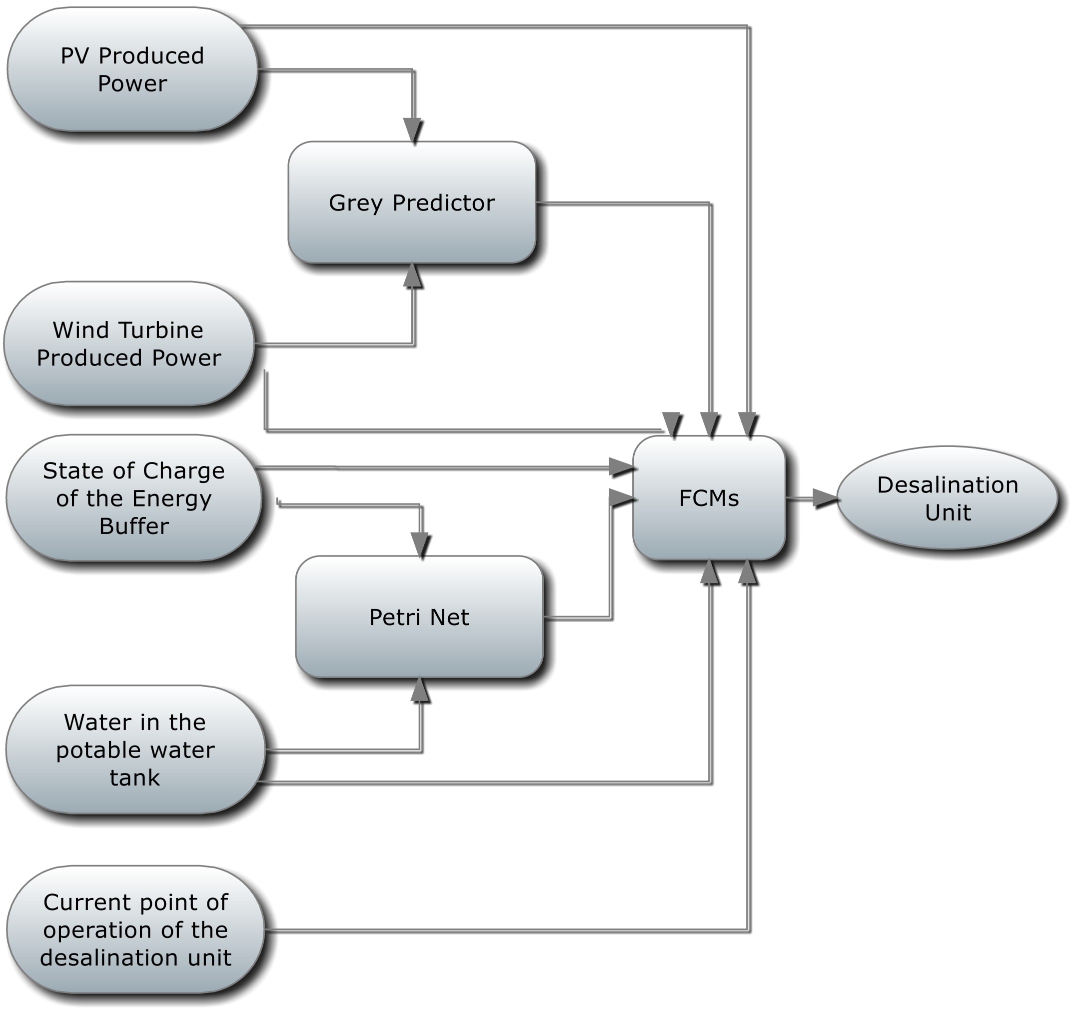

Fig. 3. Schematic Presentation of the Energy Management System

References

[1] Manolakos D, Mohamed ES, Karagiannis I, Papadakis G. Technical and economic comparison between PV-RO system and RO-Solar Rankine system. Case study: Thirasia island. Desalination. 2008;221:37-46.
[2] Mohamed ES, Papadakis G. Design, simulation and economic analysis of a stand-alone reverse osmosis desalination unit powered by wind turbines and photovoltaics. Desalination. 2004;164:87-97.
[3] Mohamed ES, Papadakis G, Mathioulakis E, Belessiotis V. A direct coupled photovoltaic seawater reverse osmosis desalination system toward battery based systems - a technical and economical experimental comparative study. Desalination. 2008;221:17-22.
[4] Buran B, Butler L, Currano A, Smith E, Tung W, Cleveland K, et al. Environmental benefits of implementing alternative energy technologies in developing countries. Applied Energy. 2003;76:89-100.
[5] Manolakos D, Papadakis G, Papantonis D, Kyritsis S. A stand-alone photovoltaic power system for remote villages using pumped water energy storage. Energy. 2004;29:57-69.
[6] Zoulias EI, Glockner R, Lymberopoulos N, Tsoutsos T, Vosseler I, Gavalda O, et al. Integration of hydrogen energy technologies in stand-alone power systems

analysis of the current potential for applications. Renewable and Sustainable Energy Reviews. 2006;10:432-62.
[7] Kaldellis JK, Kavadias KA, Kondili E. Renewable energy desalination plants for the Greek islands--technical and economic considerations. Desalination. 2004;170:187-203.
[8] Mohamed ES, Papadakis G, Mathioulakis E, Belessiotis V. The effect of hydraulic energy recovery in a small sea water reverse osmosis desalination system; experimental and economical evaluation. Desalination. 2005;184:241-6.
[9] Kyriakarakos G, Dounis AI, Arvanitis KG, Papadakis G. A fuzzy cognitive maps–petri nets energy management system for autonomous polygeneration microgrids. Applied Soft Computing. 2012;12:3785-97.
[10] Dimitriou E., Mohamed E.S., Kyriakarakos G., G. P. Experimental investigation of the performance of a rεverse osmosis desalination unit under full and part load operation. Desalination and Water Treatment. Accepted for publication 2014.
[11] Li X, Song Y-J, Han S-B. Frequency control in micro-grid power system combined with electrolyzer system and fuzzy PI controller. Journal of Power Sources. 2008;180:468-75.
[12] Kyriakarakos G, Dounis AI, Arvanitis KG, Papadakis G. A fuzzy logic energy management system for polygeneration microgrids. Renewable Energy. 2012;41:315-27.
[13] Kyriakarakos G, Piromalis DD, Dounis AI, Arvanitis KG, Papadakis G. Intelligent demand side energy management system for autonomous polygeneration microgrids. Applied Energy. 2013;103:39-51.