Optimal Energy Management Solutions Using Artificial Intelligence Techniques for Photovoltaic Empowered Water Desalination Plants Under Cost Function Uncertainties

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ABSTRACT Two modern methods of the energy management system (EMS) based on a modified cost function are addressed in this paper. Fuzzy logic (FL) and Harris Hawks Optimization (HHO) is implemented to achieve the optimal performance of seawater desalination plants (SWDP) within the minimum feed-in tariff (FiT). The technical difficulties involved in the variation of energy price from one time to another and the system parameters uncertainties. For example, the price of energy is higher at the peak time and the price is lower at normal times. Also, the peak time can change from one day to another day. The proposed management system can deal with these variations and uncertainty cases. The suggested EMS is achieved through a bidirectional electrical energy interchange approach (π-EEIA). The main concept behind the proposed π-EEIA is how and when to inject the excess generated energy of renewable energy into the utility grid or charge the battery depending on the minimum dynamic cost criterion and vice versa.

To accomplish this study a 700 m³/day SWDP located in Egypt fed on solar energy and a utility network has been constructed and analyzed. The system includes SWDP fed from a photovoltaic (PV) array as well as the utility grid in addition to a battery energy storage system (BESS). The main objective of this study is the management and coordination between the energy exchange process from the solar energy, the utility network, and BESS to provide sufficient electrical energy for SWDP within the minimum FiT. The system is constructed and validated using the MATLAB/SIMULINK™ software package. The proposed FL and HHO-based EMSs are investigated in the presence of the system uncertainties such as the change in the energy (excess or shortage) as well as the change in the energy price in the utility network (high or low) with (normal or peak) time. The attained results demonstrate that the proposed FL and HHO-based EMSs provide high dynamic performance and accurate coordination between various energy resources and BESS.

The results show that FL-based EMS achieves a profit of 10.28 $ but the HHO-based EMS achieves a profit of 10.11 $ in the same period.

INDEX TERMS Hybrid system, management control system, power cost signal, PV system, seawater desalination plants.

NOMENCLATURE

Acronyms
EMS Energy management system.
FL Fuzzy logic.
I. INTRODUCTION

Continued expansion of networks and energy consumption led to an interest in energy management to avoid energy losses and reduce operating costs. Large utilization of renewable energy resources (RERs), coordination between loads, and energy storage systems (ESSs) are commonly used in smart grids. The core challenge is represented in the high variability of RERs under the uncertainty of the continuous weather changes and loads. The controlling difficulty stems from the probability of the feeding process of loads from RERs and the stored energy in ESSs [1].

This process requires a high level of management system that coordinates the various generation resources with ESSs in the presence of a utility grid. Several related types of research are used in this area.

Recently different management strategies have been applied to energy systems. Hrvoje Novak has presented the energy management system (EMS) which was used in the railways through coordination between two systems of different trains. The developed EMS regulates the consumption of energy from different sources and the time coordination between them to reduce energy demand as well as the cost [2].

Bo Zhao and Xiangjin Wang illustrated a central management system for coordination with several microgrids that use RERs [3]. The obtained results proved the proper coordination of energy exchange between these networks. Rishi Kant and Ebrahim discussed a standalone hybrid AC/DC microgrid system that includes a photovoltaic (PV), fuel cell (FC), and various ESSs such as supercapacitors, batteries, and capacitors [4], [5]. The results provide better performance for energy management. Adhithya Ravichandran showed a system for a microgrid that includes RERs, ESSs, and electric vehicles [6]. The suggested EMS operates through a program to coordinate the production of RERs and the process of storing, consuming, and charging electric vehicles. The results provide better development in the field of future energy forecasts.

Wen-Jye Shyr, et al., suggested a system that controls lighting management via the internet using light sensors [7]. Elsisi, et al., developed a novel energy management scheme of controllable loads in multi-area power systems with wind power penetration based on a new supervisor fuzzy nonlinear sliding mode control [8]. The attained results validated the efficiency of the new supervisor fuzzy nonlinear sliding mode control in achieving energy management among various RERs. Fady and Olivier presented an algorithm using the simulation horizon for several different scenarios as the results showed a significant decrease in the cost of electricity and demonstrated the efficiency of the proposed robust optimization algorithm [9]. Benmouna, et al., constructed a novel energy management technique for hybrid electric vehicles via interconnection and damping assignment passivity-based control [10]. The developed EMS proved its capability in continuous supply load balance while considering the constraints of load and the different available sources. Giovanni Pau, and Mario Collottasuggested a general study on energy management technologies used in some countries, such as Russia, the European Union, and America [11]. Sanjeev, Jinsoo Han, D. Westermann presented a study to develop an algorithm to control energy sources through the use of hybrid storage devices (batteries, capacitors) [12], [13], [14]. The results showed an improvement in the battery life. However, the selection of a suitable control approach represents a big challenge for energy management systems.

Mahmoud H. and Matteo Boaro showed a system consisting of four houses, each containing a PV system, load, and FC [15], [16]. The systems are controlled by exchanging information for the four homes via the internet through the smart meter and the fuel cell system that is controlled by artificial intelligence (AI) for the heat exchange with the thermal load as a substitute for natural gas-based DC power source. Zilong Yang suggested three systems each consisting of four houses containing an inverter, PV array, and batteries, one of which is wind energy [17]. The energy management process was achieved through controlling the output active and reactive powers and also the frequency for each inverter. The results show the stable operation of power and frequency with enhanced redistribution. Maheswaran Gunasekaran presented EMS for a hybrid DC microgrid comprised of a PV array, wind energy, hydrogen cells, batteries, diesel generator, and electrical loads [18]. This system is managed by measuring the difference between the generated power and load power to switch ON/OFF batteries to charge or discharge the excess energy into the DC microgrid. The results showed...
that the maximum power generated from RERs is employed to feed loads or store them into batteries with a good performance. Hasan Mehrjerdia showed EMS with three system levels [19]. The first level is the utility grid and the second level is a diesel generator, wind, batteries and the third level is a house that contains solar cells. Several scenarios were proposed to exchange energy between the three levels depending on renewable energy and the price of energy during the hours of the day and the excess energy was stored in batteries when the energy cost is 0.1 dollars instead of 0.25 dollars, which reduces the cost of energy. Thus, the fast sharing of the data to exchange energy is important to decrease the cost of energy.

Dae-Man Han suggested a system that integrates diversified physical sensing information and controls various consumer home devices with the support of active sensor networks [20], [21]. Mario Collotta and Christoph Molitor proposed a novel energy management approach for smart homes that combines a wireless network based on low-energy Bluetooth for communication among home appliances [22], [23]. A home energy management implementation can lead to a socially and economically beneficial environment by addressing consumers’ and utility concerns. Christos, and Hossein Shahinzadeh studied five different configurations of a seawater desalination plant (SWDP) that use renewable energy [24], [25]. The aim of the presented study is to determine the optimum technical and economic system by minimizing the total system installation and operation cost for 20 years of lifetime. According to the optimal sizing results, the implementation of an energy management system that had been designed on the basis of fuzzy cognitive maps presented the lowest cost and lowest power losses [26]. This paper regarded an experimental investigation of a PV-powered small-scale SWDP that employs hydraulic energy recovery based on a DC microgrid concept and incorporates short-term electric energy storage in the form of hybrid capacitors. However, centralized management requires a big computational burden.

A decentralized energy management system that relies on intelligent agents and employs fuzzy cognitive maps was developed and implemented in [27]. This paper presented the design and investigation of a decentralized energy management system for the autonomous poly-generation microgrid topology. The possibility to control each unit of the microgrid independently is given by the decentralized energy management system. The designed system was based on a multi-agent system and employed fuzzy cognitive maps. It was then compared through a case study with an existing centralized energy management system. The technical performance of the decentralized solution performance is better than the existing centralized one in terms of financial and operational benefits. Yao Chen presented the development of a risk management system for railway risk analysis using fuzzy reasoning approach and fuzzy analytical hierarchy decision-making process. In the presented system, the fuzzy reasoning approach is employed to estimate the risk level of each hazardous event in terms of failure frequency, consequence severity, and consequence probability [28]. The results show a reduced risk. An EMS based on the current network price cost function had been developed in [29] and [30]. In this research, another energy price has been added (it could be another network at a different price from the current price of the existing network) but in this study, the alternative price is the price of storing energy in batteries.

The main objective of this study is the management and coordination between the energy exchange process from the solar energy, the utility network, and BESS to provide sufficient electrical energy for SWDP within the minimum FiT. In this paper, the energy management is performed by a new Harris Hawks optimization (HHO) algorithm. The proposed HHO algorithm is chosen because this algorithm requires a few adjustable factors that improve the performance of the energy system with a fast convergence rate and overcome the trapping in local optima issue instead of other techniques [31], [32]. Furthermore, the fuzzy logic system is dedicated to validate the results of the proposed HHO that is commonly used for energy management [33], [34], [35].

The major contributions of the presented article can be summarized as follow:

1) New Fuzzy logic (FL) and Harris Hawks Optimization (HHO) based EMSs are developed and implemented in this study to achieve the optimal performance of seawater desalination plants.
2) A dynamic feed-in tariff (FiT) is considered in this article instead of the fixed cost approach.
3) The suggested EMSs are applied to a real 700 m3/day SWDP located in Egypt fed on solar energy and a utility network.

The remaining parts of this paper are structured as follows: the system description had been shown in Section II. Section III discusses the real case study. Section IV presents the cost function and energy balance mathematical formulation. Section V shows the energy management technique. In Section VI, the results and discussion are demonstrated. Section VII shows the conclusion.

II. SYSTEM DESCRIPTION

The proposed system combined a grid with a PV array, two stages of SWDP loads, batteries, and a management system. Each stage of SWDP loads operates according to the village’s water use. The water pumping station is activated when the potable water tanks are emptied automatically. In this case, loads are supplied from the PV array, if energy is available, otherwise, the management system withdraws the energy from the utility network or ESSs based on the optimal minimum cost criterion. The system injects excess energy into the network or stores it in batteries when the SoC is less than 80% and it also discharges energy from batteries to load when the SoC is higher than 20%. The feeding of load energy and the control process is based on the energy price of the utility network as depicted in Fig. 1.
III. REAL CASE STUDY

In this research, loads are driven from real loads installed in mid-2016 in Mirette touristic village designated on the coast of the Red Sea in Hurghada - Egypt. The plant produces 700 m³/day of desalinated seawater.

A. SEAWATER DESALINATION PLANTS

Mirette company performed analyze of water generation and electricity consumption to address the performance of the constructed SWDP. Water production and energy consumption had been measured using new smart meters. Measurements were recorded daily at fixed periodical times. The yearly reading schedules of 2017 from January to December are selected to accomplish this research work. This plant performs potable water generation in two stages and can work at full load simultaneously. Presently, this plant consumes electricity from the main grid. Annual energy consumption (kWh/year), peak load value (kW), average load (kW), and average daily energy consumption (kWh/day) are shown in Table 1.

TABLE 1. Loads data for SWDP stage.

| Item                        | Stage (1)     | Stage (2)     |
|-----------------------------|---------------|---------------|
| Energy (MWh/year)           | 503.38        | 258.255       |
| Peak load (kW)              | 204.11        | 123.66        |
| Average load (kW)           | 57.58         | 29.59         |
| Average load consumption (kWh/day) | 1382          | 710.3         |

The daily load curve for the power consumption is constructed from the obtained measurements. The maximum and the minimum value of the load power are deducted from the daily loads of the hotel. The end of May was chosen as the maximum value of the load power within the other months of the year for the initial stage with total load consumption equaling 204.11 kW, as cleared in Fig. 2.

B. PHOTOVOLTAIC ARRAY CHARACTERISTICS

The suggested photovoltaic array is constructed as follows: five modules in series and one hundred ninety-one parallel modules of 320.5-kW SunPower X21-335-BLK. The factors of the applicable photovoltaic module are listed in Table 2.

IV. COST FUNCTION AND ENERGY BALANCE

The main objective of this paper is to find a method to manage the system to achieve the highest profit while respecting the constraints mentioned in the following section:

A. SYSTEM CONSTRAINTS

1) Excess energy must be sold when the energy price of the utility network is higher than the energy price of energy storage systems.

2) The energy must be purchased from the utility network during an energy shortage such that the energy price of the utility network is less than the energy price of energy storage systems.
TABLE 2. Parameters of the PV module.

| Parameter                  | Value        |
|----------------------------|--------------|
| W                          | 335.205      |
| V                          | 67.5         |
| Vmp                       | 57.3         |
| Voc                       | -0.25        |
| Ncell                     | 96           |
| Isc                       | 6.23         |
| Ir                         | 5.85         |
| Voc                       | 0.04         |
| Isc                       | 6.2395       |
| IR                         | 2.18E-12     |
| Ids                       | 0.96065      |
| Rs                        | 431.0177     |
| Rs                        | 0.51919      |

3) The battery switch is turned ON to charge at: (a) SoC $\leq 80\%$, (b) excess solar energy, and (c) the price of energy recovery from the battery is higher than the utility network.

4) The battery switch is turned ON to discharge at: (a) SoC $\geq 20\%$, (b) shortage in solar energy and (c) the price of energy recovery from the battery is less than the utility network.

5) The battery switch is turned OFF at: (a) SoC $\leq 20\%$ and (b) shortage in solar energy.

6) The battery switch is turned OFF at: (a) SoC $\geq 80\%$ and (b) excess solar energy.

Remark: The change in the state of charge of batteries in this case study is tiny and lies between 77.8% and 77.85% as shown in Fig. 4. So, the change of SoC can be neglected in short charging/discharging periods.

**B. ENERGY BALANCE EQUATION**

The general energy mix can be achieved by balancing all generated power with total load demand considering losses.

The general energy balance equation is formulated such that the electricity provided from renewable energy resources, diesel generators, energy storage systems, and utility networks is equalized to the total demand loads and total losses. The general energy balance equation is as follows:

$$E_w + E_{pv} + E_{gen} \pm E_{grid} = E_{load} \pm E_{batt} + \sum \text{loss} \quad (1)$$

where $E_w$ is the wind energy, $E_{pv}$ is the solar energy, $E_{gen}$ is the diesel generator energy, $E_{grid}$ is utility network energy and $E_{load}$ is the load energy. $E_{batt}$ batteries energy. The energy provided by the change of RERs according to the variation of weather such as solar irradiance, direction, and speed of the wind, as well as electrical loads variability.

In this paper, diesel generators and wind turbines are not used that means: $E_{gen} = 0$ and $E_w = 0$ therefore,

$$E_{pv} \pm E_{grid} = E_{load} \pm E_{batt} + \sum \text{loss} \quad (2)$$

The provided energy can be reformulated to be a function of time as follow:

$$P_{pv} x t_{pv} \pm P_{grid} x t_{grid} \pm P_{batt} x t_{batt} - P_{load} x t_{load} - \sum P_{loss} x t_{loss} = 0 \quad (3)$$

The management system aims to achieve energy balance at any time ($t_x$) in the day as follows:

$$P_{pv} (t_x) \pm P_{grid} (t_x) \pm P_{batt} (t_x) - P_{load} (t_x) - \sum P_{loss} (t_x) = 0 \quad (4)$$

**C. COST FUNCTION FORMULATION**

Md. Alamgir Hossain presented a dynamic penalty function to the charging terminals of the cost function to efficiently manage the battery energy and thereby reduce operational costs [29]. The charging and discharging periods of the battery are effectively controlled based on the solar power generation and residential real-time electricity prices by using particle swarm optimization (PSO). The performance index, which is also known as the objective or cost function, is generally formulated as buying and selling electricity costs of a microgrid as follows:

$$\text{Cost} (t) = P_{grid} C (t) \quad (5)$$

where C (t) is the real-time grid electricity price, $P_{grid}$ is a positive or negative value indicating Buying or selling energy?

The lowest energy costs are represented by the minimum value of the objective function in case of the best control policies that are given by:

$$\text{Cost} (t) = \sqrt{ (S_1 (t) \times \frac{C (t)}{C_{min}})^2 + (S_2 (t))^2 } \quad (6)$$

$$S_1 (t) = P_{load} (t) - P_{solar} (t) + u (t) \quad (7)$$

$$S_2 (t) = BL_{max}-(BL + u (t)) \quad (8)$$
where $P_{\text{load}}$, $P_{\text{solar}}$, and $u(t)$ stand loads, total solar power, and battery targets at the time $(t)$, respectively. $BL_{\text{max}}$ is battery maximum energy level, $BL(t)$ is battery energy level at the time $(t)$, and the minimum energy cost is calculated by [30]:

$$\text{Cost}(t) = \sqrt{(S_1(t) \times C(t))^2 + ((f_{\text{pc}}(C)) \times S_2(t))^2}$$  \hspace{1cm} (9)

As the optimal control is performed by formulating a cost function, it is suitably analyzed and then a dynamic penalty function $(k)$ in order to obtain the best cost function is proposed.

$$f_{\text{pc}}(C) = k - C(t)$$  \hspace{1cm} (10)

where Cost$(t)$ is minimum energy cost, $C(t)$ is energy cost at time $(t)$, $(k)$ is changing parameter that indicates a penalty formulation for the best charging of the battery system. Changing the value of $k$, which is 35 in this paper, has a great enhancement to reduce electricity costs. The lowest values of the Cost$(t)$ refer to discharging the battery in case of low power generation and big electricity prices, in contrast, the lowest prices and big generation refer to the charging of the battery.

D. SYSTEM MANAGEMENT FORMULATION

In this research, another energy price has been added (it could be another network at a price different from the current price of the network) but in this study, the other price is the price of storing energy with batteries. The management system is developed to store the excess solar energy in the batteries or inject it into a utility network. Moreover, the energy is taken from the utility or discharged from batteries during energy shortage. The suggested EMS was made to compare the price of energy storage and the price of the utility network, the management process would withdraw the energy from the network or batteries, whichever is less cost, and inject the excess solar energy into the batteries or the grid, whichever is profitable. The lowest energy costs are represented by the minimum value of the objective function in the case of the best control policies. The energy excess is sold when the energy price is higher and purchased when the energy when the energy price is lower. Charging the excess energy into batteries when the energy price is lower and discharging when the energy price is higher. Equation (5) was developed for this purpose, as the decision to purchase and sell to the network was entered in addition to charging and discharging as equations (5) and (12).

$$S(t) = P_{\text{solar}}(t) - P_{\text{load}}(t)$$  \hspace{1cm} (11)

$$\text{Cost}(t) = S(t) \times C_{\text{grid}}(t) - S(t) \times C_{\text{batt}}(t)$$  \hspace{1cm} (12)

$$a = S(t) \times C_{\text{grid}}(t)$$  \hspace{1cm} (13)

$$b = S(t) \times C_{\text{batt}}(t)$$  \hspace{1cm} (14)

$$\text{Cost}(t) = (a - b)$$  \hspace{1cm} (15)

where $C_{\text{grid}}$ is energy price for the utility network ($$/kWh), $C_{\text{batt}}$ is energy price of battery storage ($$/kWh), $P_{\text{solar}}$ is solar power (kW), $P_{\text{load}}$ is load power (kW). The equations (11 to 15) are constructed using MATLAB/SIMULINK$^\text{TM}$ as shown in Fig. 5.

FIGURE 5. The proposed management system in MATLAB/SIMULINK$^\text{TM}$ based on equations (11 to 15).

V. ENERGY MANAGEMENT SYSTEM

Energy management systems must improve the system performance, reduce risks, ensure public safety and reduce costs. However, in many circumstances, the application of probabilistic risk analysis tools-based energy management systems may not give satisfactory results because the risk data are incomplete or there is a high level of uncertainty involved in the risk data. In this paper, two methods are developed for energy management system as follows:

A. FUZZY MANAGEMENT SYSTEM

The fuzzy analytical hierarchy process (Fuzzy-AHP) Technique is then incorporated into the cost model to use its advantage in determining the relative importance of profit-making contributions. It is possible to advance in cost assessment. It determines the appropriate decision to sell or purchase energy from the grid or store excess energy in batteries or discharge to complete the shortage to achieve the highest profit.

Fig. 6 presents the variations of the output power of the PV array according to the change in irradiance including (500-1000 W/m$^2$) range at a temperature of 25 degrees.

B. HARRIS HAWKS OPTIMIZATION (HHO)

Harris Hawks optimizers mimic movements of Harris Hawks in different dynamical patterns and manners. This can be formulated by an algorithm and appear in the equations given in [36], [37], and [38].
FIGURE 6. Levelized irradiance implemented in MATLAB change in irradiance (500-1000 W / m²) at a temperature of 25 degrees.

C. HARRIS HAWKS OPTIMIZATION-BASED ENERGY MANAGEMENT SCHEME

Harris Hawks optimization-based energy management technique (HHOM) is implemented using MATLAB/SIMULINK™. The main parameters of the HHOM technique are \( N=5 \), \( T=10 \), \( \text{dim}=1 \), \( K_s = \text{Rabbit Location} \), and \( \text{Rabbit Energy} \). Where \( N \) is the search agents’ size, \( T \) is the iterations limit, \( K_s \) is the position, and \( \text{Rabbit Energy} \) is the best location (best output or objective function). The system is controlled by the inputs where \( C_{\text{grid}} \) is energy price for the utility network ($/kWh), \( C_{\text{batt}} \) is the energy price of battery storage ($/kWh), \( P_{\text{solar}} \) is solar power (kW), \( P_{\text{load}} \) is load power (kW). The previous items discussed in the equations (11 to 15) were implemented using MATLAB/SIMULINK™ as demonstrated in Fig. 5. The developed HHOM technique gives a decision based on the best output or objective function to give value (\( K_s \)). This value is the control function to switch ON/OFF the utility network or battery switches. The flowchart of the HHOM management system is illustrated in Fig. 7. The output of the HHOM approach represents the grid switch or the batteries switch as shown in Fig. 8.

The main core of the developed control structure for the suggested energy management system is a PI regulator. In the presented research, the Integral Absolute Error (IAE), Integral Square Error (ISE), Integral Time Absolute Error (ITAE), and Integral Time Square Error (ITSE) are chosen as performance indices to accomplish the tuning process [39], [40], [41], [42], [43], [44]. The most significant results with the number of iterations (itr), objective function (Obj. fun.) value, Overshoot (OS), and the maximum power (\( P_{\text{max}} \)) in kW is tabulated in Table 2. The best results are selected based on minimum values of the objective function, overshoot, settling time, rise time, and maximum power as shown in Table 3. Highlighted in yellow. Although, the maximum power in the previous table had been attained at (ISE) = 320.1057 kW with small discrepancies compared to (ITSE) = 320.1035 kW. But, the results of ITSE supersede ISE in the overall profile.

VI. RESULTS AND DISCUSSION

A. SCENARIOS OF POWER AND ENERGY PRICE

The system under study contains multiple sources of energy like PV array, utility network, and batteries. There are two scenarios as follows:

**Excess Energy Scenario:**
- Excess energy (loads less than PV array) and the energy price of the utility network is higher than the energy price of energy storage systems.
- Excess energy (loads less than PV array) and the energy price of the utility network is less than the energy price of energy storage systems.

**Shortage Energy Scenario:**
- Shortage in energy (loads higher than PV array) and the energy price of the utility network is higher than the energy price of energy storage systems.
- Shortage in energy (loads higher than PV array) and the energy price of the utility network is less than the energy price of energy storage systems.

**FIGURE 7. Flowchart of proposed HHOM Management System.**
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C. VARIABLE ENERGY PRICE

Energy storage costs vary according to the type of storage (Batteries, Compress air storage, Hydrogen storage, Pump hydropower, Flywheels, Superconducting magnetic energy storage, Supercapacitors). In this paper, energy storage in batteries was used. The energy price in the utility network at a normal time is 0.1 ($) and 0.15 ($) at peak times. The average cost of storing energy in batteries is approximately 20%, the cost is a result of the price of batteries and losses in batteries. A percentage is added by 20% over the energy price for the utility network at the normal time. The energy price of the stored energy in batteries is 0.12 ($) as shown in Fig. 9. Determination of the best decision based on the price of the energy purchase at a lower price or sold at a higher price is the main target of the proposed EMS to achieve the highest profit.

D. HHO TRUTH TABLE MANAGEMENT

The system was operated according to system constraints in section (V-A). The system measured PV array output, load power, energy price ($/kWh) from the utility network, and energy price of battery storage ($/kWh) normal at all times. The control system closed and open the utility network and the batteries switch to turn ON/OFF for HHO management as shown in Fig. 10.

E. FUZZY TRUTH TABLE MANAGEMENT

The system was operated by MATLAB as previously but replaced the management method with a Fuzzy management system. The system shows a similar operation. The control system closed and open the utility network and the batteries switch to turn ON/OFF for HHO management as shown in Fig. 10.

TABLE 3. MATLAB–Simulink HHO Error result- minimum error and minimum Overshoot at (itse).

| iter no. | p_max | Obj. fun. | OS   | Kp    | Ki    |
|---------|-------|-----------|------|-------|-------|
| 7       | IAE   | 320.1053  | 1.40E-07 | 4.264853 | 0.35541 | 0.23  |
| 3       | ISE   | 320.1057  | 2.93E-08 | 4.251056 | 0.56288 | 0.494 |
| 5       | ITAE  | 320.1053  | 8.09E-08 | 4.003863 | 0.5017  | 0.113 |
| 9       | ITSE  | 320.1055  | 1.66E-08 | 4.000275 | 0.90198 | 0.414 |

TABLE 4. Battery and grid status.

| power     | Type  | Case       |
|-----------|-------|------------|
| P_{batt}  | battery | charge (-ive) |
| P_{batt}  | battery | discharge (+ive) |
| P_{batt}  | battery | OFF 0 |
| P_{grid}  | grid   | Feed load (-ive) |
| P_{grid}  | grid   | Injected to grid (+ive) |
| P_{grid}  | grid   | OFF 0 |

- Shortage in energy (loads higher than PV array) and the energy price of the utility network is less than the energy price of energy storage systems.
  1. SoC >= 80%.
  2. SoC <= 20%.

B. VALIDATION OF HHOM WITH FUZZY LOGIC MANAGEMENT STRATEGY

To validation of the results of the proposed managementsystem, the proposed HHOM is compared to another managementsystem that is commonly used, such as the fuzzy logic system.

Firstly: the MATLAB program is used with a controller by fuzzy logic management. The time period was divided into 25 sectors. To get the energy at each sector the power measurement multiply time at each sector. Power positive or negative at each sector represents the power injected into the network, withdrawal, battery charging, or discharging. Fig. 16 and Table 4 show the results.

Secondly: The management system was replaced from fuzzy logic to Harris Hawks management in the same manner controller. Figs. 15 and 16 show the results. The results were compared for each system in Table 5.
The aggregated system output power for PV array, load, utility network, and battery power is introduced. Power analysis at each point for the HHO and fuzzy power management system is discussed in detail in this section.

The power is summarized by the following periods:

1) During the period from 0.5 to 0.7, the load is greater than the PV array output. The shortage in the required energy is compensated by the utility network because the utility network energy price is less than the battery energy price during that period.

2) During the period from 0 to 1, the load reaches zero and there is an excess of the solar energy being charged into the batteries because the utility network energy price is less than the battery energy price.

3) At a period from 1 to 1.3, the network is disconnected and the load power is greater than the PV array output, the SoC is less than 20 %, and the shortage is fed from the grid because SoC is less than 20 %.

4) At a period from 1.3 to 1.5, the load power is greater than the PV array output, the SoC is less than 20 %, and the shortage is fed from the grid because SoC is less than 20 %.

5) During the period from 1.5 to 2, the utility network is disconnected and the load power is less than the PV array output which results in an energy excess of solar energy. The energy excess is charged into the batteries because the utility network energy price is less than the battery energy price.

6) At a period from 2 to 2.5, the load power is less than the PV array output resulting in excess solar energy. The excess solar energy is injected into the utility network because the utility network energy price is greater than the battery energy price.

Remark: The control system works according to the previous constraints. When the network switch was turned ON, the battery switch turned OFF and vice versa. The decision to switch ON/OFF is based on the difference in the cost between the energy price of the utility network and batteries, as well as the presence of an excess of solar energy or shortage. Power coordination of HHO and fuzzy management systems is illustrated in Figs. 12 and 13, respectively.

Batteries can be the condition of a load (-ive) that charges energy or (discharge) a source (+ive) that feeds the load. The grid can be a load (+ive) that takes up the excess of solar energy, or it can be a source (-ive) that feeds the loads at a shortening of the solar energy as shown in Table 4.

G. ENERGY COST SYSTEM
The authors of the presented article had developed a user-friendly software package using MATLAB program to obtain the truth table of the control in switches for sold or purchasing energy to the grid and the battery switches for charging or discharging process in the battery management. The
decision to switch ON/OFF is based on the difference in the energy price of the utility network and batteries, and the appropriate coordination of an excess of solar energy or shortage as shown in Fig. 14. The cost at each point had been calculated in $/kWh for sold energy, purchased or battery charge, discharge for HHOM, and fuzzy EMSs as shown in Figs. 15 and 16, respectively.

H. COST COMPARISON

By comparing management systems in terms of profit, the fuzzy-based management achieves a profit of 10.283$ but the HHOM-based management achieves a profit of 10.112$ with 1.667% less than the fuzzy system in the same period as shown in Table 5.

I. THE SYSTEM SIMULATION UNDER DIFFERENT CONDITIONS

The loads are driven from the real loads installed in one the city of Siwa in the Western Desert - Egypt. These loads operate under different and changing conditions. This region consumes electricity from the main network. Maximum load value (kilowatts) 19.9 MW. The suggested photovoltaic array is constructed as follows: five modules in series and 12000 parallel modules of 20.11 MW SunPower X21-335-BLK. The aggregated system output power for PV array, load, utility network, and battery power is introduced.
The control system works according to the previous constraints. When the network switch was turned ON, the battery switch turned OFF and vice versa. The decision to switch ON/OFF is based on the difference in the cost between the energy price of the utility network and batteries, as well as the presence of an excess of solar energy or shortage. Power coordination management systems are illustrated in Fig. 17. In addition, the management systems in terms of two system conditions are listed in Table 4. It is clear from this Table that the Load 19.9 MW, PV=20.11 MW management achieves a profit of $51.891 but the Load 328 kW management achieves a profit of $10.112 $ at the same period.

VII. CONCLUSION

Technical and economic management systems, based on two methods namely, fuzzy and HHO management schemes are addressed in this article. These schemes were developed for Seawater Desalination Plants (SWDPs) to achieve the optimal performance of the operation with a minimum cost of the system. The economic minimum cost is based on the energy generated, consumed, grid and storage energy prices. The results show high performance, maximum profit, and accurate coordination between the applicable energy resources. By comparing management systems in terms of net profit, the fuzzy system achieves a profit of 10.283 $ but the HHO-based management system achieves a profit of 10.112 $. The profit percentage of HHO-based EMS is less than the fuzzy system by 1.667 % in the same period. The results show the convergence of the two suggested systems. The HHO-based management method is a reliable method besides the fuzzy management method.

REFERENCES

[1] P. Rullo, L. Braccia, P. Luppi, D. Zamoffen, and D. Feroldi, “Integration of sizing and energy management based on economic predictive control for standalone hybrid renewable energy systems,” Renew. Energy, vol. 140, pp. 436–451, Sep. 2019, doi: 10.1016/j.renene.2019.03.074.
[2] H. Novak, V. Lešić, and M. Vašak, “Hierarchical model predictive control for coordinated electric railway traction system energy management,” IEEE Trans. Intell. Transp. Syst., vol. 20, no. 7, pp. 2715–2727, Dec. 2019, doi: 10.1109/TITS.2018.2882087.
[3] B. Zhao, X. Wang, D. Lin, M. M. Calvin, C. J. Morgan, R. Qin, and C. Wang, “Energy management of multiple microgrids based on a system of systems architecture,” IEEE Trans. Power Syst., vol. 33, no. 6, pp. 6410–6421, Nov. 2018, doi: 10.1109/TPTS.2018.2882087.
[4] R. K. Sharma and S. Mishra, “Dynamic power management and control of a PV PEM fuel-cell-based standalone AC/DC microgrid using hybrid energy storage,” IEEE Trans. Ind. Appl., vol. 54, no. 1, pp. 526–538, Jan./Feb. 2017, doi: 10.1109/TIA.2017.2756032.
[5] M. A. Ebrahim, B. Talat, and E. M. Saied, “Implementation of self-adaptive Harris hawks optimization-based energy management scheme of fuel cell-based electric power system,” Int. J. Hydrogen Energy, vol. 46, no. 29, pp. 15268–15287, Apr. 2021, doi: 10.1016/j.ijhydene.2021.02.116.
[6] A. Ravichandran, S. Sirosoupour, P. Malays, and A. Emadi, “A chance-constraints-based control strategy for microgrids with energy storage and integrated electric vehicles,” IEEE Trans. Smart Grid, vol. 9, no. 1, pp. 436–459, Jan. 2018, doi: 10.1109/TSG.2016.2552173.
[7] W.-J. Shyr, L.-W. Zeng, C.-K. Lin, C.-M. Lin, and W.-Y. Hsieh, “Application of an energy management system via the Internet of Things on a university campus,” EURASIA J. Math., Sci. Technol. Educ., vol. 14, no. 5, pp. 1759–1766, Feb. 2018, doi: 10.12973/eurasialjmste/80790.
[8] M. Elsisi, N. Bazmohammadi, J. M. Guerrero, and M. A. Ebrahim, “Energy management of controllable loads in multi-area power systems with wind power penetration based on new supervisor fuzzy nonlinear sliding mode control,” Energy, vol. 221, Apr. 2021, Art. no. 119867, doi: 10.1016/j.energy.2021.119867.
[9] F. Y. Melhem, O. Grunder, Z. Hammoudan, and N. Moubayed, “Energy management in electrical smart grid environment using robust optimization algorithm,” IEEE Trans. Ind. Appl., vol. 54, no. 3, pp. 2714–2726, May/June 2018, doi: 10.1109/TIA.2018.2803728.
[10] A. Bennouna, M. Becherif, D. Depernet, and M. A. Ebrahim, “Novel energy management technique for hybrid electric vehicle via interconnection and damping assignment passivity based control,” Renew. Energy, vol. 119, pp. 116–128, Apr. 2018, doi: 10.1016/j.renene.2017.11.051.
[11] G. Pau, M. Collotta, A. Ruano, and J. Qin, “Smart home energy management,” Energies, vol. 10, no. 3, p. 382, 2017, doi: 10.3390/en10030382.
[12] P. Sanjeev, N. P. Padhy, and P. Agarwal, “Effective control and energy management of isolated DC microgrid,” in Proc. IEEE Power Energy Soc. Gen. Meeting, Jul. 2017, pp. 1–5, doi: 10.1109/PESGM.2017.8273786.
[13] J. Han, C.-S. Choi, W.-K. Park, I. Lee, and S.-H. Kim, “Smart home energy management system including renewable energy based on ZigBee and PLC,” IEEE Trans. Consum. Electron., vol. 60, no. 2, pp. 198–202, May 2014, doi: 10.1109/TCE.2014.6851994.
[14] D. Westermann, S. Nicolai, and P. Bretschneider, “Energy management for distribution networks with storage systems—A hierarchical approach,” in Proc. IEEE Power Energy Soc. Gen. Meeting-Convers. Dei. Electr. Energy 21st Century, Jul. 2008, pp. 1–6, doi: 10.1109/PES.2008.4596533.
[15] M. H. Elkarez, A. Hoballah, and A. M. Azmy, “Artificial intelligence-based optimization of automated home energy management systems,” Int. Trans. Electr. Energy Syst., vol. 26, no. 9, pp. 2038–2056, Sep. 2016, doi: 10.1002/etep.2195.
[16] M. Boaro, D. Fuselli, F. D. Angelis, D. Liu, Q. Wei, and F. Piazza, “Adaptive dynamic programming algorithm for renewable energy scheduling and battery management,” Cognit. Comput., vol. 5, no. 2, pp. 264–277, Jun. 2013, doi: 10.1007/s12559-012-9191-y.
[17] Z. Yang, C. Wu, H. Liao, and H. Xu, “Design of energy management system in distributed power station,” in Proc. Int. Conf. Sustain. Power Gener. Supply, Apr. 2009, pp. 1–5, doi: 10.1109/SUPERGEN.2009.5348233.

[18] M. Gunasekaran, I. H. Mohamed, B. Chokkalingam, L. Mihet-Popa, and S. Padmanaban, “Energy management strategy for rural communities DC micro grid power system structure with maximum penetration of renewable energy sources,” Appl. Sci., vol. 8, no. 4, p. 585, 2018, doi: 10.3390/app8040585.

[19] H. Mehrjerdi, “Multilevel home energy management integrated with renewable energies and storage technologies considering contingency operation,” J. Renew. Sustain. Energy, vol. 11, no. 2, Mar. 2019, Art. no. 025101, doi: 10.1063/1.5085496.

[20] D.-M. Han and J.-H. Lim, “Design and implementation of smart home energy management systems based on ZigBee,” IEEE Trans. Consum. Electron., vol. 56, no. 3, pp. 1417–1425, Aug. 2010, doi: 10.1109/TCE.2010.5606278.

[21] M. A. Ebrahim, K. A. El-Metwally, F. M. Bendary, and W. M. Mansour, “Transient stability enhancement of a wind energy distributed generation system using fuzzy logic stabilizers,” Wind Eng., vol. 36, no. 6, pp. 687–700, Dec. 2012, doi: 10.1260/0309-524X.36.6.687.

[22] C. Molitor, A. Benigni, A. Helmedag, K. Chen, D. Calì, P. Jahangiri, D. Muller, and A. Monti, “Multiphysics test bed for renewable energy systems in smart Homes,” IEEE Trans. Ind. Electron., vol. 60, no. 3, pp. 1235–1248, Mar. 2013, doi: 10.1109/TIE.2012.2190254.

[23] M. Collotta and G. Pau, “A novel energy management approach for smart Homes using Bluetooth low energy,” IEEE J. Sel. Areas Commun., vol. 33, no. 12, pp. 2988–2996, Dec. 2015, doi: 10.1109/JSAC.2015.241293.

[24] C.-S. Karavas, K. G. Arvanitis, and G. Papadakis, “Optimal technical and economic configuration of photovoltaic powered reverse osmosis desalination systems operating in autonomous mode,” Desalination, vol. 466, pp. 97–106, Sep. 2019, doi: 10.1016/j.desal.2019.05.007.

[25] H. Shahnizadeh, M. Moazzami, S. H. Fathi, and G. B. Ghareshpetic, “Optimal sizing and energy management of a grid-connected microgrid using Homer software,” in Proc. Smart Grids Conf. (SGC), Dec. 2016, vol. 3, pp. 1–6, doi: 10.1109/SGC.2016.7249245.

[26] C.-S. Karavas, K. G. Arvanitis, G. Kyriakarakos, D. D. Piromalis, and G. Papadakis, “A novel autonomous PV powered desalination system based on a DC microgrid concept incorporating short-term energy storage,” Sol. Energy, vol. 159, pp. 947–961, Jan. 2018, doi: 10.1016/j.solener.2017.11.057.

[27] C.-S. Karavas, G. Kyriakarakos, K. G. Arvanitis, and G. Papadakis, “A multi-agent decentralized energy management system based on distributed intelligence for the design and control of autonomous polygeneration microgrids,” Energy Convers. Manag., vol. 103, pp. 166–179, Oct. 2015, doi: 10.1016/j.enconman.2015.06.021.

[28] M. An, Y. Chen, and C. J. Baker, “A fuzzy reasoning and fuzzy-analytical hierarchy process based approach to the process of railway risk information: A railway risk management system,” Inf. Sci., vol. 181, no. 18, pp. 3946–3966, Sep. 2011, doi: 10.1016/j.ins.2011.04.051.

[29] M. A. Hossain, H. R. Pota, S. Squartini, and A. F. Abdou, “Modified PSO algorithm for real-time energy management in grid-connected microgrids,” Renew. Energy, vol. 136, pp. 746–757, Jun. 2019, doi: 10.1016/j.renene.2019.01.005.

[30] M. A. Hossain, H. R. Pota, and C. M. Moreno, “Real-time battery energy management for residential solar power system,” IFAC-PapersOnLine, vol. 52, no. 4, pp. 407–412, 2019, doi: 10.1016/j.ifacol.2019.08.244.

[31] A. A. Heidari, S. Mirjalili, H. Faris, I. Aljaraheem, M. Alfaour, and H. Chen, “Harris hawks optimization: Algorithm and applications,” Future Gener. Comput. Syst., vol. 97, pp. 849–872, Aug. 2019.

[32] H. M. Alabool, D. Alarabiat, L. Abualigah, and A. A. Heidari, “Harris hawks optimization: A comprehensive review of recent variants and applications,” Neural Comput. Appl., vol. 33, no. 15, pp. 8939–8980, Aug. 2021.

[33] D. A. Aviles, J. Pascual, F. Guinjoan, G. G. Gutierrez, R. G. Orguera, J. L. P. Proano, P. Sanchis, and E. T. Motoasoa, “An energy management system design using fuzzy logic control: Smoothing the grid power profile of a residential electro-thermal microgrid,” IEEE Access, vol. 9, pp. 25172–25188, 2021.

[34] P. Dimitroulis and M. Alamaniotis, “A fuzzy logic energy management system of on-grid electrical system for residential prosumers,” Electric Power Syst. Res., vol. 202, Jan. 2022, Art. no. 107621.
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