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OPTIMAL MANAGEMENT OF RENEWABLE ENERGY SOURCES CONSIDERING SPLIT-DIESEL AND DUMP ENERGY

H. Shayeghi [1] **S. Asefi** [1] **E. Shahryari** [1] **R. Dadkhah Dolatabad** [2]

1. Electrical Engineering Department, University of Mohaghegh Ardabili, Ardabil, Iran
hshayeghi@gmail.com, sajjad.asefi1992@gmail.com, elnaz.shahryari@yahoo.com
2. Technical and Vocational Institute of Razi, Technical and Vocational University, Ardabil, Iran
r.dadkhahdolatabad@gmail.com

Abstract- Implementation of a tri-objective optimal design of an off-grid renewable energy system for a residential building is evaluated in this study. The considered system is consisting of split-diesel, wind and photovoltaic power sources and battery for energy storage. We have formulated optimal sizing of the system as an optimization problem and it solved using Jaya algorithm (JA). The objective we followed is to minimize the initial capital cost, carbon emissions and dump energy, while taking the time-varying characteristics of generation and demand into account. To achieve these objectives, instead of single big diesel generator, three small diesel generators (split-diesel) are used regarding some predetermined rules based on renewable energy resources which are available and battery state of charge.

Keywords: Renewable Energy Sources, Optimal Management, Split-Diesel Generator, Jaya Algorithm.

I. INTRODUCTION

Transition to a future energy system which is common among many nations, especially based on low or zero carbon electricity, requires investigation on optimal management of renewable energy sources more than before. In this regard, an efficient choice for solving the problem of supplying power to isolated and remote areas is utilizing hybrid energy system.

Regarding the available challenges of grid supply, in order to fulfill the electrical energy requirements of residents of remote areas, utilizing alternative energy sources are suggested. The applied sources could be categorized into three parts. Renewable (i.e. PV, wind, Biomass and etc.), non-renewable (such as gas turbines and diesel generators) and storage devices (like battery, SMES, super capacitor and etc.).

As renewable energy sources such as photovoltaic and wind are highly dependent on weather and climate conditions, so they challenge the major problem of intermittency and unpredictability [1]. So these sources will not be able to fulfill the load demand unless the weather provides sufficient wind speed or solar radiation.

The above mentioned problems are the major reasons of applying storage device or backup source in the micro-grid. So that, during periods which needed criteria for absorbing energy from wind or PV (i.e. cut-in speed and solar radiation) are not available, we can manage to utilize the backup energy source to supply deficit energy.

Although, diesel generators are independent of climate for supplying power but applying them have harmful effects such as CO_2 diffusion that pollutes the environment [2] and have high costs for maintenance and operation.

The following provides some publications which have presented the development and feasibility of hybrid energy systems that are not connected to the grid. In [3], feasibility of isolated hybrid energy system for a stand-alone society have been studied and results demonstrate that the most appropriate choice for the society is wind, diesel and battery hybrid system. The available potential for wind and photovoltaic energy of chosen areas in Corsica Island are evaluated in [4], in order to show that utilizing hybrid PV and wind system with storage devices can provide a highly dependable source for supplying the isolated location. Optimal sizing of a remote hybrid wind and PV system with battery from both technical and economical point of view has been performed in [5].

In [6] modeling of a hybrid power system containing PV and diesel generator with variable speed is provided to supply an isolated rural community. Accordingly, authors have tried to make a comparison between the performance of the variable and constant speed diesel generators, while considering PV. Performance of a hybrid system containing wind, PV, diesel and battery according to climate measurements for each hour of a place in southern Algeria is investigated in [7]. The applicability of inserting a diesel generator into hybrid wind and PV system was provided in [8] for Saudi Arabia. Due to the available situation they concluded when diesel price is 0.6 dollars per litter, the hybrid system would be considered cost competitive. In [9] two methods of making hybrid systems for small isolated energy sources including wind, PV and micro-hydro sources for two villages were reported.

Utilizing a hybrid energy system which brings out the most efficiency and increase economic and environmental benefit, needs additional objectives to be considered. Now we are going to consider works in which different objective functions such as minimizing costs, dump energy and CO_2 emission has been taken into account for hybridization of energy systems.

In [10] minimization of total cost of the system during a life time for 20 years applying Genetic Algorithm (GA) in order to specify the efficient type and number of units of a hybrid wind and PV system is provided. To evaluate the system optimal design, and reach the specific power supply loss probability with a minimum annual system cost, an optimization model is proposed in [2].

In [11], the authors utilized GA to select the optimal hybrid energy system including PV, wind, split-diesel and battery to minimize life cycle cost, pollutant emissions and wasted energy. In order to decrease the total cost of the system for a wind PV and battery storage hybrid system, a search method related to stochastic gradient was applied in [12]. In [13] to reduce the total cost and the pollutant emissions to the smallest possible amount, Pareto evolutionary algorithm is applied to design remote wind, PV and diesel hybrid system. Optimal sizing of a hybrid grid-connected system containing PV and wind energy sources was performed in [14] to just minimize the life cycle cost.

In this investigation, we have designed an optimal sizing hybrid system consisting of split-diesel, wind, PV and battery in order to minimize initial capital cost, carbon emissions and dump energy, while considering the time-varying characteristics of demand and generation. It is to be noted that the presented model will absolutely help utility to mitigate intermittency of RES. In this paper, a simple and powerful optimization algorithm, called Jaya Algorithm (JA) is applied for optimal solving of our constrained problem. JA has the ability to solve whether constrained or unconstrained optimization problems. The fundamental concept of algorithm is that the solution obtained for a problem should move towards the best solution and should avoid the worst solution. This does not need any algorithm-specific control parameters except common control parameters [15].

The paper is categorized to following sections. Section II presents the mathematical models for RES and load. Section III provides the applied objective function. Section IV briefly describes the applied algorithm. Section V presents results and discussion and finally the paper's conclusion part is provided in section VI.

II. SYSTEM MODELING

As mentioned before energy sources considered in this study are the 3-split small rated diesel generators, wind turbine system, PV system and battery. In the following subsections the mathematical model for RES and load are provided.

A. Load Modeling

The load curve of the IEEE-RTS system is assumed to be followed in this study [16]. Each year has been divided into four different parts which indicate, winter (hour 1 to 24), spring (hour 24 to 48), summer (hour 48 to 72) and fall (72 to 95). It is obvious that load curve of a day is representing each season, i.e. this load curve is assumed to be followed during the season. So, the load curve of four 24-h days (24×4 = 96 h) is representing a year (8760 h). The seasonal maximum and minimum in load demand occurred during summer and fall, respectively. It is to be noted that the peak load of the system, which occurs in summer is shown in Figure 1. Regarding the former explanations, in order to obtain load demand for each season, we should just multiply the system peak demand of that hour, to the corresponding load factor of that time. As shown in Figure 2, each year has four seasons. A load curve for a 24-h day is representing each season. Means that the 96-h load curve is repeated 91.25 times to become one year (91.25×96 = 8760).

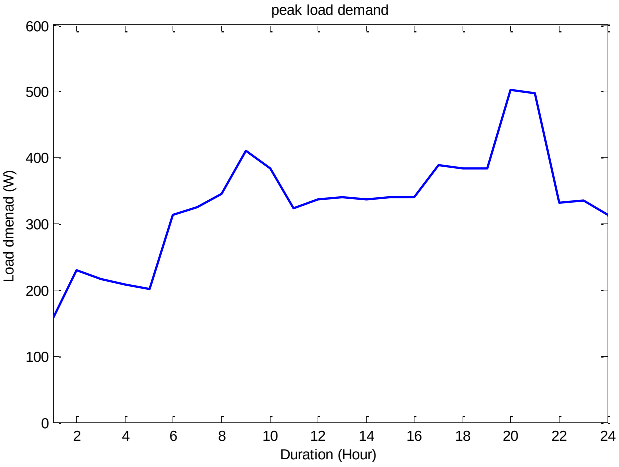

Figure 1. Peak load demand of the system

Here, 96 h in four seasons of a year are corresponding to 96 periods (load levels). So, the total annual energy dumped or CO_2 emission regarding a time period (Δt) of 1 h can be expressed as:

$$E_{dump} = 91.25 \times \sum_{i=1}^{96} P_{dump}^{t} \Delta t \qquad (1)$$

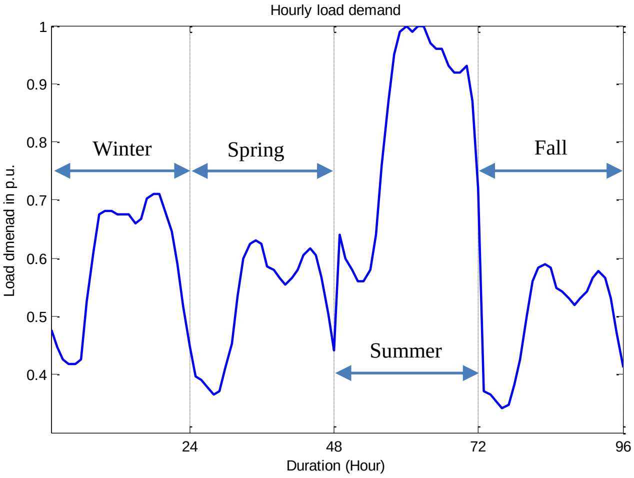

Figure 2. Seasonal load demand of the system (p.u.)

B. Photovoltaic System

The output power of a photovoltaic module at each hour is calculated by:

$$P_{pv} = A_{pv} \times H_{t(AV)} \times \eta_{pv} \tag{2}$$

where, A_{pv} represents the area of the PV module in m^2, $H_{t(AV)}$ indicates the average global solar irradiation for that place and η_{pv} is the efficiency of PV module. The parameters and details about the PV module is provided in datasheet presented in [11]. The seasonal output power for a photovoltaic module is provided in Figure 3.

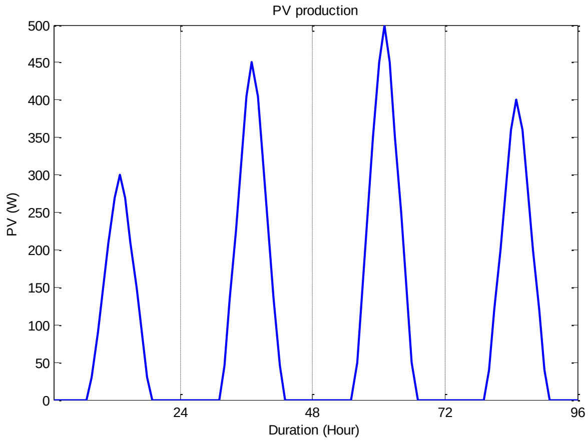

Figure 3. Hourly output of a PV module

C. Wind System

The output power obtained by wind turbine is evaluated applying the following equation:

$$P_{wind\_out} = P_w \times A_w \times \eta_g \tag{3}$$

where, P_w (W/m^2) is the output power of wind turbine, A_w (m^2) is the area swept by wind turbine and η_g is the total efficiency of wind generator and all devices connected to the turbine. Calculating the output power of turbine needs to understand other features like V_{ci} (cut-in speed of wind in (m/s)), V_r (rated speed of wind in (m/s)) and V_{co} (cut-out speed of wind in (m/s)) which are provided in [11].

Figure 4 presents the output power of a wind turbine for the selected four days. It is to be noted that applying the hourly average uniform random wind speed data, the output of a wind turbine is evaluated.

D. Battery and Split-Diesel

In this investigation our first priority is to utilize clean energy. So, we would not use diesel generator unless we have lack of energy to meet the demand not only utilizing renewable energy sources but also using energy stored in the battery. To calculate the deficit or energy excess we have in hour system we use the following equation:

$$E_{ed}(t) = E_{ren}(t) - \frac{E_L(t)}{\eta_{inv}} \tag{4}$$

where, $E_L(t)$ and $E_{ren}(t)$ are the demanded energy and the energy generated by renewable sources at time t, respectively, and η_{inv} is the efficiency of the inverter.

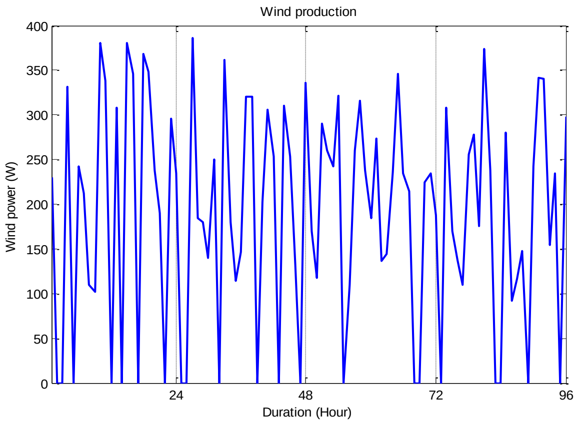

Figure 4. Hourly output of a wind turbine

Battery charging only occurs when there is much more (i.e. exceeds) of renewable energy (i.e. $E_{ed}(t) > 0$) than needed and the battery state of charge is below the preset maximum (i.e. $SOC(t) < SOC_{\max}$). In order to calculate the state of charge during charging at time t, $SOC(t)$, the following equation is given:

$$SOC(t) = SOC(t-1).(1-\sigma) + \left(E_{ren}(t) - \frac{E_L(t)}{\eta_{inv}}\right).\eta_B \tag{5}$$

When there is deficit of renewable energy (i.e. $E_{ed}(t) < 0$) and the battery state of charge is above the preset minimum (i.e. $SOC(t) > SOC_{\min}$) the battery will be discharged to supply the deficit energy as much as it can. To calculate the state of charge during charging at time t, $SOC(t)$ is given by

$$SOC(t) = SOC(t-1).(1-\sigma) + \left(\frac{E_L(t)}{\eta_{inv}} - E_{ren}(t)\right) \tag{6}$$

where, η_B and σ are the battery efficiency and hourly self-discharge rate, respectively. All the necessary data are presented in [11].

If there is a deficit in renewable power supply (i.e. $E_{ed}(t) < 0$) and the battery SOC is at the minimum (i.e. $SOC = SOC_{\min}$), the generators will operate. A model of 3 split diesel generators has been applied, so that we can lower the fuel consumption and consequently decrease CO_2 emission. Size of each generator is considered to be able to supply 40 percent of the demanded load. These diesel generators are managed by a controller which selects the number generators must start working regarding the load debt to be fulfilled. The strategy of operation of the generators is described in the following steps, where S_1, S_2 and S_3 are control switches (1 or 0):

- Step 0: If there is a deficit in renewable power supply and battery SOC is at the minimum, in the following steps choose appropriate number of generators to start.
- Step 1: If the needed energy can be met by one of the diesel generators, just start it and the rest be off. (S_1=1, and S_2=S_3=0).
- Step 2: If the required energy is more than to be met by one generator but can be handled by two generators, so start two of them (S_1=1, S_2=1 and S_3=0).
- Step 3: If still much energy is needed, so turn all three generators “ON” (S_1=S_2=S_3)

III. OBJECTIVE FUNCTION

The objective we followed in this investigation is to propose a configuration that represents the optimal number of each energy source required in the system. The applied algorithm aims to minimize the initial capital cost, CO_2 emission and dump energy, while considering the time-varying characteristics of demand and generation. The final solution which algorithm will find contains six elements, including number of photovoltaic modules (N_1), quantity of wind turbines (N_2), number of generators at each split parts (N_3, N_4 and N_5) and finally the required number of batteries (N_6).

Now, let's consider how to take into account each part of this objective function. First of all, we are going to calculate initial cost (Table 1). The initial capital cost of each system component is additional cost of each element utilized in system. As these costs are provided in Table 1 for each element, determining the optimal number of each element will bring out the total cost of the system.

$$C_{init} = N_1 C_{init,pv} + N_2 C_{init,wind} + N_3 C_{init,gen1} + \\ + N_4 C_{init,gen2} + N_5 C_{init,gen5} + N_3 C_{init,bat} \qquad (7)$$

where, $C_{init,element}$ indicates the cost of a unit element module installed in system.

Table 1. Initial capital cost of each element [11]

Component	*Cost* ($)
PV	630
Wind turbine	300
Batt	300
Diesel generator (per W)	0.3
Diesel Fuel (per liter)	0.7

The next objective we are going to address is CO_2 emission which depends on the working hours of the diesel generators. As CO_2 is a result of fuel consumption, so we should calculate the fuel consumed by diesel generators first. Fuel consumption (lit/h) of a generator depends on its rated power and actual power which has been shown in the following equation:

$$F(t) = \left(0.246 \times \frac{E_{ed}(t)}{1h}\right) + \left(0.08415 \times P_r\right) \qquad (8)$$

where, P_r (kW) is the rated power of the diesel generator [11]. The total fuel consumed by the system is sum of all fuel consumptions related to each generator. We have selected cost ($), in order to bring objectives to a same base. Using the following relation, we can bring consumed fuel to a monetary base:

$$E_{CO2}(t) = S_{E(CO2)}(\text{kg/l}) \times F(t)(\text{l/h}) \qquad (9)$$

that $S_{E(CO2)}$ indicates the specific emission of carbon dioxide which is 2.7 kg/l.

Dump energy is the third objective we have considered in this study. This energy (also called as waste energy) occurs when we have more energy from RES than the needed demand and at the same time the battery is fully charged. There are ways like utilizing three-phase resistor, transmitting this energy to the grid and using to produce hydrogen, to name a few.

Detailed description of the ways to avoid dump energy is presented in literature [17]. In order to convert dump energy to a monetary based value, the percentage of PV and wind contribution to dump are calculated using their respective cost of energy.

IV. JAYA ALGORITHM

Regarding to success of the TLBO algorithm, another algorithm-specific parameter-less algorithm is proposed in this paper [15]. As we remember from TLBO algorithm, there are two phases, one is teacher phase and the other is learner phase. But, Jaya algorithm has only one phase and it is very easy to use, whether the problem is constrained or unconstrained. So, the working of the proposed algorithm is much different from that of the TLBO algorithm. The flowchart of this algorithm is given in Figure 5.

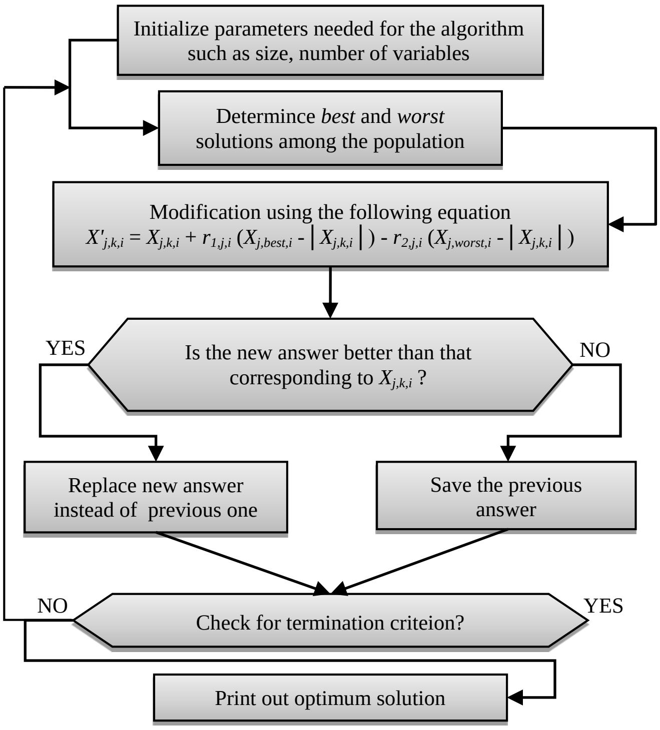

Figure 5. Flowchart of the proposed algorithm

Imagine $f(x)$ as the objective function to be minimized, which here we have used sum of three objectives, i.e. initial capital cost, carbon emissions and dump energy. At any iteration i, 'm' indicates number of design variables (i.e. j=1,2,…,m) and 'n' indicates number of candidate solutions (i.e. population size, k=1,2,…,n). Amongst the entire candidate solutions, best candidate *best* obtains the best value of $f(x)$ (i.e. $f(x)_{best}$) and the worst candidate *worst* obtains the worst value of $f(x)$ (i.e. $f(x)_{worst}$). If $X_{j,k,i}$ is the value of the jth variable for the kth candidate during the ith iteration, then the modification of its value will be done by Equation (10).

$$X'_{j,k,i} = X_{j,k,i} + r_{1,j,i}\left(X_{j,best,i} - |X_{j,k,i}|\right) - r_{2,j,i}(X_{j,worst,i} - |X_{j,k,i}|) \qquad (10)$$

where, $X_{j,best,i}$ shows the best candidate value and $X_{j,worst,i}$ shows the *worst* candidate value, both for jth variable.

$X'_{j,k,i}$ is the improved value of $X_{j,k,i}$ while $r_{1,j,i}$ and $r_{2,j,i}$ both are random numbers for the jth variable during the ith iteration selected from the [0, 1] interval. The phrase "$r_{1,j,i}$ ($X_{j,best,i}$- $\lvert X_{j,k,i}$)" indicates the willing of the solution to move closer to the best solution and the phrase "-$r_{2,j,i}$ ($X_{j,worst,i}$- $\lvert X_{j,k,i}$)" indicates the willing of the solution to avoid the worst solution. $X'_{j,k,i}$ is accepted if it gives better function value. All the accepted function values at the end of iteration are maintained and these values become the input to the next iteration. The flowchart of the proposed algorithm can be seen in figure 1. The main idea behind the name of Jaya algorithm is the fact that, the algorithm has the willing get closer to success (i.e. obtaining the best solution) and tries to move away from failure (i.e. avoiding the worst solution). Reaching the best solution somehow considered as achieving victory and hence it is named as Jaya (a Sanskrit word meaning victory).

So, in this paper, our algorithm tries to find a feasible solution considering N_1, N_2, N_3, N_4, N_5 and N_6 as variables.

V. RESULTS AND DISCUSSIONS

By running the algorithm, we finally obtained the results which is summarized in Table 2. Figure 6 shows behavior of the system due to optimal configuration during winter season which has the lowest PV production in year.

Table 2. Optimization result

Variable	N_1	N_2	N_3	N_4	N_5	N_6
Value	2	2	1	1	1	1

As the number of each element applied in the system became clear regarding Table 2, now we can provide all cost calculation and plot the performance of the optimal configuration during the year.

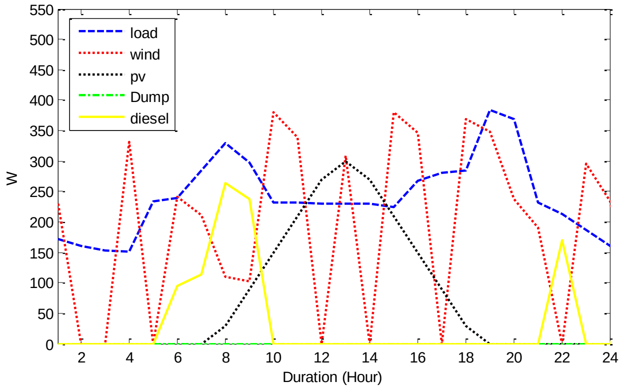

Figure 6. System behavior for optimal configuration during winter

In Figure 7 behavior of the system due to optimal configuration during spring season is presented. In addition, in this season we have dump energy. Figure 8 shows behavior of the system due to optimal configuration during summer season which has the highest PV production in year. Figure 9 shows system operation due to optimal configuration during summer season.

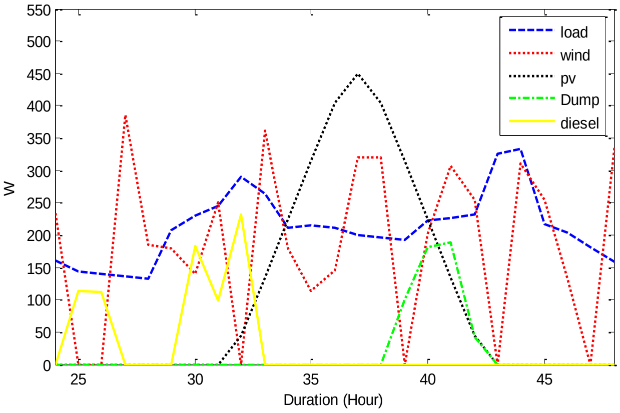

Figure 7. System behavior for optimal configuration during spring

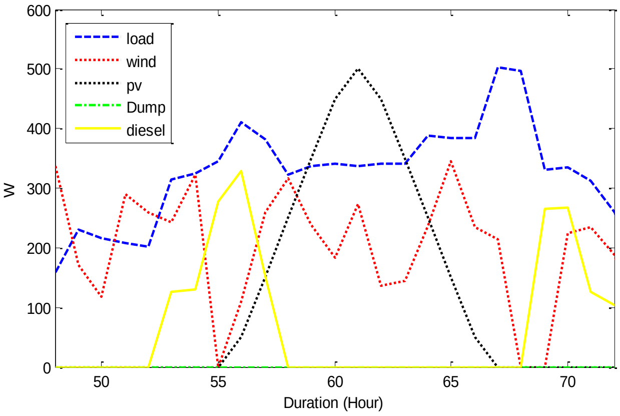

Figure 8. System behavior for optimal configuration during summer

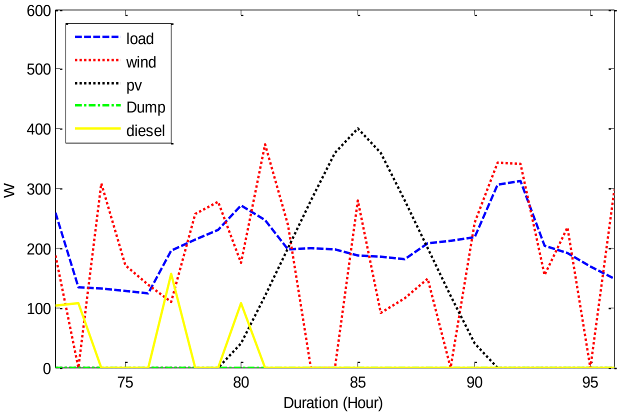

Figure 9. System behavior for optimal configuration during fall

Figure 10 presents the SOC of the battery in the entire year. It's obviously clear that in Spring the battery SOC reaches to the maximum amount and this is the main reason of having dump energy at that period. And finally the following figure provides the objective function value, using Jaya algorithm, which converges to its minimum amount.

Figure 11 shows fitness convergence curve of the proposed algorithm. In order to better analyzing the system operation, we have provided the numerical results of the considered objectives in Table 3.

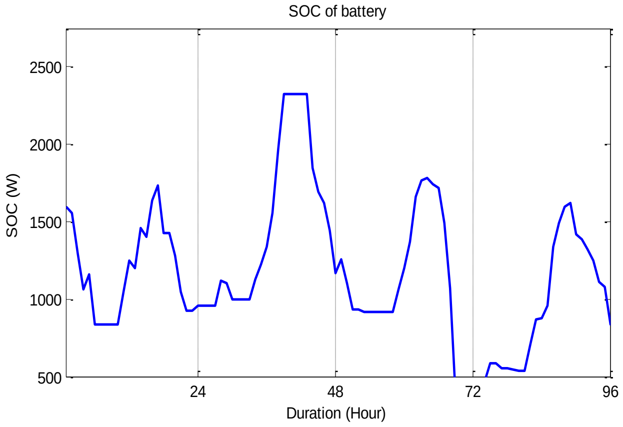

Figure 10. Battery state of charge during the year

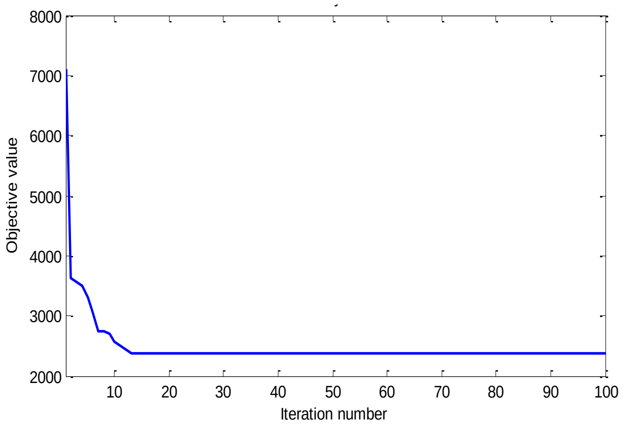

Figure 11. Fitness convergence curve of the proposed algorithm

Table 3. Results of JA algorithm

Initial cost	CO_2 cost	Fuel cost	Dump cost	Dump Energy
2340.79 $	214.152 $	370.13 $	3106.32 $	46.7 (kW)

VI. CONCLUSION

In this paper, a yearly examination was implemented for the system under investigation which consists of split-diesel, wind and photovoltaic power source and battery for energy storage. The first priority of work was to utilize clean energy (i.e. PV and wind) as our main power sources and in order to remove the intermittent nature of these sources, battery and diesel generators were applied, respectively. The problem considered as an optimization problem and to solve it, we have applied Jaya algorithm. The applied algorithm aims to minimize the initial capital cost, CO_2 emission and dump energy, while considering the time-varying characteristics of demand and generation. Applying the presented characteristics of demand, we can decrease the needed data and simulation time to a high amount. The obtained results show that the presented method can effectively achieve to an optimal solution.

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BIOGRAPHIES

Hossein Shayeghi received the B.S. and M.S.E. degrees in Electrical and Control Engineering in 1996 and 1998, respectively. He received his Ph.D. degree in Electrical Engineering from Iran University of Science and Technology, Tehran, Iran in 2006. Currently, he is a Full Professor in Technical Engineering Department of University of Mohaghegh Ardabili, Ardabil, Iran. His research interests are in the application of robust control, artificial intelligence and heuristic optimization methods to power system control design, operation and planning and power system restructuring. He has authored and co-authored of 5 books in Electrical Engineering area all in Farsi, one book and two book chapters in international publishers and more than 350 papers in international journals and conference proceedings. Also, he collaborates with several international journals as reviewer boards and works as editorial committee of three international journals. He has served on several other committees and panels in governmental, industrial, and technical conferences. He was selected as distinguished researcher of the University of Mohaghegh Ardabili several times. In 2007 and 2010 he was also elected as distinguished researcher in engineering field in Ardabil province of Iran. Furthermore, he has been included in the Thomson Reuters' list of the top one percent of most-cited technical Engineering scientists in 2015 and 2016, respectively. Also, he is a member of Iranian Association of Electrical and Electronic Engineers (IAEEE) and Senior member of IEEE.

Sajjad Asefi received B.Sc. degree in Electrical Engineering from Faculty of Technical Engineering, Guilan University, Rasht, Iran in 2015. Currently, he is a M.S.E. student in Technical Engineering Department, University of Mohaghegh Ardabili, Ardabil, Iran and head of Student Branch of Iranian Smart Grid Association in the same university. His areas of research are application of optimization and applying PSS in bulk power system, heuristic optimization in power system control and automatic generation control (AGC) of multi-source power system, power system reliability, demand side management, renewable energies and their application in power (especially distribution) system.

Elnaz Shahryari was born in Tabriz, Iran. She received the B.Sc. degree from University of Tabriz, Tabriz, Iran, in 2012 and the M.Sc. degree from University of Mohaghegh Ardabili, Ardabil, Iran, in 2014 both in Electrical Engineering. She is currently working toward the Ph.D. degree in Electrical Engineering at University of Mohaghegh Ardabili. Her research interests include modeling and analysis of distributed generations, power market, and control

Rashid Dadkhah Dolatabad received the B.S. degree in Electrical Engineering from Mazandarann University, Babol Branch, and the M.S.E. degree in Electrical Engineering from Ardabil Branch, Islamic Azad University, Ardabil, Iran. His research interest is power system operation.