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An application of LAPO: Optimal design of a stand alone hybrid system consisting of WTG/PV/diesel generator/battery

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Abstract. Given the recent surge of interest towards utilization of renewable distributed energy resources (DER), in particular in remote areas, this paper aims at designing an optimal hybrid system in order to supply loads of a village located in Esfarayen, North Khorasan, Iran. This paper illustrates the optimal design procedure of a standalone hybrid system which consists of Wind Turbine Generator (WTG), Photo Voltaic (PV), Diesel-generator, and Battery denoting as the Energy Storage System (ESS). The WTGs and PVs are considered as the main producers since the site's ambient conditions are suitable for such producers. Moreover, batteries are employed to smooth out the variable outputs of these renewable resources. To this end, whenever the available power generation is higher than the demanded amount, the excess energy will be stored in ESS to be injected into the system in the time of insufficient power generation. Since the stand-alone system is assumed to have no connection to the upstream network, it must be able to supply the loads without any load curtailment. In this regard, a Diesel-Generator can also be integrated to achieve zero loss of load. The optimal hybrid system design problem is a discrete optimization problem that is solved, here, by means of a recently-introduced meta-heuristic optimization algorithm known as Lightning Attachment Procedure Optimization (LAPO). The results are compared to those of some other methods and discussed in detail. The results also show that the total cost of the designed stand-alone system in 25 years is around 92 M€ which is much less than the grid-connected system with the total cost of 205M€. In summary, the obtained simulation results demonstrate the effectiveness of the utilized optimization algorithm in finding the best results, and the designed hybrid system in serving the remote loads.

Keywords: hybrid system; standalone; meta-heuristic optimization algorithm; renewable energy resources

1. Introduction

There is an increasing trend toward utilization of renewable energy resources since fossil fuels are running out and cause irreversible environmental damages(Wang and Nehrir 2008). Moreover,

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the transmission and distribution chain of energy is costly and may result in huge energy waste. Nowadays, power grids provide a dominant share of energy due to ease of transmission, distribution, and consumption. However, long-line transmission lines and interconnected distribution networks may cause several serious problems such as active power loss, power quality degradation, delivery issues, and reliability and stability concerns. These problems accompanied by some other issues, such as economic and technical limitations related to large power plants' construction, environmental pollution, and financial and energy crises, increase the interest of employing on-site generation. These types of generators are known as Distributed Energy Resources (DER) and installed at the lowest level of power grids, i.e., close to end consumers (Han *et al.* 2009).

Rural electrification is a controversial problem, since it is costly to serve such remote areas by means of the main power grid through long transmission lines with high power losses. To tackle this issue, micro-grids (MGs), as small scale power grids, are viable solutions in order to supply the electrical loads in remote areas. MGs facilitate the integration of renewable DERs and avoid the need for long transmission lines to connect the remote areas to the main grid (Abido 2003, Mostafaeipour *et al.* 2017, Mostafaeipour *et al.* 2017).

Generally speaking, MGs include a set of DERs (mainly renewable ones), an Energy Storage System (ESS), a backup generator, and loads, as depicted in Fig. 1. MGs may supply a residential building (Tasdighi *et al.* 2014), a commercial building (Wang *et al.* 2016), or even a village (Lampião *et al.* 2017, Puglia *et al.* 2017). Different kinds of resources, e.g., Combined Heat and Power (CHP), Wind Turbines Generation (WTG), and/or PV arrays, can be integrated into MGs in order to supply the power demands (Javadian and Haghifam, 2008b, 2008a). Those MGs that are close to the main grid can be connected to the upstream network and operate in two different operation modes, namely, grid-connected, and islanding. When a MG operates in grid-connected mode, power may be drawn from or injected into the main network. Due to some issues, such as major disturbances in upstream network, power quality and maintenance problems, the MG's operator may be obligated to disconnect it from the main grid to continue operating in islanding mode (Tamizkar *et al.* 2009, Demiroren and Yilmaz 2010).

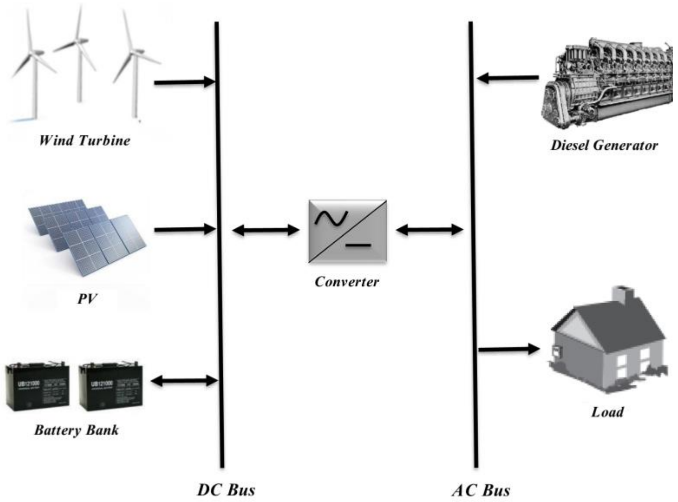

Fig. 1 Scheme of a micro-grid

Since remote areas' electrification is costly, standalone MGs have been considered widely in the recent decades (Li *et al.* 2015, Ma *et al.* 2015, Jing *et al.* 2018, Kaur *et al.* 2018, Liu *et al.* 2018, Parida and Chatterjee 2018). Furthermore, the integration of renewable energy resources can effectively reduce fossil fuel consumption and result in global warming reduction and its following consequences. Since Iran is a rich region in terms of renewable energies such as solar and wind (Rezaei and Ghofranfarid 2018), renewable DERs have attracted much attention in recent years in order to enhance power quality and system stability, and reduce the cost of transmission and distribution networks. However, the noticeable investment cost of these resources is still a barrier in their widespread utilization. Thus, in practical projects regarding DERs' integration and MGs' utilization, economic evaluation and optimization are required in the design phase.

Literature review

In (Ramli *et al.* 2018) the Multi-Objective Self-Adaptive Differential Evolution (MOSaDE) algorithm has been used to solve the problem of optimal design of a hybrid system consisting of PV, wind, diesel, and battery. In that paper, Loss of Power Supply Probability (LPSP), Cost of Electricity (COE), a Renewable Factor (RF) related to the cost of the hybrid system, and reliability, are considered as the objectives. The targeted system was supposed to supply the loads in the city of Yanbu, Saudi Arabia. In another work, a hybrid system is designed to electrify the city of Cujubim in Brazil (Noguera *et al.* 2018). The hybrid system included PVs, diesel generator, batteries, and also an Organic Rankine Cycle (ORC) which is used for heat recovery of the exhaust gases from the diesel-generator. That paper employed Particle Swarm Optimization (PSO) algorithm to solve the optimization problem. Mahmoudimehr and Shabani studied the optimal design of a hybrid photovoltaic-hydroelectric standalone system for coastal areas in north and south of Iran (Mahmoudimehr and Shabani 2018). A combined method, which is a combination of a straightforward quasi-steady operational strategy and the Genetic algorithm, has been employed for solving the optimization problem. A simulation-based meta-heuristic optimization approach has been proposed for the optimal design of hybrid systems for buildings in (Sharafi *et al.* 2015). The problem has been solved as a multi-objective optimization problem using PSO considering renewable energy ratio maximization, and total net present cost and CO2 emission minimization. In (Olatomiwa *et al.* 2015), different power generation schemes for a rural area in Nigeria have been investigated. The researchers obtained the optimal configuration among different other ones based on the cost of the system, fuel consumption, and also CO_2 emission. Two different hybrid systems, including (i): PV/Diesel/Battery, and (ii): PV/Wind/Diesel/Battery, have been analyzed techno-economically in (Olatomiwa *et al.* 2015). The obtained results revealed that the former was much better than the latter from economic and technical perspectives. In another work, a hybrid system for tourism sectors in the South China Sea, Malaysia (SCSM), has been proposed (Hossain *et al.* 2017). The results showed that the best hybrid system consists of PV, wind, diesel, converter, and battery. In the last three mentioned studies, the commercial Hybrid Optimization Model for Electric Renewable (HOMER) software is utilized. In order to deal with frequent load shedding of a grid-connected remote village, located in the east of Iran, the use of a hybrid PV/biomass/diesel system is investigated in (Kasaeian *et al.* 2019). In order to acculturate the renewable technology into Indian society by field-on-laboratory demonstration (FOLD), a hybrid nono-grid consists of PV/WTG/Battery has been designed in (Tudu *et al.* 2019). A negative emission hybrid renewable energy system is proposed in (Li *et al.* 2019). The system includes PV/WTG/Biomass with biochar production which could potentially provide energy generation, carbon sequestration, and waste treatment services within one system.

There are numerous attempts have been performed for the optimal design of hybrid systems in the literature (Shi *et al.* 2015, Maleki *et al.* 2016, Mehrpooya *et al.* 2016, Suchitra *et al.* 2016, Arikoglu 2017, Kaabeche *et al.* 2017, Moradi and Mehrpooya 2017, Khalilnejad *et al.* 2018, Wu *et al.* 2018). A comprehensive review in this area of research can be found in (Olatomiwa *et al.* 2016).

This paper aims at evaluating the potential of using renewable energy resources for sustainable and reliable power delivering to a village (Saremran) in Esfaryen, North Khorasan (northeastern of Iran), Iran. The geographical evaluation of this location reveals that the levels of solar irradiance and wind speed are acceptable. Hence, PVs and WTGs are considered as the main producers for a hybrid system to serve the loads of the village. A number of batteries as ESS and a diesel generator as a backup generator are also taken into consideration. This system is going to be designed in such a way that the cost of energy supply is minimized; while, the loads are fed fully secured without any load shedding and interruption. The costs of the system include the investment, operation, and maintenance. All the costs are real based on practical prices and the equipment is commercially available. The optimization problem is solved by means of a recently introduced optimization algorithm known as Lightning Attachment Procedure Optimization (LAPO) algorithm. The results, obtained by this method, are compared to those of some other methods in order to verify the achieved results.

In summary, the contribution of this paper is fourfold as follows:

1- A hybrid system is designed based on real environmental information.

2- Investment, operation, and maintenance costs are considered in the cost function.

3- The commercially available equipment is taken into account.

4- A recent meta-heuristic optimization algorithm is utilized.

The reminder of the paper is organized as follows: in Section 2, the problem is mathematically formulated. In Section 3, the methodology used for solving the optimization problem is illustrated. The simulation results are discussed in Section 4. Finally, the paper is concluded in Section 5.

2. Problem formulation

The main goal of this paper is to design a hybrid system in order to supply the load demands of a remote village. Generally speaking, there are two main solutions to supply such a village, either through the main grid or utilization of MGs. The former, as a conventional method, is to connect the village to the main grid and transmit the power from large power plants through high (or medium) voltage power transmission lines. The latter is to use a standalone MG (hybrid network) that can supply the load demands solely without any connection to the upstream network. Utilization of such a system has different merits, including but not limited to, 1- integration of renewable DERs, which are more environmentally friendly, 2- preventing the costs of long transmission lines and substations, and 3- removing the active power loss in transmission lines. However, such a system must be optimally designed to minimize the costs of investment, operation, and maintenance, and also assure serving the loads in all situations. Hence, the optimal design of this hybrid system is an optimization problem which is explained in the following.

2.1 Objective function

As mentioned earlier, the objective function is to minimize the cost of the hybrid system producers; while a secure power supply is guaranteed. Thus, the problem can be formulated as follows:

$$\begin{aligned} \min \quad & F = Cost(x) \\ S.T. \quad & h(x) \le 0 \\ & g(x) = 0 \end{aligned} \tag{1}$$

where x is the set of the decision variables, *Cost* is the total cost of the system, h is a set of inequality, and g is a set of equality constraints.

2.2 Cost of the system

The cost function encompasses the costs related to solar arrays, wind turbines, batteries, and diesel generators. There are three costs, including investment, operation, and maintenance, for each equipment. Thus, the cost functions can be presented as follows:

$$\begin{aligned} Cost = {} & N_{PV}\left(C_{PV}^{inv} + C_{PV}^{o\&m}\right) + N_{WTG}\left(C_{WTG}^{inv} + C_{WTG}^{o\&m}\right)) + \left(N_{BAT}\left(C_{BAT}^{inv} + C_{BAT}^{rep}\right)\right) \\ & + \left(N_{dg}\left(C_{dg}^{inv} + C_{dg}^{o\&m}\right)\right) \end{aligned} \tag{2}$$

where indices *PV, WTG, BAT*, and *dg* denote Photo Voltaic, Wind Turbine Generator, Battery, and Diesel Generator, respectively. Indices *inv, o&m,* and *rep* refer to investment, operation & maintenance, and replacement costs, respectively. *C* is the cost, and *N* is the number of apparatuses. The lifetime of WTGs, PVs, and diesel generators are considered to be 25 years. Thus, the initial costs per turbine, cell, and the diesel generator are paid once in 25 years, but the maintenance & operation costs are annual. The lifetime of the batteries is 8 years, accordingly, a replacement cost is also considered for the batteries (Wei *et al.* 2007).

According to the load demand and the ambient conditions, the generated power by the renewable DERs may be higher or lower than the power consumption. When extra power is available, it will be stored in the ESS to be discharged in case of insufficient generation. If the DERs accompanied by the ESS are not able to serve the loads, the backup system is employed. In order to obtain the optimal number of different apparatuses, the ability of the system in serving the loads must be checked for a whole year.

2.3 Instrument model

2.3.1 Photo voltaic

The active power generated by PV arrays is a function of the open circuit voltage, the short circuit current, and a fill factor as follow:

$$P_{md} = FF \times V_{oc} \times I_{sc} \tag{3}$$

where P_{md} is the PV output power, FF is the fill factor, V_{oc} is open circuit voltage, and I_{sc} is short circuit current, as follows:

$$I_{sc} = I_{Nsc}(G_a / G_N)^{C_3} \tag{4}$$

$$V_{oc} = \frac{V_{Noc}}{1 + C_2 \times ln\dfrac{G_N}{G_a}}\left(\frac{T_N}{T_a}\right)^{C_1} \tag{5}$$

$$\mathrm{FF}=\left(1-\frac{R_s}{\frac{V_{oc}}{I_{sc}}}\right)^{\frac{\frac{V_{oc}}{\frac{nKT}{q}}-\ln\left(\frac{V_{oc}}{\frac{nKT}{q}}+0.72\right)}{1+\frac{V_{oc}}{\frac{nKT}{q}}}} \tag{6}$$

$$P_{PV} = P_{md} \times N_s \times N_p \tag{7}$$

where G_N and G_a are nominal (in standard condition) and actual solar irradiance, respectively, T_N and T_a are nominal and actual ambient temperatures, respectively, V_{Noc} and I_{Nsc} are nominal open circuit voltage and short circuit current, R_s is the module resistance, C_1, C_2, and C_3 are three different constant coefficients that present the nonlinear relationship between solar irradiance and cell temperature and PV output, n is the density factor (n = 1.5), T is the temperature of the modulus PV (in Kelvin), K is Boltzmann's constant (1.38×10^{-23} J / K, and q is the charge of an electron $1.6{=}\times 10^{-19}$(Kayal and Chanda 2013).

2.3.2 Wind turbine

The amount of power, generated by WTGs, is a function of different parameters, e.g., wind speed and turbine characteristics. For wind speed lower than a critical value (cut-in), or higher than crucial value (cut-off), no power can be produced by WTGs. The power output of a WTG can be calculated using the following equations:

$$P_{WTG} = \begin{cases} 0 & V_w \le V_{cut-in} \\ \frac{1}{2} C_p(\lambda, V_w Vz\ \beta)\rho A V_w^3 & V_{cut-in} < V_w < V_{rated} \\ \mathrm{P}_{rated} & \mathrm{V}_{rated} \le V_w < V_{cut-off} \\ 0 & V_w \ge V_{cut-off} \end{cases} \tag{8}$$

$$\mathrm{P}_{rated} = \frac{1}{2} C_p(\lambda, \beta)\rho A V_{rated}^3 \tag{9}$$

where P_{WTG} is the power output of a WTG, V_w is the wind speed, V_{cut-in} is the cut-in speed, $V_{cut-off}$ is the cut-off speed, V_{rated} is the nominal wind speed for the WTG, and P_{rated} is the nominal power output of the WTG. ρ is the air density, and A is the area that is swept by the wind turbine's blades. C_p is the power coefficient of the turbine which is a characteristic of the WTG and is a function of β (blade pitch angle), and λ (the tip speed ratio). C_p can be calculated through field experiments and λ through following equation:

$$\lambda = \frac{r.\omega}{V_w} \tag{10}$$

where ω and r are the angular velocity and the radius of the wind turbine's blade, respectively.

2.3.3 Battery

Since the renewable DERs outputs fluctuate, an ESS is needed to smooth out their output by storing the excess power and compensating the power shortage. In this paper, batteries are considered as the ESS. There are multiple batteries connected in series and parallel to achieve the desired voltage and current, respectively. An important point related to battery charging and discharging is the state of charge (SOC), which must be kept within a desired range. The SOC of a set of batteries can be calculated as follows:

$$SOC(t+1) = SOC(t) + \frac{\left(P_{bat}(t) / V_{bus}\right) \times \Delta t \times \eta_{bat}}{C_n} \tag{11}$$

where SOC(t) is the state of charge of the batteries at time t, P_{bat} is the power which needs to be charged or discharged, Δt is the time step, η_{bat} is the battery efficiency that is considered to be 80% in charging period and 100% in discharging period, and C_n is the nominal capacity of total batteries. C_n can be calculated as follow:

$$C_n = \frac{N_{bat}}{n_s} C_{bat} \tag{12}$$

where N_{bat} is the total number of batteries, n_s is the batteries connected in series, and C_{bat} is the nominal capacity of a battery. n_s can be calculated as follow:

$$n_s = \frac{V_{bus}}{V_{bat}} \tag{13}$$

where V_{bus} is the bus voltage and V_{bat} is the output voltage of a battery. SOC must be kept between SOC_{min}, which is here considered to be 20%, and SOC_{max}, which is considered to be 100%. It should also be mentioned that the initial SOC is assumed to be 50%.

2.3.4 Diesel generator

A backup system is also needed to supply the load demands when the producers and ESS are not able to supply all the loads. Since diesel generators are fast in terms of start-up, they are commonly used as the backup system. The power output of a diesel generator can be calculated as follows:

$$P_{diesel} = \begin{cases} P_L - P_G - P_{batt} & if \;\; P_{diff} > 0 \\ 0 & if \;\; P_{diff} < 0 \end{cases} \tag{14}$$

$$P_{diff} = P_L - P_G - P_{batt} \tag{15}$$

where P_{diesel}, P_L, P_G, and P_{batt} are the diesel generator output, load demand, power produced by other producers, and power discharged from the ESS, respectively.

3. Solving methodology

3.1 LAPO

Lightning Attachment Procedure Optimization algorithm is a recently introduced method proposed by Foroughi et al. in 2017 (Nematollahi *et al.* 2017, 2018). The method is inspired by the nature of lightning downward movement and attachment to the ground. To reach the best global solution, this method mimics four important parts of the lightning attachment procedure, namely 1- emanating the lightning from the cloud, 2- downward movement of lightning channel, 3- upward leader formation and propagation from the ground or earthed objects, and 4- attachment of downward leader and upward leader (Foroughi *et al.* 2018).

A cloud's electrical charge is collected in three sections, including a large portion of positive charges at the top of the cloud, a large portion of negative charges accumulated at the bottom of the cloud, and a small positive charge at the bottom of the cloud. When the amount of electric charges increases, a breakdown may occur between huge or small positive and the huge negative charges. In this situation, the voltage gradient on the edge of the cloud increases and the lightning emanates from several points. Likewise, in the LAPO algorithm, a number of solutions are considered as the initial guess representing the lightning emanating points from the cloud. When the lightning goes down toward the ground, the opposite charges are congested on the sharp points on the ground and some upward leaders are also formed and move up as well. Several initial solutions are also considered to take into account the emanating points of the upward leaders. Thus, the initial guess is, in fact, the emanating points for downward and upward leaders. Based on the upper and lower boundaries, the initial guess ($X_{\text{testpoints}}$) are defined as follows:

$$X^{i}_{\text{testpoint}} = X^{i}_{\min} + (X^{i}_{\max} - X^{i}_{\min}) \times rand \tag{16}$$

where X_{min} and X_{max} are lower and upper bounds of variables; and *rand* is a random variable lies within the range of [0, 1]. The objective function is calculated for each solution to obtain the corresponding fitness value. In order to update the solutions, the fitness value of X_{ave}, i.e., the average of all solutions, is required. Mathematically,

$$X_{ave} = mean(X_{\text{testpoint}}) \tag{17}$$

$$F_{ave} = obj\,(X_{ave}) \tag{18}$$

To update the solution *i*, a random solution *j* is selected so that $i \neq j$. The fitness value of solution *j* (F_j) is compared to F_{ave}. Then,

If $F_j < F_{ave}$

$$X^{i}_{\text{testpoint\_new}} = X^{i}_{\text{testpoint}} + rand \times (Xave + rand \times (X^{j}_{\text{potential point}})) \tag{19}$$

If $F_{ave} < F_j$

$$X^{i}_{\text{testpoint\_new}} = X^{i}_{\text{testpoint}} - rand \times (Xave + rand \times (X^{j}_{\text{potential point}})) \tag{20}$$

Based on the comparisons, the solution *i* is updated via Eq. (19) or (20). Finally, if the new solution has better fitness value than the older one, it is kept; otherwise, it is discarded, as follows:

$$\begin{array}{ll} X^{i}_{\text{tetpoint}} = X^{i}_{\text{testpoint\_new}} & if \;\; F^{i}_{\text{testpoint\_new}} < F^{i}_{\text{tetpoint}} \\ X^{i}_{\text{testpoint\_new}} = X^{i}_{\text{tetpoint}} & otherwise \end{array} \tag{21}$$

Solutions are also updated in another phase based on upward leader modeling. To do so, an exponent factor is defined as follows:

$$S = 1 - \left(\frac{t}{t_{\max}}\right) \times \exp\left(-\frac{t}{t_{\max}}\right) \tag{22}$$

where *t* and t_{max} are the current iteration and the maximum number of iterations, respectively. The updating process in this phase is as follows:

$$X_{\text{testpoint\_new}} = X_{\text{testpoint\_new}} + rand \times S \times (X_{\min} - X_{\max}) \tag{23}$$

where X_{min} and X_{max} are the best and the worst solutions in the population, respectively. In order to enhance the performance of the LAPO algorithm, in each iteration, the average of the whole population and the corresponding fitness value, are calculated. If the fitness value of the worst solution is worse than the average one, it is replaced by the average solution. In other words, the worse solution is updated in each iteration to expedite the convergence of the algorithm.

3.2 Solving algorithm

In this section, the stepwise algorithm of the hybrid system optimal design is illustrated. The step by step algorithm is as follows:

- Step 1: in the very first step, the required parameters are defined. These parameters include load profile, wind speed, solar irradiance, temperature, producers' limitation, the maximum and the minimum number of devices which can be employed, cost functions of different apparatuses, technical characteristics of different devices, the minimum charge of the storage system, etc.
- Step 2: in this step, the parameters needed for the optimization algorithm including the number of variables, the size of the population, the total number of iterations, the upper and lower bounds of variables, etc., are defined.
- Step 3: random variables are generated based on the variables' boundaries and the size of the population.
- Step 4: fitness value for each solution is calculated as follows:
- Step 4.1.: For i_S = 1: N_S (N_s: number of total solution, i.e., the size of the population)
- Step 4.2.: For i_h = 1:24 (number of hours in a day)
- Step 4.3.: For i_d = 1:365 (number of days in a year)
- Step 4.4: calculate the total power output of WTG(s), PV(s), and consequently P_g, based on the hourly detail of wind speed, solar irradiance, temperature, and the number of apparatuses considered in the solution.
- Step 4.5: if P_g is equal to P_d (power demand), the load is supplied; otherwise,
    a. If P_g is higher than P_d, the ESS is charged
    b. Otherwise, the ESS is discharged.
- Step 4.6.: if the ESS needs to be discharged, and the power available in the ESS is lower than the required power, the ESS is discharged to SOC_{min}, and the remaining required power is supplied by means of diesel generator (P_{diesel}).
- Step 4.7.: if P_{diesel} is higher than, or lower than 20% of, the maximum power of diesel generator a penalty factor turned to be 1.
- End
- End
- Step 4.8.: the total cost of the solution is calculated. If the penalty factor is 1, a big value is added to the cost of the solution.
- End
- Step 5: if the convergence criterion is satisfied, go to Step 7, otherwise go to next step.
- Step 6: Update the solutions based on the LAPO algorithm, then go to Step 4.

- Step 7: Stop the algorithm.

The flowchart of algorithm is depicted in Fig. 2.

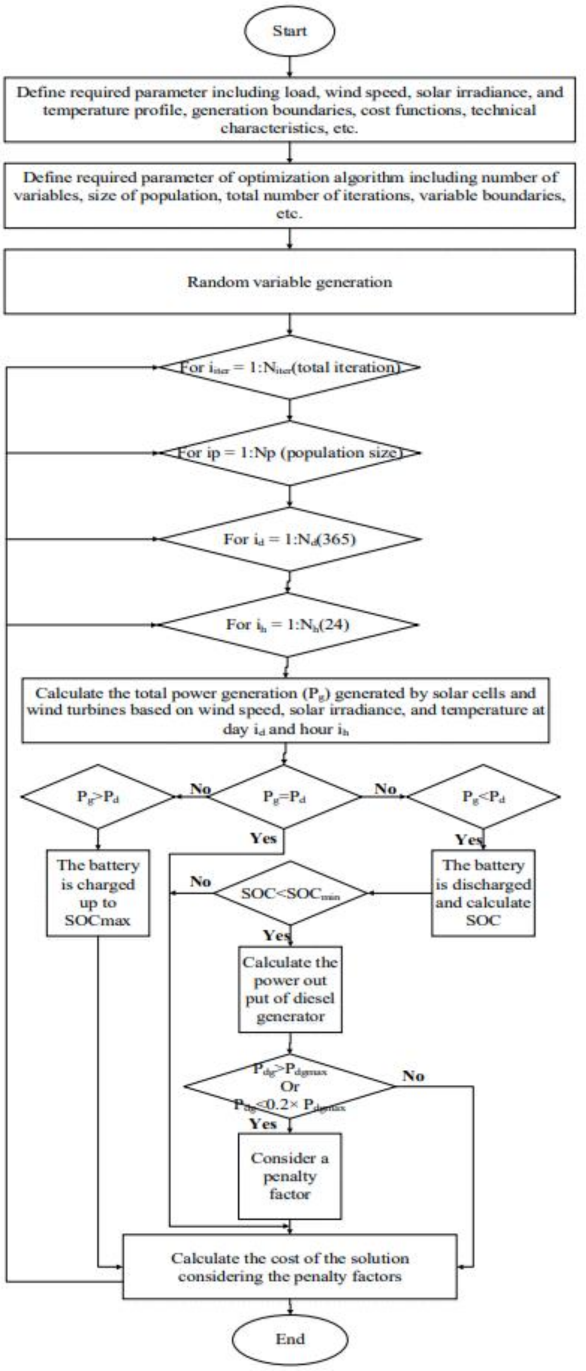

Fig. 2 Flowchart of algorithm for solving optimal system design problem

4. Simulation results

In this section, a hybrid system for electrification of a village in Esfarayen, North Khorasan Iran, is optimally obtained. The targeted system is going to supply the electrical loads in all situations without any connection to the main grid. Three different types of DERs, including PV and WTG (main producers), and diesel generator (backup) are considered. In addition, batteries, as the ESS, are also factored in. The main objective of this work is to decide the optimal number of each device in order to feed the loads during a year with the minimum system cost.

First of all, the ambient conditions of the under-study site should be investigated to find the best system for supplying the load demands. To this end, the profiles of solar irradiance, wind speed, and temperature are received from the North Khorasan Meteorological Organization, where the mean values are depicted in Figs. 3-5. The yearly load profile of the village is also shown in Fig. 6.

To solve the optimization problem of system design, the LAPO algorithm is employed and the final results are compared to those of some other methods, namely, Teaching-Learning-Based Optimization (TLBO) algorithm, Grey Wolf Optimizer (GWO), Artificial Bee Colony (ABC), and Particle Swarm Optimization (PSO) algorithm.

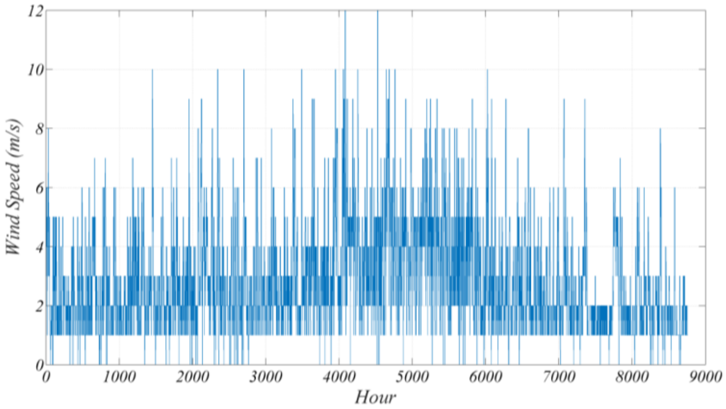

Fig. 3 Mean yearly wind speed in Esfarayen, North-/khorasan, Iran

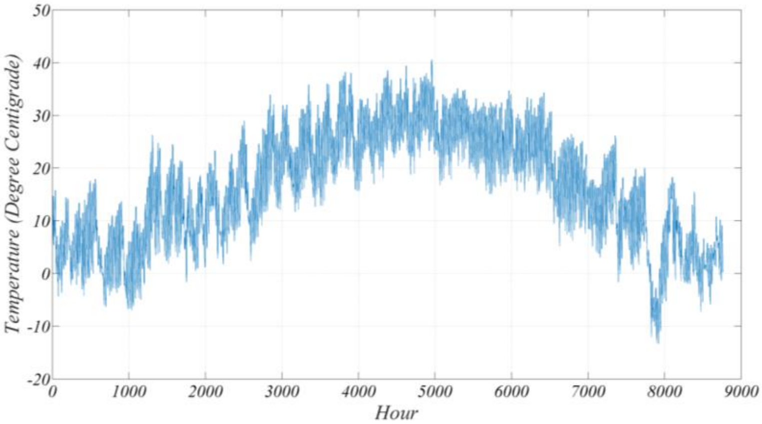

Fig. 4 Mean yearly temperature in Esfarayen, North-/khorasan, Iran

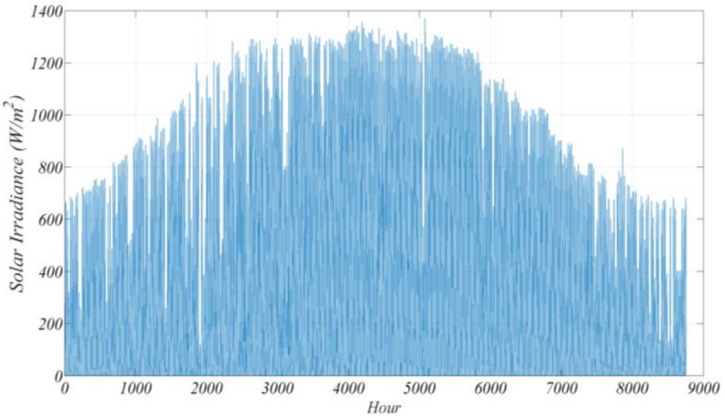

Fig. 5 Mean yearly solar irradiance in Esfarayen, North-/khorasan, Iran

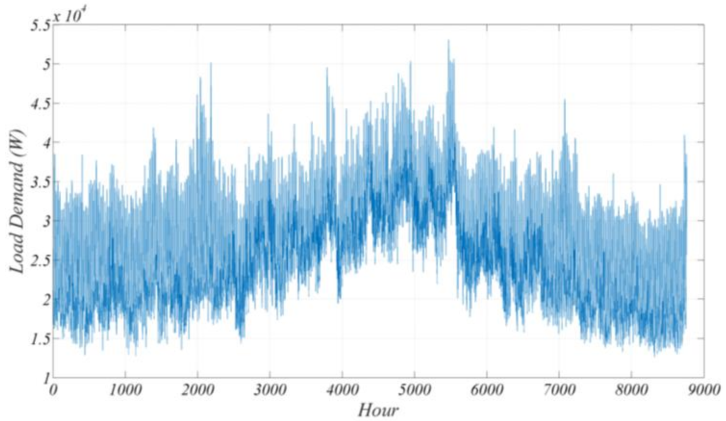

Fig. 6 Mean yearly load profile of the village under study

Table 1 Technical characteristics of solar cell (Koutroulis *et al.* 2006)

Life time (year)	Cost of maintenance and repair (€/year)	Investment cost (€/w)	P_{max}(W)	I_{max}(A)	V_{max}(V)	I_{SC}(A)	V_{oc}(V)
25	5.19	519.14	100	5.73	17	6.5	21

Table 2 Technical characteristics of wind turbine (Koutroulis *et al.* 2006)

Life time (year)	Cost of maintenance and repair (€/year)	Investment cost (€/kw)	Cut-of-Speed(m/s)	Cut-in-Speed(m/s)	Rated Speed(m/s)	Rated Power(W)
25	16.81	1681	28	3	12	5000

Table 3 Technical characteristics of diesel generator (Dufo-López and Bernal-Agustín 2008)

Life time (year)	Cost of maintenance, repair, and operation (€/year)	Investment cost (€/kw)	Rated Power(VA)
25	0.24	2800	7000

Table 4 Technical characteristics of battery (Koutroulis *et al.* 2006)

Life time (year)	Cost of maintenance and repair (€/year)	Investment cost (€/kAh)	Replacement cost (€/kAh)	Charging Efficiency (%)	Voltage(V)	Rated Capacity(Ah)
8	1.26	2268	1260	90	24	100

Table 5 Parameter of solar cell simulation (Wei *et al.* 2007)

Rs(Ω)	C3	C2	C1	Item
0.012	1.21	0.058	1.15	Value

The characteristics of the PV, WTG, diesel generator, and ESS, used in this work, are listed in Tables 1 to 4. The parameters, needed for PV simulation, are also listed in Table 5.

The final results of the system design, obtained by the LAPO algorithm, are shown in Table 6. As can be seen, a major portion of loads is supplied by WTGs, due to low investment & maintenance cost per each W, as well as appropriate conditions for wind power generation. The location has also adequate solar irradiance; however, high investment and maintenance costs per each W for PVs reduce the number of PVs. Based on the geographical details, for many hours during a year, renewable DERs are not able to produce any power. Thus, high numbers of batteries need to be employed to supply the load demands during the hours with insufficient power generation. An important point is that the optimization method obtained no diesel generator for such a system.

When there is no power generation by the producers, batteries supply the load demands. However, if there is no power generation and the batteries' SOCs are in their minimum, diesel generators can start power generation and supply the loads. In fact, a diesel generator is employed as a backup system to supply the load when both the renewable producers and ESS are not able to supply the load demands. However, the diesel generator must be utilized optimally. Regarding this, in this paper, it is considered that whenever a diesel generator needs to be turned on, it should generate at least 20% of its rated power.

For the system under study, when a diesel generator is added to the hybrid system, there would be some situations where the diesel generators must generate lesser than 20% of its rated power. This situation even occurs when the limitation is decreased to 10% of rated power. Thus, zero number is obtained for diesel generators. In another investigation, the Loss of Load (LOL) is taken into consideration. In this situation, up to 10% of the total annual load demand is allowed to be interrupted during a year. However, no big difference occurs. Thus, it can be concluded that for the village under study, no diesel generator is needed.

Table 6 Final decision for the stand-alone hybrid system obtained by LAPO

Device	Rated Power	Investment Cost	Replacement Cost	Maintenance Cost	Life Time (Year)	Number of Devices	Total Cost in 25 years
WTG	5000 W	1681 €	-	16.81 (€/year)	25	23	92659.71 €
PV	100 W	519.14 €	-	5.19 (€/year)	25	25	
Battery	100 Ah	226.8 €	126 €	1.26 (€/year)	8	71	
Diesel Generator	7000 VA	2800 €	-	0.24 (€/kwh)	25	0	

Table 7 The costs of standalone system compared to two other scenarios

	Stand-Alone	Scenario 2	Scenario 3
Cost of energy purchased from the grid	0 (€/year)	7110 (€/year)	7110 (€/year)
Maintenance and replacement Cost	645(€/year)	300(€/year)	300(€/year)
Investment Cost of equipment	76686 €	0 €	30000 €
Total Cost in 25 years	92659.71 €	185250 €	215250 €

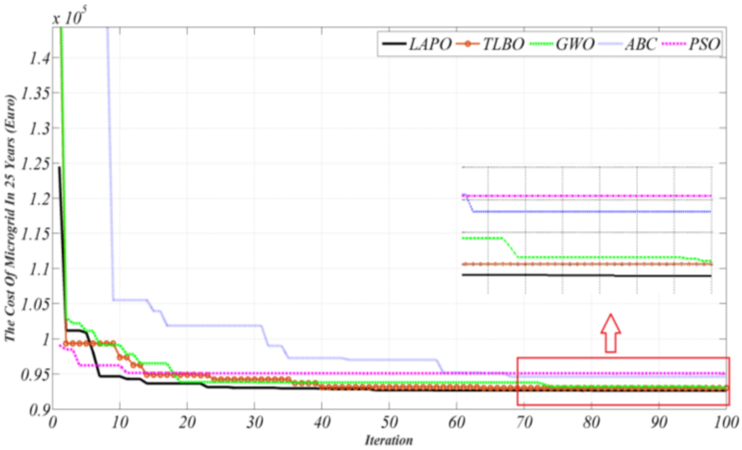

Fig. 7 Convergence behaviors of different methods

In order to show whether the system is optimal, different costs corresponding to the system for different scenarios are compared in Table 7. The scenarios are as follows: *Scenario 1*: is the stand-alone hybrid system obtained by the LAPO algorithm, *Scenario 2* is the case when the system is connected to the upstream network and the costs of the purchasing energy and network maintenance are taken into account, *Scenario 3*: is the case when the system is connected to the main grid and in addition to the costs of purchased energy from the upstream network and the maintenance, the cost of feeder construction is also considered. The price of energy is assumed to be 0.04 €/kwh. From the results in Table 7, it can be inferred that the investment and maintenance costs of a standalone system are much higher compared to two other scenarios. However, in a standalone system, the cost of produced energy is zero, whereas, in the second and third scenarios, the annual cost of purchasing energy from the upstream network is 7110 €. As the 25-year total cost of each scenario illustrates, the stand-alone system is more efficient than two other systems. This is due to the suitability of ambient conditions for the installation and utilization of renewable DERs in the village.

In order to ensure the obtained results, the convergence behavior of LAPO is compared to those of some other methods in Fig. 7. As one can see, the best performance belongs to the LAPO algorithm, which is suggested for solving the problem of the optimal hybrid system design in this paper.

5. Conclusions

Optimal design of a hybrid system consisting of WTG/PV/ Battery is discussed in this paper.

Such a system is designed to supply a remote village in Esfarayen, North Khorasan, Iran. In the design system process, investment, operation, and maintenance costs of DERs are taken into consideration. A diesel generator is also factored in as a backup system. It is assumed that the diesel generator must generate at least more than 20% of its rated power whenever it is needed. Given this constraint, no diesel generator is required for the hybrid system based on the results of the optimization algorithm. The overall costs of the designed stand-alone system are compared to those of two other scenarios (both connected to the main grid). The results reveal that the stand-alone system is much more efficient than the scenarios where the village is connected to the main grid. The Lightning Attachment Procedure Optimization (LAPO) algorithm is suggested for solving the problem of optimal hybrid system design and the results are compared to those of some other methods. The effectiveness of the suggested algorithm is concluded from the comparisons.

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