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New Computing Method for Techno-Economic Analysis of the Photovoltaic Water Pumping System Using Fuzzy based NSGAII Optimization Approach

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Original scientific paper

This paper presents an optimization of photovoltaic water pumping system (PWPS) considering the reliability criteria and economic aspects. In this way loss of load probability (LLP) as reliability criteria and life cycle cost (LCC) as economic criteria are used to simulate the performance of the PWPS. The sizing of a photovoltaic pumping system means the sizing of the photovoltaic module numbers and water tank storage capacity in terms of storage days. In the proposed algorithm, an external archive of non-dominated solution is kept which is updated during iteration. In addition, for preserving the diversity in the archive of Pareto solutions, the crowding distance operator is used. This attribute gives more flexibility to the planner for choosing the best final scheme among the obtained solutions. Of course in order to decision making, a fuzzy based NSGAII method is applied in this paper to select the favored solution among non-dominated solutions.

Key words: Solar Energy, Photovoltaic Pumping Water, Loss of Load Probability, Life Cycle Cost, Fuzzy Based NSGAII

Nova računalna metoda za tehno-ekonomsku analizu sustava fotonaponom napajane vodene pumpe bazirano na neizrazitoj logici. U radu je predstavljen optimizacijski problem upravljanja sustavom fotonaponom napajane vodene pumpe (FNVP) koji uzima u obzir kriterij pouzdanosti i ekonomski aspekt. Tako su vjerojatnost gubitka snage kao kriterij pouzdanosti i cijena životnog ciklusa kao ekonomski kriterij odabrani za simulaciju rada FNVP sustava. Dimenzioniranje FNVP sustava svodi se na dimenzioniranje broja fotonaponskih modula i kapaciteta spremnika vode u smislu dana opskrbe vodom. U predloženom algoritmu, nedominantna (Pareto optimalna) rješenja se pohranjuju u eksternu bazu i ažuriraju u svakoj iteraciji. Dodatno, za očuvanje raznolikosti baze Pareto rješenja koristi se *crowding distance* operator. Ta karakteristika daje veću fleksibilnost projektantu u odabiru najboljih parametara sustava među dobivenim rješenjima. S ciljem odabira jedinstvenog rješenja u skupu nedominantnih rješenja u radu je korišten genetski algoritam sortiranja nedominantnih rješenja.

Ključne riječi: energija sunca, fotonaponom napajana vodena pumpa, vjerojatnost gubitka snage, cijena životnog ciklusa, NSGAII baziran na neizrazitoj logici

1 INTRODUCTION

The water availability and accessibility are two main factors in the development of rural and remote areas in developing countries which generally composed by numerous villages and farmers.

Due to decrease the rain fall in many arid zones, ground water seems to be the only alternative to this dilemma, so the utilization of water pumping systems will become the only solution for lifting water from the ground. The widely utilization of water pump system for irrigation applications and on the other hand with attention of scarcity of fossil resources used in traditional water pumping systems and with attention to prices' rise and their undesirable environmental impacts, it seems emergency to replace this with new energy sources. A recently proposed solution to this problem is the use of renewable energy sources (RES) including solar energy [1-2], wind energy [3], biomass sources [4] and hybrid forms of energy [5-6] to power water pumping systems.

Iran is blessed with much solar energy resources and so encouraged to be utilized for water pumping. Thus, the photovoltaic water pumping systems (PWPSs) are very appropriate to use because of the availability of solar energy and water in the no deep underground sheet. Water pumping systems and renewable energy resources optimization has been investigated by many researchers. Wade and Short in [7] presented the optimization of a linear actuator to use in a solar powered water pump. They presented both development of a new solar powered water pump and the optimization design process used in the creation of the pump. In another research, authors presented a method for estimating the loss-of-load probability (LLP) of a photovoltaic water pumping system [8]. The study has been carried out for constant profile, using a tank with a two day autonomy capacity and two pumping heads applied to a centrifugal pump [9-10]. The economical aspects have not been considered in their researches. Mathematic models of photovoltaic motor pump systems has been derived and analyzed by [11]. The performances are calculated using the measured meteorological data of different sites located in Sahara and coastline regions of Algeria.

With information available on the solar irradiation, pump and characteristics of photovoltaic arrays, the best pump and photovoltaic could be selected for the application, therefore the aim of this research is to studying the possible application of solar energy to support electrical power needed by water pump systems in remote-rural of Iran.

This paper deals with a multi-objective optimization problem with conflicting objectives aims that try to find the best compromise tradeoffs among the feasible solutions in the search space. Of course in order to decision making, a fuzzy based method is applied in this paper to select the favored solution among non-dominated solutions. Through fuzzy set theory, a linear membership function assigned for each objective function. Due to nature of this optimization problem the non-dominated sorting genetic algorithm (NSGAII) has been implemented.

2 PHOTOVOLTAIC WATER PUMPING SYSTEM – PWPS

Figure 1 shows the topology of solar energy powered water pump used for irrigation and drinking purposes for rural communities of south area of Iran.

The presented system is consisted of an array consists of photovoltaic panels, An inverter DC/AC, a pump unit, whose characteristics depend on those of the water source and a structure for supporting the PV array.

3 MATHEMATICAL MODEL OF PV

Output electric power from the photovoltaic generator is given by the following equation [12]:

$$P_{pv} = \eta_{pv} A_{pv} I_r, \tag{1}$$

Where $\eta_{pv}$is the power conversion efficiency of the module (power output from system divided by power input from sun); $A_{pv}(m^2)$is the surface area of PV panels; $I_r(W/m^2)$is the solar radiance.

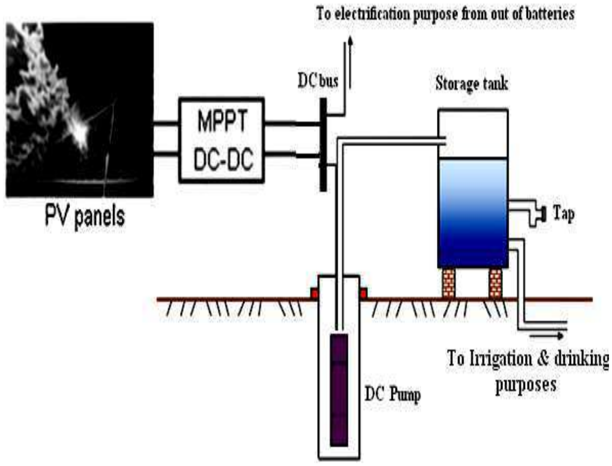

Fig. 1. Block diagram of a stand-alone photovoltaic water pumping system

For sizing optimization procedure, effective area of photovoltaic generator (A_{pv}) is defined as decision variable if A_{pv} is measured in m^2, P_{pv} is numerically equal to peak power rating of the array.

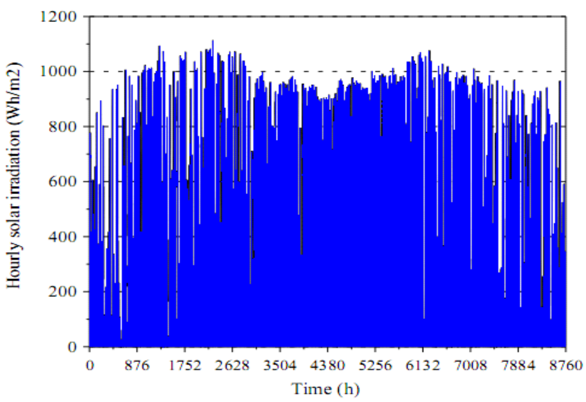

Fig. 2. Hourly values of meteorological parameters-solar irradiation on titled plane

4 PUMPING SUBSYSTEMS MODEL

In this paper, a mathematical model which directly links the output water flow rate *Q* versus the input operating electric power *Pa* and total head *h* is used. This model is based on the analysis of the experimental results of two types of pumping subsystems [13]. This model is presented as follows:

$$P_a(Q,h) = a(h)Q^3 + b(h)Q^2 + c(h)Q + d(h), \tag{2}$$

where *a(h)*, *b(h)*, *c(h)* and *d(h)* depend on total head and can be described by the following equations:

$$a(h) = a_0 + a_1 h + a_2 h^2 + a_3 h^3 \tag{3}$$
$$b(h) = b_0 + b_1 h + b_2 h^2 + b_3 h^3 \tag{4}$$
$$c(h) = c_0 + c_1 h + c_2 h^2 + c_3 h^3 \tag{5}$$
$$d(h) = d_0 + d_1 h + d_2 h^2 + d_3 h^3 \tag{6}$$

5 WATER STORAGE TANK MODEL

Water storage tank is sized to meet the load demand during non-availability period of renewable energy source, commonly referred to as days of autonomy. Depending on the photovoltaic cells production and the load requirements, the state of charge (*SOC*) of water storage tank can be calculated from the following equations [14]:

Water storage tank charging,

$$SOC(t) = SOC(t-1) + \left[E_{WT}(t) - \frac{E_L(t)}{\eta_{conv}}\right]\eta_{tank} \tag{7}$$

Water storage tank discharging,

$$SOC(t) = SOC(t-1) - \left[\frac{E_L(t)}{E_L(t)}\eta_{conv} - E_{WT}(t)\right]\eta_{tank}, \tag{8}$$

where *SOC(t)* and *SOC(t -1)*are the states of charge of water storage tank *(*Wh*)* at the time *t* and *t-1*,respectively; $E_{WT}(t)$ is the total energy generated by PV arrays (Wh); $E_L(t)$ is the energy hydraulic demand at the time *t* (Wh); η_{conv} and η_{tank} are the conversion efficiency and charge efficiency of water storage tank, respectively.

η_{tank} is taken equal to 1. Also the η_{conv} in this study is considered as a constant parameter and is taken equal to 0.95.

At any time ***t***, the charged quantity of the water storage tank is subject to the following constraints:

$$SOC(t) \le SOC_{\max} \tag{9}$$
$$0 \le SOC(t) \tag{10}$$

6 OBJECTIVE FUNCTIONS FORMULATION

Two objective functions have been considered for the PWPS optimization problem as follows:

1. Reliability requirements: minimizing loss of load probability (LLP)

2. Cost considerations: minimizing Life Cycle Cost (LCC)

6.1 Reliability requirements: minimizing loss of load probability

In this work, we adopted the load losses probability method to the solar energy pumping systems with a similarity between the electrochemical storage batteries and the water storage in tanks. Thus, the *LLP* is defined as the ratio between the water deficit and the total requirement of water. The sizing of a solar energy pumping system means the sizing of the PV arrays and the water tank. This way, the PV modules capacity, *CA* is defined as the ratio between the volume of pumped water Q_v and the average daily consumption of water D_{av}. The capacity of storage, C_S is the ratio between the useful capacity of the tank, C_{UT} and the average daily consumption of water. The equations are given by [12]:

$$C_A = \frac{Q_v}{D_{av}} \tag{11}$$
$$C_S = \frac{C_{UT}}{D_{av}} \tag{12}$$

With

$$Q_v = E_{pv} E_{sub} A_G \frac{H_{inc}(0)}{2.72\, h C_{UT}} \tag{13}$$

where E_{pv} and A_G are, respectively, the efficiency and the area of the photovoltaic array, E_{sub} is the subsystem efficiency, $H_{inc}(0)$ is the average of the daily global solar radiation received on the photovoltaic array.

The PV array efficiency, E_{pv} is the ratio between the operating electrical power and the solar power received on the total surface of the PV modules.

E_{sub} is the pumping subsystem efficiency and is defined as the ratio between the hydraulic power of the pump and the operating electrical power of the subsystem.

If the tank is completely full at the end of the day j, then its state of filling, *STF (j)*, is equal to 1. Otherwise at the end of the day ***j***, the filling state of the tank is given by the following relationship [12]:

$$\begin{aligned} SFT(j) = \min\{&SFT(j-1) + \dots \\ &\dots + E_{pv} E_{sub} A_G \frac{H_{inc}(j)}{2.72 h C_{UT}}; 1\Big\} \end{aligned} \tag{14}$$

With

$$0 \le SFT(j) \le 1 \tag{15}$$

In the case, where the stocked and pumped water is inferior to the water requirement, the volume of lacking water is accounted at the end of the day ***j***.

$$SFT(j) \ge (\frac{1}{C_S}) \Rightarrow Q_{lac}(j) = 0 \tag{16}$$

$$SFT(j) < (\frac{1}{C_S}) \Rightarrow Q_{lac}(j) = (1 - SFT(j)) D_{av} C_S \tag{17}$$

In (16) and (17) $Q_{lac}(j)$ is the volume of lacking water in the day *j*. The *LLP* corresponding to the solar energy water pumping system is given by:

$$LLP = \frac{\sum_j Q_{lac}(j)}{N_j D_{av}} \tag{18}$$

where N_j is the number of operating days.

So the first objective function that must be minimized is determined as follows:

$$f_1 = \min\left(\frac{\sum_j Q_{lac}(j)}{N_j D_{av}}\right). \tag{19}$$

6.2 Cost considerations: minimizing Life Cycle Cost

Life cycle cost of a pumping system can be calculated using the following equation:

$$LCC = C_{inv} + C_{maint} + C_{remp} \tag{20}$$

Financial expenses (C_{inv}) a system include the initial capital expenditure, design and installation of system. This cost is still considered payment occurring in the initial year of installing the system or by annuities. The maintenance costs (C_{maint}), is the sum of all costs annually scheduled. The replacement costs (C_{rempl}) is the sum of all costs of replacing equipment provided during the life cycle of the system occurs only in specific years.

6.2.1 Initial costs

The financial costs (C_{inv}) of a system include the initial capital expenditure for equipment, design and installation of the system.

6.2.2 Maintenance costs

Maintenance costs also some recurrent costs, are usually specified as a percentage of the cost of initial capital.

All costs are subject to an annual inflation rate (e_0) and a discount rate (d). Maintenance costs are expressed as follows:

$$C_{maint} = \mathrm{M}_0\left(\frac{1+e_0}{d-e_0}\right)\left[1-\left(\frac{1+e_0}{1+d}\right)^{nv}\right] \tag{21}$$

$$C_{maint} = \mathrm{M}_0 N \quad if \quad d = e_0 \tag{22}$$

M_0 is the operating and maintenance cost during the first year, n_v is the life of pumping system.

Table 1. The costs and life time aspect for the system components

Component	P.V	DC motor	Water tank	Conv.
Unit price (DA/W)	280	200	35000	45
Maintenance cost in the first year %	3 % of price	3 % of price	1 % of price	1 % of price
Life time (year)	25	10	25	10
Real interest rate	8	–	–	–
Inflation Rate	4	–	–	–

6.2.3 Replacement costs

The replacement cost of each component of the system is given by the following equation [15-16].

$$C_{remp} = C_u \sum_{j=1}^{n}\left(\frac{1+e_1}{1+d}\right)^{((n_v j)/(n+1))} \tag{23}$$

Where C_u is the unit cost of component replacement, e_1 is the inflation rate cost of replacement components, n is the number of replacing on the life cycle.

The following unit price, maintenance cost and lifetime of each component (PV arrays, motor pump set, water storage tank and converter) in this study are assumed as listed in Table 1.

Therefore the second objective function is considered as follows:

$$f_2 = \min\left\{C_{inv} + C_{maint} + C_{remp}\right\}. \tag{24}$$

Because of implementation of DC motor in this research, the DC/DC boost converter is used and the economic parameters of this component is listed in Table 1 and in order to investigate the effect of long term additional cost of DC/DC converter the maintenance cost in the first year % and life time (year) are considered in this optimization and simulation and therefore the tank water capacity versus number of storage days is investigated as output result in Table 6.

7 PRINCIPLES OF MULTI-OBJECTIVE OPTIMIZATION

Multi-objective optimization problems with conflicting objectives may not hold just one solution, and in the most cases there is a number of solutions without an absolute preference amongst them. Hence, a multi-objective optimization problem with conflicting objectives aims to find the best compromise trade-offs among the feasible solutions in the search space. These kinds of solutions are known as non-dominated solutions or Pareto solutions.

The set of non-dominated solutions or Pareto solutions, construct the Pareto front or front of non-dominated solutions. This set provides a number of options for decision makers to choose the best option with regard to the other quantitative or qualitative parameters. In general, a multi-objective optimization problem can be formulized as follows:

$$\min_{x\in X^{n_x}} \quad \mathrm{f(x)} = \left\{ \ \mathrm{f_1(x)} \quad \mathrm{f_2(x)} \quad ,..., \quad \mathrm{f_M(x)} \ \right\} \tag{25}$$

$$g(x) \leq 0\,,\ h(x) = 0 \tag{26}$$

where $g(x) \leq 0$, $h(x) = 0$, are the sets of the problem constraints that determine the boundaries of the feasible solution space in n_X dimensional search space, and f(x) is an M dimensional vector of objective values. A map between decision variables of $x \in X^{Nx}$ and objective space of $f \in F^M$ is determined by objective functions.

8 NSGAII ALGORITHM WITH STORAGE TANK

The computational algorithm of NSGA-II is used to address the PWPS problem through the following steps:

Step 1 Initialization. In this step a population is generated randomly in the search space as initial solutions of the algorithm.

Step 2 objective evaluations. For each individual of the population, the values of objective functions are evaluated in this section.

Step 3 Non-dominated sorting. The NSGA-II algorithm sorts a population into distinctive non-dominated levels (fronts). Initially, it achieves the Pareto optimal set of the present population (RANK = 1), then it disregards temporarily these solutions and search again the Pareto optimal set among the residual individuals of the population (RANK = 2). This procedure is repeated until all fronts are recognized and allocated to all individuals. This attribute is one of the two features that illustrate the fitness of the solutions. The second feature is crowding distance.

Step 4 Crowding distance. After completing the non-dominated sorting, the crowding distance is applied to sort the individuals in the same front.

In order to estimate the density of solutions neighboring the i^{th} individual in each non-dominated set, the average normalized distances of the two adjacent neighbors for each objective function are calculated and summed all together, as follows [17]:

$$CD(X_i) = \sum_{j=1}^{m} \left| \frac{f_j(X_{i+1}) - f_j(X_{i-1})}{f_j^{\max} - f_j^{\min}} \right| . \tag{27}$$

Where $CD(X_i)$is the overall crowding distance of solution X_i, ***m*** is the number of objective functions, $f_j(X_{i+1}), f_j(X_{i-1})arej^{th}$objective function values of the two nearest neighbors of the i^{th}individual,$f_j^{\max}, f_j^{\min}$ are the maximum and minimum values of j^{th}objective function.

Step 5 Selection. The binary tournament based selection carried out between two randomly chosen individuals from the population.

Step 6 Cross-over.

Step 7 Mutation

The above procedure except Step 1 is repeated for the maximum number of iterations. Fig.3 shows the NSGAII algorithm's flowchart.

In order to decision making, a fuzzy based method is applied in this paper to select the favored solution among non-dominated solutions. Through fuzzy set theory, a linear membership function assigned for each objective function Eq. (28) and (29) are used respectively, for normalizing monotonically decreasing and increasing objective functions [18].

$$\mu_i^k = \frac{f_i^{\max} - f_i^k}{f_i^{\max} - f_i^{\min}} \tag{28}$$

$$\mu_i^k = \frac{f_i^k - f_i^{\min}}{f_i^{\max} - f_i^{\min}} \tag{29}$$

$f_i^{\max}$, $f_i^{\min}$ are the maximum and minimum values of **ith** objective function.

Mathematically, none of the solutions in the trade-off region has a priority with respect to other solutions. Due to the subjective imprecise nature of the decision maker's judgment, a fuzzy satisfying method is applied here to select the preferred solution among non-dominated solutions. Through fuzzy set theory, each objective function is presented with a linear membership function.

If the objective function is monotonically decreasing, Eq. (28) is used for normalizing vice versa if the objective function is monotonically increasing Eq. (29) is applied.

The normalized membership function of the kth non-dominated solution is defined as follows:

$$\mu^k = \frac{\sum_{i=1}^{m} \mu_i^k}{\sum_{k=1}^{N_p} \sum_{i=1}^{m} \mu_i^k}, \tag{30}$$

where N_p is number of non-dominated solutions and m is number of objective functions.

The solution with the maximum membership value is selected as the best compromising solution.

Of course in order to decision making, a fuzzy based method is applied in this paper to select the favored solution among non-dominated solutions. Through fuzzy set theory, a linear membership function assigned for each objective function.

9 SIMULATION AND RESULTS

The technical characteristics of the PV modules and motor pump are listed in Tables 2 and 3. The load profile is assumed to be constant with a total daily requirement of $56\ m^3$ of water

Table 2. Specifications of the photovoltaic array used in this study

Voc [V]	Isc [A]	Vmx[V]	Imax[A]	Pmax [W]
21.7	3.4	17.4	3.16	55

Since solar energy, derives from the sun, is available only during the day and varies as the sun follows its daily and yearly cycles, as well as being affected by cloud cover. The solar power is assumed to be constant during the time step (1 hour in this study). Table 4 lists the parameters of the NSGA-II algorithm.

Table 3. Specifications of the motor pump used in this study

Motor	Rated power (W)	Range Voltage (V)	Maximum Current (A)
DC	400	0-48	13

Table 4. Parameters of the NSGA-II algorithm

Max_Iter	Population Size	Crossover Rate	Mutation Rate
250	50	0.8	0.4

In order to better evaluate the quality of the obtained non-dominated solutions, 2-D figures of non-dominated solutions for specified objective have been presented in Figs. 4 and 5 for head of pumping 14 m (for low depth area) and for 40 m (for high depth area) respectively.

Table 5 represents some of non-dominated solutions, and Table 6 shows the photovoltaic water pumping system capacities in terms of small photovoltaic module numbers and water storage tank capacity versus number of storage days in those solutions. The obtained non-dominated solutions allow the system operator to practice their personal preference in selecting any one of them for implementation.

Table 5 shows some of the obtained non-dominated solutions between 25 non-dominated solutions. The obtained non-dominated solutions allow the system operators to use their personal preference in selecting any one of them for implementation. Table 6 shows the related variables for the obtained solutions. The optimum values of the non-dominated solutions for each objective function have been

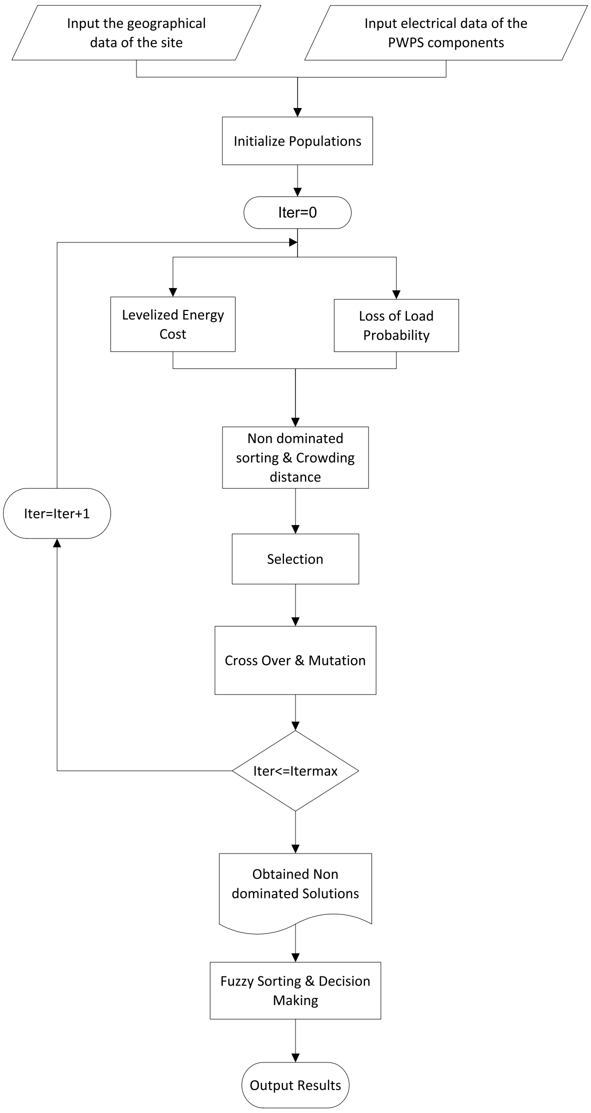

Fig. 3. Flow chart of the NSGAII algorithm

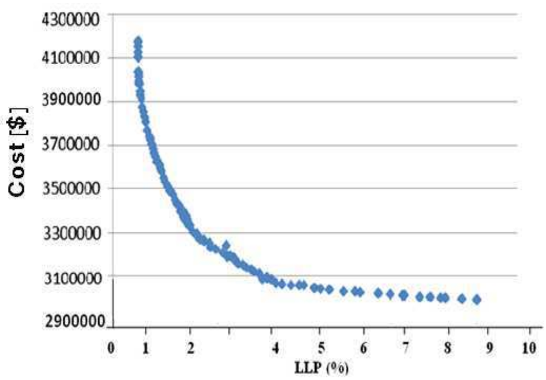

Fig. 4. Pareto front, 2-D representation of non-dominated solutions for LLP and LEC for head of pumping$= 14m$

Table 5. Some of the non-dominated solutions for the PWPS optimization problem

Fuzzy Ranking	Loss of load probability	Life Cycle Cost ($)	Normalized membership function
1	*0.00826*	*4730490.74*	*0.0124843*
2	0.00686	4811901.59	0.0124253
3	0.00735	4837330.83	0.0124025
4	**0.00563**	3951902.29	0.0123903
5	0.01832	4476129.72	0.0123746
6	0.01102	4678214.63	0.0123532
7	0.00982	3999628.14	0.0123354
8	0.01303	4194904.08	0.0123212
9	0.00948	4391033.79	0.0123187
10	0.01410	4133029.32	0.0122959
11	0.00781	4076129.72	0.0122830
12	0.01212	4265987.44	0.0122423
13	0.02121	4470429.82	0.0122262
14	0.01257	4208318.11	0.0122128
15	0.02232	3522473.67	0.0122094
16	0.01234	**3250515.16**	0.0121938
17	0.03232	3607850.21	0.0121876
18	0.04220	3407850.21	0.0121524
19	0.02232	3565987.44	0.0121398
20	0.03410	3770429.82	0.0121295
21	0.03632	3630490.74	0.0121134
22	0.04262	3511901.59	0.0120953
23	0.05131	3551902.29	0.0120938
24	0.05541	3476129.72	0.0120876
25	0.06232	3378214.63	0.0120624

highlighted in Table 5. However with considering two conflicting objective function the best compromising solution is the solution with the maximum membership value. The best compromising solution with fuzzy ranking 1 is highlighted in the first row of Table 5. The corresponding normalized membership function is 0.0124843 and related loss of load probability is 0.00826 and life cycle cost ($) is 4730490.74. As seen in Table 6 for the best compromising solution with fuzzy ranking 1 which is highlighted in the first row of Tab.5. The corresponding normalized membership function is 0.0124843 and related loss of load probability is 0.00826 and life cycle cost ($) is 4730490.74 and related number of photovoltaic module is 2 and number of storage days is 6.

10 CONCLUSION

In this paper, the photovoltaic water pumping optimization with optimal sizing of photovoltaic arrays capacity and water tank storage days is investigated. The decision variables of the PWPS problem are discrete so that this optimization problem is the combination of discrete variables. The objectives of this problem are loss of load probability (LLP) and life cycle cost (LCC) minimization, so that this problem has been considered as multi -objective optimization problem.

In the proposed algorithm, an external archive of non-dominated solution is kept which is updated during iteration. In order to decision making, a fuzzy based method is applied in this paper to select the favored solution among non-dominated solutions. This attribute gives more flexibility to the planner for choosing the best final scheme among the obtained solutions. However with considering two conflicting objective function the best compromising solution is the solution with the maximum membership value

Table 6. Related decision variables for obtained non-dominated solutions

Fuzzy Ranking	Number of photo-voltaic module	Number of storage days
1	*2.000*	*6.000*
2	2.000	5.000
3	3.000	8.000
4	3.000	6.000
5	3.000	7.000
6	3.000	8.000
7	4.000	9.000
8	4.000	8.000
9	4.000	7.000
10	4.000	6.000
11	5.000	8.000
12	5.000	6.000
13	3.000	7.000
14	3.000	6.000
15	2.000	5.000
16	2.000	6.000
17	4.000	5.000
18	5.000	6.000
19	4.000	3.000
20	3.000	6.000
21	4.000	6.000
22	4.000	8.000
23	3.000	6.000
24	3.000	6.000
25	4.000	8.000

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