Optimum unit sizing of a stand-alone hybrid PV-WT-FC system using Jaya algorithm

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Abstract—In this paper, Jaya algorithm is used for finding an optimal unit sizing of renewable energy resources (RERs) components, including photovoltaic (PV) panels, wind turbines (WTs) and fuel cell (FC) with an objective to reduce the consumer total annual cost in a stand-alone system. The system reliability is considered using the maximum allowable loss of power supply probability \((LPSP)\) provided by the consumer. The methodology is applied to real solar irradiation and wind speed data taken for Hawksbay, Pakistan. The results achieved show that when \(LPSP\) values are set to 0\% and 2\%, the PV-FC is the most cost-effective system as compared to PV-WT-FC and WT-FC systems.

Index Terms—Stand-alone system, unit sizing, renewable energy sources, energy storage system, Jaya algorithm.

I. INTRODUCTION

Traditional energy generation is widely dependent on the use of fossil-fuel resources such as oil, coal, and natural gas. These resources are exhausted and depleted with consumption [1]. Further, the usage of these sources has caused problems like environmental pollution and global warming. The present-day demands new ways of creating energy sources that are more environment-friendly, clean, sustainable and inexhaustible by nature. Renewable energy resources (RERs) are widely used to generate electricity from solar, wind, geothermal, hydropower and other sources that are naturally replenished and also have great potential to produce energy [2]. Among the other RERs, photovoltaic (PV) panels and wind turbines (WTs) are the most dominant and encouraging technologies that are used to meet the consumer’s load demand [3].

The RERs can be implemented using two ways: grid-connected (GC) or stand-alone (SA) modes. In GC mode, the RERs inject the produced electricity to a power utility network while in the SA mode, it directly powers up the consumer’s electrical demands [4]. The SA system causes reliability concerns due to the non-availability of electricity backup from a utility network. Further, the intermittent nature of solar energy and wind systems cause a non-linear and unpredictable RERs output power. Thus, using a single renewable energy system (RES) in SA environment results in energy variations. This effect causes an energy mismatch situation where the consumer’s load requirements are not met by the generation capacity. In order to overcome the reliability and aforesaid challenge, hybrid RES (HRES) along with an energy storage system (ESS), including the fuel cell (FC) and batteries are used to meet the consumer’s load demand [5]. The complementary features of wind and solar energies are combined in HRES with the backup of ESS which further makes it more sustainable and reliable as compared to single RES [6].

The major issue in HRES is the optimum unit sizing of individual components comprising of PVs, WTs, and batteries. The proper combination of HRES is required for the strategic decisions, including feasibility study or an initial capital investment cost calculation. A methodology used to determine the right and accurate sizing of HRES components by maintaining the system reliability at minimum system cost is referred as unit sizing [7]. O versizing of system components may overcome the reliability problem; however, it also results in an increased system cost. On the other side, undersizing of system components can lead to the loss of supply (LOS) problem, where generation is less than the consumer’s load requirement. Therefore, an optimum unit sizing of HRES is essential for the determination of the exact number of system components that leads to system reliability at reduced cost [8].

Meta-heuristic approaches are widely used in the literature for unit sizing [9]-[12]. In [9], the authors used firefly algorithm to determine the optimal and right-sizing of the SA PV system and its components. In [10], harmony search (HS) optimization technique is proposed for an off-grid hybrid solution consisting of PVs and biomass power generators. Agricultural wells located in Barda, Iran are targeted with an objective function that reveals minimization of the system total net percent cost (TNPC) while also considering the reliability factor. The comparison of results with particle swarm optimization (PSO) and genetic algorithm (GA) optimization schemes depict that HS performed better in terms of reducing TNPC. In [11], Maleki and Pourfayaz investigated optimal unit sizing of HRES, including PV, WT, and batteries. The authors analyzed and compared evolutionary algorithms, including simulated annealing, PSO and tabu search (TS) along with artificial bee swarm optimization (ABSO). The results show that ABSO performed better among other meta-heuristic algorithms with reduced cost for unit sizing of HRES. In [12], the authors used an improved ant colony optimization (ACO) scheme for the unit sizing of HRES consisting of PV, WT, batteries, and FC. Ahmed et al. used PV and ESS to minimize the consumer’s cost in GC mode [13]. The performance of
the proposed hybrid scheme (HGPO) was better than the other proposed algorithms: binary PSO (BPSO), GA, wind-driven, and binary foraging optimizations. The results showed that HGPO reduced cost by 40.05% and the peak-to-average ratio (PAR) by 41.07% as compared to non-scheduled load scenario. In [14], the authors used priority-induced demand side management strategy to shift the appliance peak load and also reduce consumer’s cost. An evolutionary accretive comfort algorithm (EACA) based on GA is used for efficient energy management [15].

All the above proposed meta-heuristic algorithms require algorithmic-specific parameters for their functioning. For instance, HS scheme uses harmony memory, pitch adjustment and consideration rate along with a number of improvisations. GA requires crossover and mutation probabilities with a selection operator. PSO needs cognitive and social parameters in addition to the inertia weight. ABSO uses a number of scouts, employed, and onlooker bees with a limit specifier. The ACO and other algorithms also require performance tuning of these algorithmic-specific parameters, otherwise, may halt in local optimum solutions or yield at an increased computational time. Therefore, the meta-heuristic algorithms that do not depend on any algorithmic-specific parameters for their execution and functioning have recently achieved a wide acceptance among the research community [16]. Jaya is a new algorithm developed by Rao to solve both constrained as well as unconstrained optimization problems [17]. The functioning of the algorithm is dependent only on common control parameters. The advantage of Jaya lies in its simplicity because it does not need any algorithmic-specific control parameters for its functioning.

Pakistan is one of the South Asian countries which is situated at a latitude of 23.45°N – 36.75°N and longitude of 61°E – 75.5°E. Pakistan is geographically located in an area where solar irradiation is immense, i.e., 5 – 5.5 kWh/m²/day in Punjab and 7 – 7.5 kWh/m²/day in Baluchistan, respectively. Further, it has great potential of 346 GW of wind power production, approximately [18]. Alternative energy development board (AEDB) is established in Pakistan with an aim to support, facilitate and encourage the implementation of RERs in the country. With the support of the World Bank, AEDB is carrying out an assessment and mapping activities in major areas of the country. In this paper, by considering these RERs potentials, a recently proposed algorithm Jaya is implemented to find an optimum unit sizing of HRES using real wind speed and solar irradiance data for Hawksbay, Pakistan. The unit sizing problem is considered with environmental concerns to have a green electricity generation and ESS.

The rest of the paper is organized as follows. In Section II, system model, objective function, and LPSP constraint are presented. The Jaya algorithm is elaborated and presented in Section III. Section IV depicts simulation results. Finally in Section V, conclusion along with future work are stated.

II. SYSTEM MODEL AND OBJECTIVE FUNCTION

The system model for the proposed HRES is represented in Fig. 1. In the proposed system configuration, wind power and PV generations are used as a primary energy resource. In order to ensure the system reliability, a combination comprising of FC, electrolyzer, and hydrogen tanks are utilized for storage. The proposed power generation and storage can be considered as complete “green” system because the RERs and ESS chosen are all environment-friendly. In case, where an excess amount of PV-WT energy is available, the electrolyzer starts producing hydrogens which are stored in the hydrogen fuel tanks (HFT). In another situation, where the energy produced by the RERs is less, the FC is utilized to produce energy to meet the load demand. As shown in Fig. 1, a hybrid (AC-DC) bus structure is used and energy conversions are performed by inverter and converter devices installed between them. To keep the model simple, it is assumed that relevant converters, i.e., AC-DC, DC-DC, etc. are installed with the respective component.

The objective required in this paper is to find an optimal combination of HRES to achieve a minimum value of total annual cost (TAC) expressed as \( \zeta_{\text{total}} \). The \( \zeta_{\text{total}} \) is obtained by combining two different costs. The first is the annual capital cost \( (\zeta_c) \) that occurs at the beginning of a project. The second cost comprises of annual maintenance cost \( (\zeta_m) \) that occurs during the project’s life. Thus, minimization of \( \zeta_{\text{total}} \) is given by the following formula:

\[
\text{Minimize } \zeta_{\text{total}} = \zeta_c + \zeta_m. \tag{1}
\]

In SA HRES, reliability is an important factor. Therefore, the concept of LPSP is regarded and implemented in this paper to have a reliable HRES. It is defined by a number between 0 and 1. A 0 value assigned to the LPSP shows that the HRES is very reliable and the consumer’s load will be always fulfilled by energy generation. On the other hand, a value of 1 LPSP means that the consumer’s load is never fulfilled or satisfied. The LPSP for one year \( (T = 8760h) \) can be expressed as:

\[
\text{LPSP} = \frac{\sum_{t=1}^{8760} (\xi^{ld}(t) - \xi^{gen}(t))}{\sum_{t=1}^{8760} \xi^{ld}(t)}, \tag{2}
\]

where \( \xi^{ld} \) and \( \xi^{gen} \) show the consumer’s load demand and total energy generated by HRES, respectively. In a situation, where the \( \xi^{gen} \) is less than \( \xi^{ld} \), it shows that loss of power supply has occurred.

In this paper, the cost minimization optimization problem is considered using the following LPSP constraint:

\[
\text{LPSP} \leq \text{LPSP}_{\text{max}}, \tag{3}
\]

where \( \text{LPSP}_{\text{max}} \) denotes the maximum allowable LPSP value specified by the consumer.

III. JAYA ALGORITHM

In Jaya, only common control parameters, including population size, termination criteria, etc. are required. In Jaya, the objective function \( f(r) \) is to be minimized at iterations \( t \), having \( “p” \) number of decision variables \( (l = 1, 2, \ldots, p) \), and \( “q” \) number of candidate solutions for a population size, \( (m = 1, 2, 3, \ldots, q) \). The best candidate achieves the best value of \( f(r) \) in the entire candidate solutions and is represented by \( f(r)_{\text{best}} \). Similarly, the worst value of \( f(r) \)
denoted as \( f(r)_{\text{worst}} \) is assigned to the worst candidate in the entire population. If \( R_{l,m,t} \) represents the value of \( l^{th} \) variable for the \( m^{th} \) candidate during the \( t^{th} \) iteration, then it is changed as per criteria defined by the following formula [17]:

\[
R'_{l,m,t} = R_{l,m,t} + \text{rand}_{1,l,t}(R_{l,\text{best},t} - |R_{l,m,t}|) - \text{rand}_{2,l,t}(R_{l,\text{worst},t} - |R_{l,m,t}|),
\]

(4)

where, \( R_{l,\text{best},t} \) and \( R_{l,\text{worst},t} \) are the values of variable \( l \) for the best and the worst candidates at \( t^{th} \) iteration, respectively. The \( R'_{l,m,t} \) depicts the updated value of \( R_{l,m,t} \) while \( \text{rand}_{1,l,t} \) and \( \text{rand}_{2,l,t} \) denote the two random numbers for the \( l^{th} \) variable during the \( t^{th} \) iteration in the range \([0, 1]\). The expression "\( \text{rand}_{1,l,t}(R_{l,\text{best},t} - |R_{l,m,t}|) \)" shows the tendency of the solution to move towards the best solution and the expression "\( \text{rand}_{2,l,t}(R_{l,\text{worst},t} - |R_{l,m,t}|) \)" indicates the tendency to avoid the worst solution. The \( R'_{l,m,t} \) is only accepted if it achieves better function value.

### IV. RESULTS AND DISCUSSION

The proposed model and methodology are implemented in the Matlab R2016a environment using a system with a processor of 2.9 GHz Intel Core i7, and 8 GB of installed memory. The Jaya optimization scheme is implemented to find the optimal combination of PVs, WTs, and HFTs in a hybrid system for minimizing TAC value.

The hourly solar insolation and wind speed profile data is obtained for Hawksbay, situated in the South of Pakistan. The dataset is obtained from the AEDB [19]. The datasets contain the data that are recorded each 10 min per day. In Fig. 2 and Fig. 3, the mean values of the irradiation and wind speed data (at a height of 10 m) for the year 2010 (comprising 8760h) are presented, respectively. The analysis of insolation data \((W/m^2)\) and wind speed data \((m/s)\) depict that the proposed site is widely suitable for electricity generation from both the sources, including sun and wind. A load profile during a year \((365 \times 24 = 8760h)\) of a home is presented in Fig. 4.

The optimum sizing results produced by the Jaya scheme for hybrid PV-WT-FC, PV-FC, and WT-FC system is summarized in Table I. This table represents the optimum number of combination for \( N_{PV} \), \( N_{WT} \), \( N_{HFT} \) along with TAC at two different \( \text{LPSP}^{\text{max}} \) values set by the consumer. AT \( \text{LPSP}^{\text{max}} = 0 \), the TAC values are high because it guarantees that the total consumer’s load will be met as compared to the second case when \( \text{LPSP}^{\text{max}} = 2\% \). At \( \text{LPSP}^{\text{max}} = 2\% \), the TAC values are economical as compared to \( \text{LPSP}^{\text{max}} = 0\% \); however, it does not guarantee to satisfy all consumer’s load during...
the year. This fact is due to the trade-off between TAC and LPSP\textsuperscript{max} value set by the consumer. Thus, with the increase in LPSP\textsuperscript{max} values from 0 has reduced the cost accordingly.

In Table I, when consumer sets LPSP\textsuperscript{max} value to 0% and 2%, then PV-FC system performed better in achieving minimum TAC values as compared to other systems (PV-WT-FC and WT-FC) for the given load. When LPSP\textsuperscript{max} is 0%, the optimum sizing is found \(N_{pv} = 84\) and \(N_{t} = 6448\), which resulted to TAC of 1051200$. While setting LPSP\textsuperscript{max} to 2%, the TAC value is reduced to 790000$ having optimum sizing values \(N_{pv} = 79\) and \(N_{t} = 4822\) with LPSP value obtained as 1.78%. The PV-WT-FC system at 0% and 2%, LPSP\textsuperscript{max} values have resulted in TAC of 1152600$ and 919800$, respectively. These TAC values are 9.65% and 16.43% higher as compared to the TAC values of the optimal case (PV-FC) system. The results showed that WT-FC system is the most expensive solution that has resulted in TAC values of 2288200$ and 1633300$ at LPSP\textsuperscript{max} 0% and 2%, respectively. 

On similar lines, the hourly power generation from WTs is depicted in Fig. 6. In Fig. 6a, the generation of WTs at LPSP\textsuperscript{max} = 0% is equal to to the generation at LPSP\textsuperscript{max} = 2% as shown in Fig. 6b because of same number of WTs (\(N_{wt} = 1\)).

The reliable supply of load demand is dependent on the amount of stored mass of energy in the HFTs. In Fig. 7, the expected stored mass of energy at different LPSP\textsuperscript{max} is shown for PV-WT-FC system for a year. When user sets LPSP\textsuperscript{max} = 0%, then it has resulted a high amount of storage capacity due to large number of HFTs (\(N_{t} = 7083\)) at huge

<table>
<thead>
<tr>
<th>Hybrid systems</th>
<th>LPSP\textsuperscript{max} (%)</th>
<th>LPSP\textsuperscript{max} (%)</th>
<th>(N_{pv})</th>
<th>(N_{wt})</th>
<th>(N_{t})</th>
<th>TAC($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV-WT-FC</td>
<td>0</td>
<td>0</td>
<td>67</td>
<td>1</td>
<td>7083</td>
<td>1152600</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.84</td>
<td>62</td>
<td>1</td>
<td>5634</td>
<td>919800</td>
</tr>
<tr>
<td>PV-FC</td>
<td>0</td>
<td>0</td>
<td>84</td>
<td>N/A</td>
<td>6448</td>
<td>1051200</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.78</td>
<td>79</td>
<td>N/A</td>
<td>4822</td>
<td>790000</td>
</tr>
<tr>
<td>WT-FC</td>
<td>0</td>
<td>0</td>
<td>N/A</td>
<td>7</td>
<td>14169</td>
<td>2288200</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.60</td>
<td>N/A</td>
<td>6</td>
<td>10090</td>
<td>1633300</td>
</tr>
</tbody>
</table>

Fig. 5b has a lower power electricity generation due to small number of PVs (\(N_{pv} = 62\)) as compared to LPSP\textsuperscript{max} = 0% given in Fig. 5a which has a high number of PVs (\(N_{pv} = 67\)) for PV-WT-FC system.
Fig. 6 shows the hourly produced WTs power for PV-WT-FC system during a year. The figure illustrates the impact of varying LPSPmax on WTs output. When LPSPmax is 0%, the WTs output is significantly higher compared to when LPSPmax is 2%. The convergence process of the Jaya scheme, as depicted in Fig. 8, demonstrates the effectiveness of the algorithm in minimizing the TAC of the PV-WT-FC system. At each iteration, the Jaya scheme decreases the TAC value based on the objective function, confirming the efficacy and performance of the proposed algorithm for the optimal unit sizing problem.

Fig. 7 presents the hourly expected mass of stored energy in HFTs for the PV-WT-FC system. The diagram reveals that at LPSPmax = 0%, the amount of storage capacity is high due to a large number of HFTs (Nt = 6448) compared to LPSPmax = 2% which has only (Nt = 4822) number of HFTs. This difference has resulted in a huge amount of TAC, i.e., 1051200$ for LPSPmax = 0% compared to LPSPmax = 2% having a smaller TAC.

Fig. 9 illustrates the hourly produced PVs power for PV-FC system during a year. Fig. 9a shows the hourly PVs power profile at LPSPmax = 0%, while Fig. 9b demonstrates the profile at LPSPmax = 2%. The high number of PVs (Npv = 84) at LPSPmax = 0% results in a power electricity generation that is significantly high compared to LPSPmax = 2%, which has only (Npv = 79) number of PV panels for PV-FC system.

Fig. 10 represents the hourly expected amount of stored energy at different LPSPmax for hybrid PV-FC system. At LPSPmax = 0%, the amount of storage capacity is high due to the large number of HFTs (Nt = 6448) compared to LPSPmax = 2% which has only (Nt = 4822) number of HFTs. This has resulted in a high amount of TAC, i.e., 1051200$ for LPSPmax = 0% compared to LPSPmax = 2% having a lower TAC due to the reduced storage demand.
TAC of 790000$. Further, the LOL is also high for $LPSP^{max} = 2\%$ due to the trade-off between the reliability and cost. The convergence process of Jaya scheme for PV-FC system is displayed in Fig. 11. As shown in Fig. 11 that Jaya scheme has quickly found the optimum results. Further, it is noted that the convergence process of PV-FC system as given in Fig. 11 is faster as compared to PV-WT-FC system depicted in Fig. 8 because of less number of decision variables involved.

Fig. 10: Hourly expected mass of stored energy in HFTs for PV-FC system during a year

![Fig. 10](image)

Fig. 11: Convergence of Jaya algorithm for PV-FC system

The hourly power profile of WTs is given in Fig. 12 for WT-FC system at two different $LPSP^{max}$ values. For $LPSP^{max} = 0\%$, the number of WTs ($N_w^t = 7$) has produced a higher power as shown in Fig. 12a when compared to $LPSP^{max} = 2\%$, which has 6 number of WTs depicted in Fig. 12b.

For WT-FC system, the amount of hourly stored energy is plotted in Fig. 13 for two $LPSP^{max}$ values. The amount of stored energy at $LPSP^{max} = 0\%$ is high due to large number of WTs ($N_w^t = 7$) and HFTs ($N^t = 14169$) as compared to $LPSP^{max} = 2\%$ value which has less quantity of WTs ($N_w^t = 6$) and HFTs ($N^t = 10090$). The LOL is evident at the time slots when the stored amount of hydrogen in HFTs has reached its lowest capacity limit. Jaya has converged very quickly to attain the optimum solution, which is shown in Fig. 14.

V. CONCLUSION AND FUTURE WORK

In this paper, we have considered an optimum unit sizing of HRES using real solar irradiation and wind speed data for Hawksbay, Pakistan. The reliability of the system is ensured using maximum LPSP ($LPSP^{max}$) constraint defined by the consumer. The optimization problem is solved using a novel meta-heuristic technique Jaya that does not require algorithmic-specific parameters. The simulation results revealed that the PV-FC is the most cost-effective system as compared to PV-WT-FC and WT-FC systems. At the given load profile, the TAC achieved is 1051200$ and 790000$ by the PV-FC system at $LPSP^{max} = 0\%$ and $LPSP^{max} = 2\%$, respectively.

In future, we will compare Jaya results with other meta-
heuristic techniques, including GA and backtracking search algorithms that require algorithmic-specific parameters for their functioning.

REFERENCES


