World Academy of Science, Engineering and Technology
International Journal of Energy and Power Engineering
Vol:17, No:2, 2023

Optimizing the Components of Grid-Independent Microgrids for Rural Electrification Utilizing Solar Panel and Supercapacitor

Astiaj Khoramshahi, Hossein Ahmadi Danesh Ashtiani, Ahmad Khoshgard, Hamidreza Damghani, Leila Damghani

Abstract**—**Rural electrification rates are generally low in Iran and many parts of the world that lack sustainable renewable energy resources. Many homes are based on polluting solutions such as crude oil and diesel generators for lighting, heating, and charging electrical gadgets. Small-scale portable solar battery packs are accessible to the public; however, they have low capacity and are challenging to be distributed in developing countries. To design a battery-based microgrid power systems, the load profile is one of the key parameters. Additionally, the reliability of the system should be taken into account. A conventional microgrid system can be either AC or coupling DC. Both AC and DC microgrids have advantages and disadvantages depending on their application and can be either connected to the main grid or perform independently. This article proposes a tool for optimal sizing of microgrid-independent systems via respective analysis. To show such an analysis, the type of power generation, number of panels, battery capacity, microgrid size, and group of available consumers should be considered. Therefore, the optimization of different design scenarios is based on number of solar panels and super saving sources, ranges of the depth of discharges, to calculate size and estimate the overall cost. Generally, it is observed that there is an inverse relationship between the depth spectrum of discharge and the solar microgrid costs.

Keywords**—**Storage, super-storage, grid-independent, economic factors, microgrid.

I. Introduction

SOLAR energy systems are evaluated based on the requirements imposed by energy technology applications. Also, modeling and analysis of storage systems are necessary to increase the effectiveness of the combinations of these systems. In previous research work, analysis based on software, to evaluate the response of the hybrid system concerning various technologies of renewable energy and energy storage, has been conducted [1]. This analysis allows us to optimize a solar photovoltaic microgrid according to the location scenario when the sun's energy for a microgrid system is widely accessible. Moreover, hour-by-hour measurements of sun data are necessary to provide a suitable forecast of electricity generation. Based on the collected data, different combinations of energy resources using possible scenarios related to predicted climate information and economic behavior during the study period have been discussed in this study. In many cases, the hardest step is to collect accurate information from the hourly demand of the analyzed microgrid along with the sun data that needs to be gathered from the synoptic station [2].

In [3] a novel method proposed and subsequently carried out to clear up the call for technology differences and DC bus voltage regulation on the power-sharing among battery and supercapacitor (SC) energy storage systems.

After data collection, including latitude and longitude of the microgrid, and the number of panels, it is utilized by the sizing software which is based on the Genetic algorithm. To obtain the optimal solution given a set of constraints, the whole period is studied. In this research, MATLAB software is used for designing and sizing.

A. Objectives of the Article

The objectives of this project are to design and develop a sustainable microgrid system for rural electrification and design an energy storage system to meet certain requirements. An energy storage system (ESS) must meet the following criteria:

1. Supplies power when power production is insufficient.
2. Charges and discharges under both normal and short-term peak load conditions.
3. Supports any kind of grid load at all time.

The methodology of this paper is based on the following to collect the results.

- Theory
1. Reviewing AC and DC microgrids topology.
2. Determining design parameters.
- Uses
1. Determining the parameters of the microgrid system that affect the dimensions and performance of ESS.
2. Using advanced genetic algorithm optimization for sizing grid-independent power systems.
- Implementation
1. Utilization of the developed algorithm for sizing grid-independent microgrids

In the design of battery-based microgrid power systems, the

Astiaj Khoramshahi is with the Energy Systems Department, Islamic Azad University, South Tehran Branch, Iran (corresponding author, phone: +982144350914; e-mail: a_khorramshahi@sut.ac.ir).

Hossein Ahmadi Danesh Ashtiani is with Energy Systems Department, Islamic Azad University, South Tehran Branch, Iran (e-mail: hdanesh1381@yahoo.com).

Ahmad Khoshgard is with the Chemical Engineering Department, Islamic Azad University, South Tehran Branch, Iran (e-mail: ahkhoshgard@gmail.com).

Hamidreza Damghani is with the Department of Electrical and Computer Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran (e-mail: hamidreza.damghani@gmail.com).

Leila Damghani is with the Department of Computer and Information Technology Engineering, Qazvin Branch, Islamic Azad University, Qazvin, Iran (e-mail: damghani.iau@gmail.com).

load profile is the key parameter. An optimal design should also account for the reliability of the system. This paper develops a tool for size optimization of grid-independent microgrid systems.

B. Limitations and Objectives of the Research

The system is assumed to be disconnected from the grid; therefore, it operates independently. Weather conditions play a vital role in determining the availability and development of solar energy in a specific region and are constantly changing with time. However, in this work we assume that weather data are fixed due to the absence of continuous recordings. Real-time data collection can boost the performance of the system via providing opportunities for adapting to the demands of the network.

II. History of Case Research in Microgrid Systems

Development of a national grid depends on the magnitude of the region and is carried out using considerable annual maintenance costs. Small-scale portable solar battery packs are available to the public; however, their applications are limited in the developing countries due to low capacity and challenges in distribution. Although the large-scale installation of solar panels is a viable option, they are usually very expensive for developing countries and the respective price tag is significant. Microgrid solutions as depicted in Fig. 1 with renewable energy sources, such as distributor generators, are needed to provide households with electricity throughout the developing world [4].

Grid-independent microgrids or island microgrids operate similar to grid-connected systems (but in the absence of a grid). Figs. 2 and 3 show the outline of grid-independent microgrids of AC and DC, respectively.

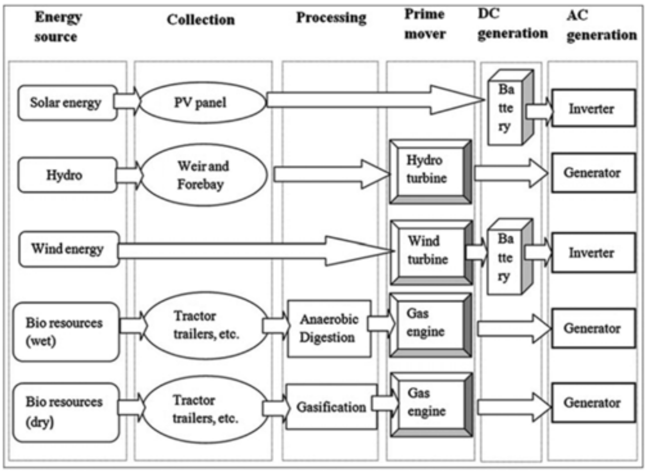

Fig. 1 Power generation cycle in grid-independent microgrids [4]

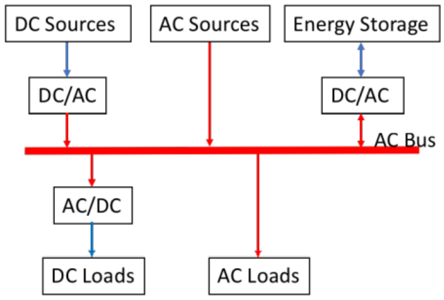

Fig. 2 AC microgrid topology of grid-independent microgrid

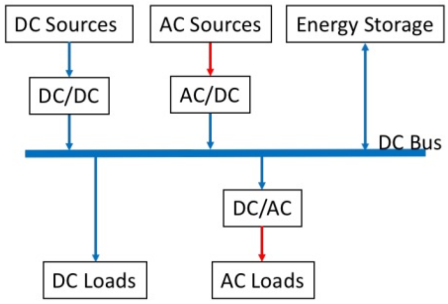

Fig. 3 DC topology of grid-independent microgrid

III. Research Method

The design parameters of solar energy systems are performance parameters that are used to determine reliability and feasibility, allowing the system designer to architect the appropriate system according to the specific application. Some of these parameters that are used in this research are introduced below and listed in Table I.

In this paper, the optimal size of a solar battery/ supercapacitor array for a standalone microgrid, using the genetic algorithm proposed by [5] is studied. Fig. 4 is the flowchart and model algorithm for the reference model. The overall costs of microgrid, namely installation costs, are minimized to meet the demand for grid load at all times with optimal reliability. Fig. 5 represents the schematic of a grid-independent microgrid of the photovoltaic-battery hybrid system.

The simulated model has been developed in MATLAB and its algorithm is shown in Fig. 6. The key parameters of the system are listed in Table I. To observe the impact of the ESS system on the demanded household power, according to the target function, the simulation formulation of the problem is presented.

TABLE I
Parameters of Microgrid System Simulator with Energy Storage

Parameter	Amount
Home power demand at the peak point	3 kW
Absorption of solar power at the peak point	2 kW
Battery energy storage capacity	20 kWh
Battery peak-power capability	2 kW
Supercapacitor energy storage capacity	3 kWh
Supercapacitor peak-power capability	10 kW

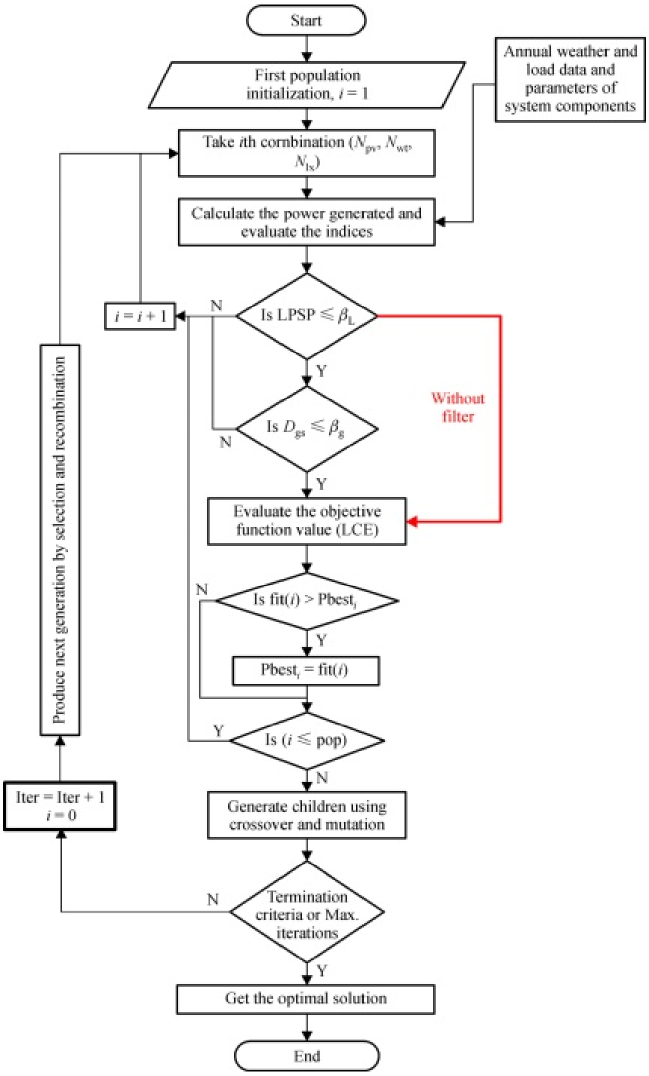

Fig. 4 Flowchart and model algorithm reference model [5]

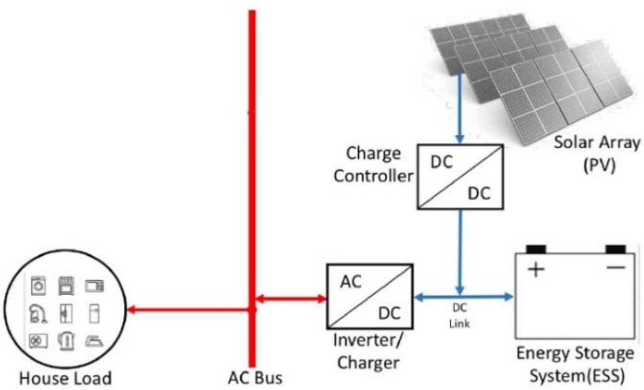

Fig. 5 Microgrid of photovoltaic-ESS

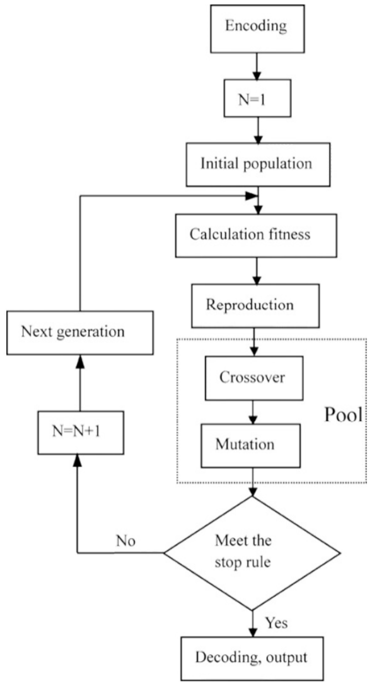

Fig. 6 Flowchart of the developed model

IV. TECHNOLOGICAL PARAMETERS

A grid-connected solar system using ESS is necessarily used in areas where grid power is not reliable, but the grid produces energy essentially through the use of high-power steam generators heated by coal, natural gas, or nuclear fusion. Grid study has shown that demand and load on the grid in the early morning and evening are the highest for residential applications. In the meantime, solar panels that convert solar optical energy (photons) from the sun to electricity through the photovoltaic effect between silicon panel intersections, reach their maximum potential when solar radiation reached its peak in the middle of the day. Therefore, they are unable to meet the high demand for the network. Energy storage is required to smoothly distribute energy from these sources. In the case of ESS operation network failure, the ESS acts as a backup to provide consumers with electricity. An ESS system in the solar microgrid is connected to the grid for rapid and emergency support and shifting from peak hours to non-peak hours is commonly used. The failure of the feeding system just as the values of sun and wind parameters is random and discontinuous, hence determining the reliability of the system is an important criterion. One of the metrics that help us to quantify the reliability of a system available is a parameter called the probability of lack of power source or LPSP, which is the ratio of total energy reduction to total demand in the period as seen in (1) [6]:

$$LPSP = \frac{\sum_{t=1}^{T} DE(t)}{\sum_{t=1}^{T} P_{load}(t)\Delta t} \quad (1)$$

The purpose of the problem is to minimize the installation costs of a grid-independent hybrid microgrid in 20 years by meeting the reliability, performance, and stability constraints. The optimization problem is formulated as in (2) and (3):

$$min\, f\,(N_{pv}, E_{ESS}) = C_{PV}.N_{PV} + C_{ESS}.E_{ESS} \tag{2}$$

$$\begin{cases} C_{PV} = (C_{cap}^{pv} + 20.C_{op}^{PV}).P_{PV} \\ C_{ESS} = y_{ESS}.C_{cap}^{ESS} + (20 - y_{ESS}).C_{op}^{ESS} \end{cases} \tag{3}$$

The N_{pv} is the number of photovoltaic panels, E_{ESS} is storage source capacity in terms of Wh, and C_{PV} is the total photovoltaic costs in dollars. The C_{ESS} cost of the ESS unit is in watt hour per dollar (Wh/\$). C_{cap}^{Pv} and C_{cap}^{Ess} is the installation costs for solar panels and ESS in watt per dollar (W/\$) and Wh/\$ of battery storage source, respectively. C_{OP}^{Pv} and C_{OP}^{Ess} the solar panel startup costs are in W/\$ and W/\$ respectively. y_{Ess} is the estimated number of *ESS* purchased within the 20-year period, including the cost of installation, the cost of maintenance and commissioning of the same component.

V. Problem Formulation

Various ESS technologies have advantages and disadvantages based on their applications. Table II represents a comparison of the three ESS technologies in question. Lead-acid batteries have high power density; however, they have lower life cycles due to high energy density. On the opposite side, ultracapacitors have higher power density but lower energy density in the classification between lead-acid batteries and ultracapacitors. The performance time of acidic-lead and lithium-ion is under 10 seconds whereas the performance time of super-storages is less than 1 second.

TABLE II
Comparison of Different Types of Energy Storage

Type	Acidic-lead	Lithium-ion	Ultracapacitor
Cell Voltage	2 volts	3.7V	2.75-2.3V
Energy density (Wh/kg)	50-30	200-75	10-5
Power density (W/kg)	300-75	300-150	Up to 10,000
Performance time	10 > S	10 > S	1 > S
Continuous Discharge Time	1 s - 10 h	1 s - 10 h	1 ms - 1 h
Working cycles per hour	2000	> 1000	100000
Advantages	High capacity, high energy density	High energy density	High power density, quick response
Disadvantages	Low power density, low working cycle	Small, hard capacity for wide-scale applications	Low energy density, expensive

A. System Constraints (Limitations)

The following limitations must be met.

1- Reliability

$$LPSP \leq LPSP_{set} \tag{4}$$

2- Photovoltaic power constraints for $N_P \geq 0$

$$P_{Pv\min} \leq P_{PV}(t) \leq P_{Pv\max} \tag{5}$$

3- Energy Storage Restrictions ESS

$$E_{ESS\min} \leq ESS(t) \leq E_{ESS\max} \tag{6}$$

$$E_{ESS\min} = (1 - DOD).E_{ESS\max} \tag{7}$$

4- Energy balance (start and end constraints)

$$E_{ESS}(0) = E_{ESS}(t) = E_{ESSstored} \tag{8}$$

5- Power Balance

$$P_{PV}(t) + P_{WT}(t) + P_{ESS}(t) = P_{Load}(t) \tag{9}$$

6- Ramp rate (slope): If $RR > RR_{set}$ then

$$Pd_{ESS}(t) \geq K_d.P_{Load}(t) \tag{10}$$

VI. Discussion and Conclusion

The results of optimization for different design scenarios based on the number of solar panels and super saving source, with a range of depths of the following discharges, for sizing calculations and estimating the overall cost, are given in Table III. In the table, it can be seen that with a super-saving source with a constant capacity of 200 kW, by increasing the depth spectrum of the discharge from 0.5 to 0.8, the overall costs of solar microgrid construction increase significantly. Similarly, with increasing the number of panels, solar photovoltaic power increases tangibly from 41.8 kW to 44.9 kW.

TABLE III
Optimal Sizing Results in Using the Number of Panels and Energy Storage Source (Superstorage)

	DOD = 0.5	DOD = 0.6	DOD = 0.7	DOD = 0.8
N_{pv}	176	168	166	164
P_{pv}	44.9 kW	42.8 kW	42.3 kW	41.8 kW
E_{ESS}	200 kW	200 kW	200 kW	200 kW
Overall costs	260000\$	256644\$	255828\$	255012\$

References

[1] A Khoramshahi, H Ahmadi Danesh Ashtiani, A Khoshgard, H Damghani, L Damghani. (2023), "Modeling the Hybrid Battery/Super-Storage System for a Solar Standalone Microgrid". Journal of Energy and Power Engineering, Vol.17, No. 2, pp. 51-56.

[2] Surface meteorology and solar energy. http://eosweb.larc.nasa.gov/sse/ (accessed on 01.08. 2022).

[3] Singh, P. and Lather, J.S. (2021), "Power management and control of a grid-independent DC microgrid with hybrid energy storage system". Sustainable Energy Technologies and Assessments, 43, p.100924.

[4] Subhes C. Bhattacharyya Debajit Palit, (2014), "*Mini-Grids for Rural Electrification of Developing Countries Analysis and Case Studies from South Asia",* Springer, Switzerland, pp. 18.

[5] Mahesh, A., Sandhu, K. S. (2020), "A Genetic Algorithm Based Improved Optimal Sizing Strategy for Solar-Wind-Battery Hybrid System Using Energy Filter Algorithm". Journal of Frontiers in Energy, Vol. 14, No. 1, pp. 139–151.

[6] Alsayed M, Cacciato M, Scarcella G, Scelba G. (2013), "Multicriteria Optimal Sizing of Photovoltaic-wind turbine Grid Connected Systems". Journal of IEEE Trans Energy Conversion; Vol. 28, No. 2, pp. 370–379.