Optimal Microgrid Sizing Incorporating Machine Learning Forecasting

Saheed Lekan Gbadamosi and Nnamdi I. Nwulu
Department of Electrical and Electronic Engineering
University of Johannesburg
Johannesburg, South Africa
gbadamosiadeolu@gmail.com, nnwulu@uj.ac.za

Abstract

This paper discusses an optimal sizing strategy of wind, PV and battery-based systems for powering an islanded microgrid system. Waikato Environment for Knowledge Analysis (WEKA) software was employed for wind speed and solar radiation time series forecasting in order to obtain predicted values for wind and solar power output. An optimization problem is developed to minimize the microgrid capital and maintenance costs. In order to achieve an optimal system configuration, a loss of power supply probability (LPSP) was evaluated for ensuring power system reliability and the optimization problem was solved using Advanced Interactive Multidimensional Modeling System (AIMMS). The results obtained from simulation shows the importance of optimal sizing in the investment and operation of microgrid systems.

Keywords

Microgrid, Photovoltaic, Wind Turbine, Battery, Energy.

1. Introduction

The steady decrease in fossil fuel resources and uncertainties associated with its prices has compelled the search for other sources of energy to meet the growing energy demand in the world. Recently, renewable energy sources (RES) are considered as alternative source of energy generation to fossil fuel owing to its environmentally friendly nature with good power quality and low operation costs [1]. Microgrid system is view as interconnection of different controllable loads, distributed generators and energy storage system operating as a single controllable system located at the customer region [2] [3]. The operation of microgrid can be in isolated mode or grid connected mode. RESs are seen as a promising energy source for microgrid system with the needs to improve operational efficiency, reliability, sustainability and lowering costs [3]. In microgrid system, RES can either be employed as single or hybrid energy source. The study in [4] advised on the use of wind, PV and battery system for achieving an optimal design of an island microgrids in a rural area, to enhance electricity sustainability through the use of renewable energies. Reference [5] considered PV, wind, battery and diesel generator for supplying energy in an isolated microgrids based on economic and operational perspectives. On the contrary, [6] is of the opinion that PV and diesel generators are of high cost when considering the cost of wheeling diesel in a remote location.

In the recent time, researchers have focused on the energy management of microgrids which entails the system operation and control of microgrids. Reference [3] investigates economic schedule of a grid connected microgrid system incorporatingRES and demand response. Reference [7] considered an optimal resource schedule for unit commitment and economic of microgrids with emphasis on minimizing the operation, maintenance, aging costs and network losses. In this study, we are considering an optimal sizing of an isolated microgrid system using wind, PV and battery as energy sources. The hourly solar radiation, temperature and wind speed in University of Johannesburg was captured for 24 hours. These parameters were forecasted for a year using machine learning software package called Waikato Environment for Knowledge Analysis (WEKA)[8] and the predicted parameters were used for the computation in the optimization process. The optimization model developed seeks to minimize the capital and maintenance costs of wind turbine, PV and battery energy storage system whilst satisfying the demand constraints. The proposed model is capable of reducing the impact of RES intermittency on their respective power output whilst meeting the required hourly load demand.

2. Microgrid modelling

In this paper, the islanded microgrid includes wind, PV and battery system. The mathematical modelling of the RES and battery storage systems are presents as follows.

2.1 Wind Energy

The hourly wind turbines power output is highly influenced by wind speed and this can be express as:

$$V_{f_t} = V_{i_t}\left(\frac{h_f}{h_i}\right)^{\gamma} \qquad (1)$$

where V_{f_t} represents the wind speed of the turbine at the required height h_f , V_{i_t} represents the wind speed at the measured height h_i and γ is the wind speed power law exponent ranging from $\frac{1}{7}$ to $\frac{1}{4}$. Here in this work, $\frac{1}{7}$ is used. The wind turbine power output is therefore expressed as a function of wind speed [9]:

$$P_{wt} = \frac{1}{2}\rho_{air} A \eta_{wt} c_{wt} v^3 \qquad (2)$$

where P_{wt} is the hourly output power from wind turbine, the air density is given as ρ_{air}, turbine rotor swept area is A, wind turbine efficiency is η_{wt}, wind turbine power coefficient is c_{wt} and the wind velocity at the required height is given as V.

2.2 Solar PV

The output power of PV is dependent on solar radiation and the configuration of the system. Therefore, the hourly output of the PV is depicted as [3]:

$$P_{pv} = A_{pv}\eta_{pv} I_{pv} \qquad (3)$$

where P_{pv} represents the hourly output power of the PV, A_{pv} represents the PV array area, η_{pv} represents the PV array efficiency and I_{pv} represents the solar radiation of the PV array.

2.3 Battery System

Here, a 12 V 200 Ah lithium-ion battery (Li-Ion) battery is used as backup to overcome the RES intermittency. The load requirement determines the state of charging or discharging of the battery state. The battery can either be placed in series or parallel connections to give the desirable DC operating voltage [5]:

$$N_{b,s} = \frac{V_{bus}^{dc}}{V_b} \qquad (4)$$

$$N_{b,p} = \frac{L}{V_{bus}^{dc}} \qquad (5)$$

where $N_{b,s}$ is the battery in series connection, $N_{b,p}$ is the battery in parallel connection, L is the load, V_b is the nominal battery voltage and V_{bus}^{dc} represents DC bus voltage.

3. Optimization Mathematical Formulation

Here, optimization formulations of the microgrid system components is explained. Wind and PV are the renewable energy source utilized and battery is employed to augment the RES in order to meet the required load. The cost of microgrid system consists of the capital and maintenance costs of wind turbine, PV and battery as well as the replacement of the battery.

3.1 Nomenclature

t	hourly time interval
N	number of hours in a day
npc	net present cost
h	height of wind turbine
$n_{\_pv}$	quantity of PV panels
$n_{\_wt}$	quantity of wind turbines
$n_{\_b}$	quantity of batteries
α_{c_pv}	PV panel capital cost
α_{c_wt}	wind turbine capital cost
α_{c_b}	battery capital cost

α_{m_pv}	PV panels hourly maintenance cost
α_{m_wt}	wind turbines hourly maintenance cost
α_{c_wtt}	wind turbine tower capital cost per meter
α_{m_wtt}	wind turbine tower maintenance cost per meter
α_{m_b}	maintenance cost of the battery
$\delta_{\_b}$	number of replacements that need to be made to the battery over the day
β	hourly self-discharge rate of the batteries

3.2 Objective Function

The objection function seeks to minimize the capital and maintenance costs of wind turbine, PV and battery as well as the replacement of the battery and it is expressed as:

$$Min\begin{bmatrix} \left\{ n_{\_pv}\left(\alpha_{c\_pv} + \sum_{t=1}^{N} \alpha_{m\_pv} \right) \right\} \\ + \left\{ n_{\_wt}\left(\alpha_{c\_wt} + \left(\sum_{t=1}^{N} \alpha_{m\_wt} \right) + h\alpha_{c\_wtt} + \left(\sum_{t=1}^{N} h\alpha_{m\_wtt} \right) \right) \right\} \\ + \left\{ n_{\_b}\left(\alpha_{c\_b} + \delta_{\_b}\alpha_{c\_b} + \left(N - \delta_{\_b} - 1 \right)\alpha_{m\_b} \right) \right\} \\ \end{bmatrix} \quad (6)$$

3.3 Model Constraints

The following model constraints are used to solve the objective function.

$$npc = \begin{bmatrix} n_{\_pv}\left(\alpha_{c\_pv} + \alpha_{m\_pv} \right) + n_{\_wt}\left(\alpha_{c\_wt} + \alpha_{m\_wt} \right) \\ + n_{\_b}\left(\alpha_{c\_b} + \alpha_{m\_b} + \delta_{\_b} \right) \end{bmatrix} (7)$$

$$P_{\_b,t} = \left[P_{\_b,(t-1)}(1-\beta) + n_{\_b}\left\{ \left(P_{\_pv} + P_{\_wt} \right) - \frac{P_{\_k}}{\eta_{\_b}} \right\} \right] \quad (8)$$

$$LPSP = \left[\frac{\sum_{t=1}^{N} P_{\_k} - \left(n_{\_pv}\sum_{t=1}^{N} P_{\_pv} + n_{\_wt}\sum_{t=1}^{N} P_{\_wt} + \sum_{t-1}^{N} n_{\_b}P_{\_b} - P_{\min\_b} \right)}{\sum_{t=1}^{N} P_{\_k}} \right] (9)$$

$$n_{\_pv} \geq 0 \quad (10)$$

$$n_{-wt} \geq 0 \quad (11)$$

$$n_{\_b} \geq 0 \quad (12)$$

$$0 \leq h \leq h_{\max} \quad (13)$$

$$LPSP \angle 0.01 \quad (14)$$

- Equation (7) defines the net present cost as key economic performance indicator.
- Constraint (8) defines the power used when charging the battery.
- Constraint (9) defines the loss of power supply probability in the network.
- Constraints (10) to (12) enforce that the PV panels, wind turbines and batteries number must be nonnegative integers.
- Equation (13) is wind turbine height constraint and it states that the height of wind turbine must not exceed its limit.
- Constraint (14) ensures that the loss of power supply probability must be sufficiently low as to ensure reliability

3.4 Case Study

The proposed islanded microgrid is situated in Auckland Park Campus (APK), University of Johannesburg South Africa. Its coordinates are 26.18^{o}S and 27.999^{o}E. The load data to be connected to the isolated microgrid are residential loads from University of Johannesburg and the data is presented in Figure 1. The reliability metric used is LPSP. The power rating of wind turbine and PV are 3000W and 200W respectively and a 12V 200Ah battery. The hourly average temperature, wind speed and solar radiation are obtained from Solar Radiation Data (SoDa) website. The temperature, date, solar radiation and wind speed were inputted into time series environment in WEKA for weather forecast. The predicted parameters are computed for optimization process. The developed optimization model was solved using AOA solver embedded in AIMMS software.

4. Results and discussion

Table 1summarizes the number of PV panels, wind turbines and batteries that will be adequate to meet the required demand for the project as well as the cost of financing the project. Table 2 presents the hourly power output from wind turbines. As can be seen from the graphical view in Figure 2, a large portion of wind power was produced for 12 hours (7am to 18pm) on daily basis owing to the availability of sufficient wind speed at that particular period for power generation. A similar case is observed in Table 3 which depicts the hourly power output from solar PV. From Figure 3, it is observed that on a daily basis the power output from PV is only available for a period of 10 hours (8am to 17 pm) due to prominent solar radiation at that period. Table 4 shows the hourly power output from the battery system. Comparing the hourly power output from wind turbines, PV panels and batteries; it is obvious more power was produced from batteries and PV panels than wind turbines. Though, the hourly predicted wind speed obtained from the forecast is 3.5 m/s which is above the cut-in wind speed. The low power output from wind turbine is as a result of high investment costs of setting up wind turbine in the system.

Table 1: Project Parameters and Incurred Costs

Variables	**Quantities**
PV panels	59
Wind turbines	2
Batteries	71
LPSP	0.01
Total cost (Rands)	830062

Table 2: Hourly Wind Power Output

Time (hr)	**Wind Power Output (W)**	**Time (hr)**	**Wind Power Output (W)**
1	6.73	13	39.01
2	7.68	14	39.14
3	6.49	15	39.01
4	6.65	16	34.25
5	7.34	17	25.05
6	15.44	18	8.53
7	26.40	19	2.95
8	34.84	20	0.24
9	42.69	21	0.92
10	46.74	22	4.69
11	45.60	23	5.82
12	41.75	24	5.44

Table 3: Hourly Solar PV Power Output

Time (hr)	**PV Output (W)**	**Time (hr)**	**PV Output (W)**
1	209.13	13	348.31
2	209.74	14	314.89
3	210.32	15	272.02
4	210.75	16	230.88
5	211.83	17	204.70
6	230.75	18	201.10
7	269.60	19	203.08
8	309.91	20	204.03
9	343.55	21	204.44
10	365.69	22	205.00
11	373.73	23	205.68
12	367.57	24	206.31

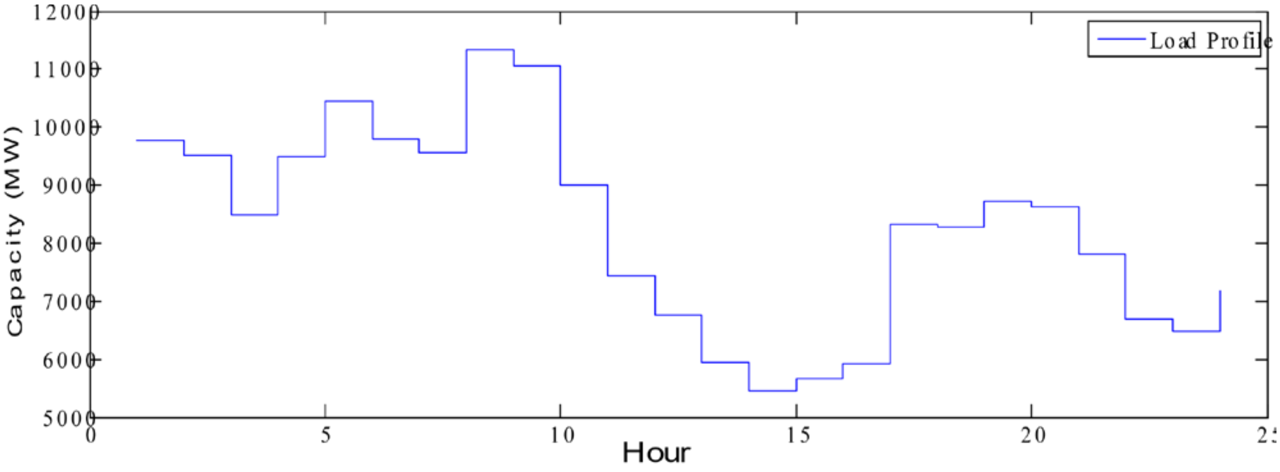

Figure 1. Load Profile of Residential Building

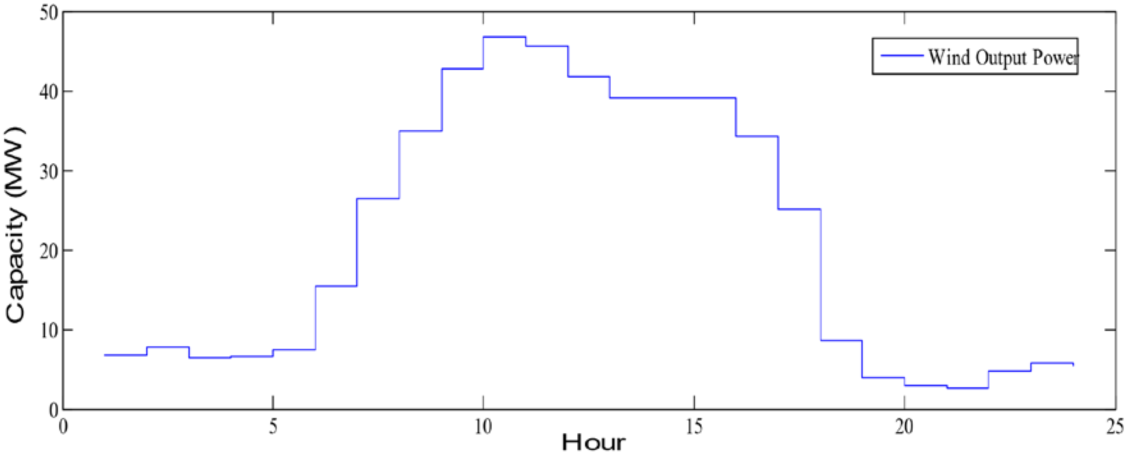

Figure 2. Hourly Optimal Wind Power

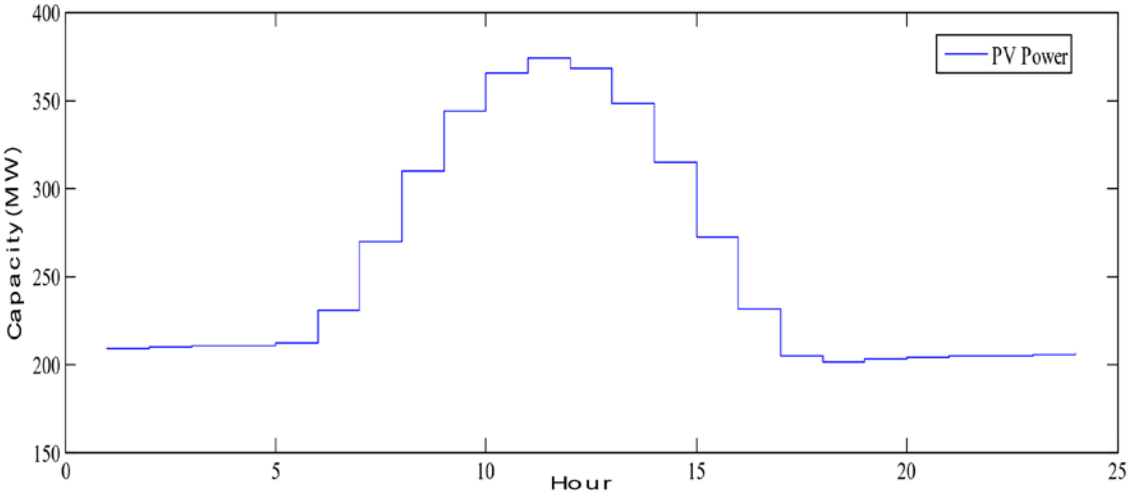

Figure 3: Hourly Optimal PV Power

Table 4: Hourly Output Power form Battery

Time (hr)	Battery Power Output (W)	Time (hr)	Battery Power Output (W)
1	106.82	13	51264.63
2	487.80	14	60131.16
3	1844.61	15	66917.77
4	2281.83	16	71630.98
5	1859.98	17	72908.03
6	2918.00	18	74053.89
7	5925.66	19	74870.07
8	9072.74	20	75815.12
9	13967.21	21	77530.55
10	21772.84	22	80335.96
11	31396.41	23	83366.63
12	41373.02	24	85772.08

5. Conclusion

In this paper, an optimal approach for sizing a microgrid for an institutional load is presented. The developed model focused on minimizing the capital and maintenance costs of wind turbine, PV and battery energy storage system whilst satisfying the demand constraints. The Mixed Integer Nonlinear Programing mathematical problem formulated was solved using AOA solvers embedded in AIMMS software and the results obtained show the effectiveness of the developed approach in achieving an optimum sizing of the microgrid.

References

[1] S. L. Gbadamosi, N. I. Nwulu, and Y. Sun, “Multi-objective optimisation for composite generation and transmission expansion planning considering offshore wind power and feed-in tariffs,” *IET Renew. Power Gener.*, vol. 12, no. 14, pp. 1687–1697, 2018.

[2] M. Husein and I. Chung, “Optimal design and fi nancial feasibility of a university campus microgrid considering renewable energy incentives,” *Appl. Energy*, vol. 225, no. May, pp. 273–289, 2018.

[3] N. I. Nwulu and X. Xia, “Optimal dispatch for a microgrid incorporating renewables and demand response,” *Renew. Energy*, vol. 101, pp. 16–28, 2017.

[4] Z. Wang, Y. Chen, S. Mei, S. Huang, and Y. Xu, “Optimal expansion planning of isolated microgrid with renewable energy resources and controllable loads,” vol. 11, pp. 931–940, 2017.

[5] M. Abedini, M. H. Moradi, and S. M. Hosseinian, “Optimal management of microgrids including renewable energy scources using GPSO-GM algorithm,” *Renew. Energy*, vol. 90, pp. 430–439, 2016.

[6] G. Bekele and B. Palm, “Feasibility study for a standalone solar – wind-based hybrid energy system for application in Ethiopia,” *Appl. Energy*, vol. 87, no. 2, pp. 487–495, 2010.

[7] M. Nemati, M. Braun, and S. Tenbohlen, “Optimization of unit commitment and economic dispatch in microgrids based on genetic algorithm and mixed integer linear programming,” *Appl. Energy*, vol. 210, pp. 944–963, 2018.

[8] S. L. Gbadamosi, N. I. Nwulu, and Y. Sun, “Harmonic and power loss minimization in power systems incorporating renewable energy sources and locational marginal pricing,” *J. Renew. Sustain. Energy*, vol. 10, pp. 1–24, 2018.

[9] B. M. Radhakrishnan and D. Srinivasan, “A multi-agent based distributed energy management scheme for smart grid applications,” *Energy*, vol. 103, pp. 192–204, 2016.