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Optimization of the Operational Cost and Environmental Impact of a Multi-Microgrid System

Tiaan Gildenhuys, Lijun Zhang*, Xianming Ye and Xiaohua Xia

Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Hatfield, Pretoria 0002, South Africa

Abstract

A multi-objective optimization model is developed for a multi-microgrid system, which not only minimizes its operational cost but also the emissions. The performance of the proposed model is evaluated by comparing its results to the results provided by a single-objective optimization model that only minimizes the operational cost. Both of these models are applied on a case study and solved through the use of hybrid functions between Matlab's genetic algorithm, fmincon and fgoalattain. The proposed model identified an energy management plan for the multi-microgrid system in the case study that increases the operational cost by 19.4% but it decreases the emissions by 73.9%.

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Keywords: Microgrid; Multi-microgrid system; Networked microgrids; Operational Cost; Emissions; Optimization.

1. Introduction

A microgrid (MG) refers to a collection of controllable distributed generating units (diesel generators, micro-turbines, fuel cells, etc.), uncontrollable distributed generating units (wind turbines, photo-voltaic systems, etc.), distributed energy storage systems (batteries, capacitors, flywheels, etc.) and loads that together form a single controllable system used to supply heat and power to a local area [1]. A grid-connected microgrid can import power from and export power to the main grid; however, a microgrid can also operate in island mode which isolates it from

* Corresponding author. Tel.:+27 012 420 2674; fax: +27 012 362 5000.
E-mail address: lijun.zhang@up.ac.za

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the main grid [1]. A microgrid can also be connected to another microgrid to form a multi-microgrid system that provides the microgrids with an opportunity to share power amongst one another [2]. The optimal energy management plan of a multi-microgrid system can be identified through the use of an optimization model. However, existing optimization models only minimize the overall operational cost of a multi-microgrid system and do not consider the emissions such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon dioxide (CO_2), etc. These emissions should not be ignored as they have substantially contributed towards climate change, which will cause severe droughts, hurricanes, flooding, change in the rainfall pattern, increase in sea levels, etc. [3]. As a result, it is recommended that an optimization model should be developed to identify the optimal energy management plan of a multi-microgrid system, which not only minimizes the operational cost but also the emissions.

Nomenclature

C_i	number of controllable/dispatchable generating units within the i-th microgrid
$C_{i,grid}(t)$	cost associated with the i-th microgrid for purchasing power from the main grid
$C_{i,j}(t)$	cost associated with the i-th microgrid for purchasing power from the j-th microgrid
E_i	number of distributed energy storage systems within the i-th microgrid
$E_{i,grid,s}(t)$	mass of the s-th emission emitted by the main grid's coal power plants
$E_{i,x,s}(t)$	mass of the s-th emission emitted by the i-th microgrid's x-th controllable generating unit
$FC_{i,x}(t)$	fuel cost of the i-th microgrid's x-th controllable generating unit during time instance t
$I_{i,grid}(t)$	income received by the i-th microgrid for selling power to the main grid
$I_{i,j}(t)$	income received by the i-th microgrid for selling power to the j-th microgrid
$LD_i(t)$	load demand associated with the i-th microgrid
M	number of individual microgrids
$OM_{i,x}(t)$	operational and maintenance cost of the i-th microgrid's x-th controllable generating unit
$OM_{i,y}(t)$	operational and maintenance cost of the i-th microgrid's y-th uncontrollable generating unit
$OM_{i,k}(t)$	operational and maintenance cost of the i-th microgrid's k-th energy storage system
$P_{i,x}^{Con}(t)$	output power of the i-th microgrid's x-th controllable generating unit
$P_{i,x}^{ConMin}$	minimum output power of the i-th microgrid's x-th controllable generating unit
$P_{i,x}^{ConMax}$	maximum output power of the i-th microgrid's x-th controllable generating unit
$P_{i,k}^{ESS}(t)$	power flowing from or to the i-th microgrid's k-th energy storage system
$P_{i,k}^{ESSMin}$	minimum power flow from or to the i-th microgrid's k-th energy storage system
$P_{i,k}^{ESSMax}$	maximum power flow from or to the i-th microgrid's k-th energy storage system
$P_{i,grid}(t)$	power flowing between the main grid and i-th microgrid
$P_{i,grid}^{Min}$	minimum power flow between the main grid and i-th microgrid
$P_{i,grid}^{Max}$	maximum power flow between the main grid and i-th microgrid
$P_{i,j}^{MG}(t)$	power flowing between the i-th microgrid and j-th microgrid
$P_{i,j}^{MGMin}$	minimum power flow between the i-th microgrid and j-th microgrid
$P_{i,j}^{MGMax}$	maximum power flow between the i-th microgrid and j-th microgrid
$P_{i,y}^{Uncon}(t)$	output power of the i-th microgrid's y-th uncontrollable generating unit
$R_{down,x,i}$	lower ramp rate limit of the i-th microgrid's x-th controllable generating unit
$R_{up,x,i}$	upper ramp rate limit of the i-th microgrid's x-th controllable generating unit
$SD_{i,x}(t)$	shutdown cost of the i-th microgrid's x-th controllable generating unit
$SOC_{i,k}^{ESS}(t)$	state of charge of the i-th microgrid's k-th energy storage system
$SOC_{i,k}^{ESSMin}$	minimum state of charge of the i-th microgrid's k-th energy storage system
$SOC_{i,k}^{ESSMax}$	maximum state of charge of the i-th microgrid's k-th energy storage system
$SU_{i,x}(t)$	start-up cost of the i-th microgrid's x-th controllable generating unit
T	number of time instances
U_i	number of uncontrollable/nondispatchable generating units within the i-th microgrid
V	number of different types of emissions
$\triangle t$	time interval

2. Proposed multi-objective optimization model

2.1. Objective functions

The first objective function minimizes the operational cost of a multi-microgrid system and is given by

$$\text{minimize} \quad F_{Total} = \sum_{i=1}^{M}\left[\sum_{t=1}^{T}\left[\begin{array}{l}\sum_{x=1}^{C_i}\left[FC_{i,x}(t)\right]+\sum_{x=1}^{C_i}\left[OM_{i,x}(t)\right]+\sum_{x=1}^{C_i}\left[SU_{i,x}(t)\right]+\sum_{x=1}^{C_i}\left[SD_{i,x}(t)\right]\\ +\sum_{y=1}^{U_i}\left[OM_{i,y}(t)\right]+\sum_{k=1}^{E_i}\left[OM_{i,k}(t)\right]+\sum_{\substack{j=1\\ j\neq i}}^{M}\left[C_{i,j}(t)-I_{i,j}(t)\right]\\ +C_{i,grid}(t)-I_{i,grid}(t)\end{array}\right]\right].$$

The second objective function minimizes the emissions and is given by

$$\text{minimize} \quad E_{Total} = \sum_{i=1}^{M}\left[\sum_{t=1}^{T}\left[\sum_{s=1}^{V}\left[\sum_{x=1}^{C_i}\left[E_{i,x,s}(t)\right]+E_{i,grid,s}(t)\right]\right]\right].$$

2.2. Decision variables

The proposed optimization model includes several decision variables, namely.

- Output power of the i-th microgrid's x-th controllable generating unit ($P_{i,x}^{Con}(t)$).
- The amount power flowing from or to the i-th microgrid's k-th energy storage system ($P_{i,k}^{ESS}(t)$).
- The amount of power flowing between the i-th microgrid and j-th microgrid ($P_{i,j}^{MG}(t)$).
- The amount of power flowing between the main grid and i-th microgrid ($P_{i,grid}(t)$).

2.3. Constraints

The constraint that ensures there is a balance between the load demand and supply is given by

$$\sum_{x=1}^{C_i}\left[P_{i,x}^{Con}(t)\right]+\sum_{y=1}^{U_i}\left[P_{i,y}^{Uncon}(t)\right]+\sum_{k=1}^{E_i}\left[P_{i,k}^{ESS}(t)\right]+P_{i,grid}(t)+\sum_{j=1}^{M}\left[P_{i,j}^{MG}(t)\right]=LD_i(t).$$

The lower and upper boundary constraints of the decision variables are given by

$$P_{i,x}^{ConMin} \le P_{i,x}^{Con}(t) \le P_{i,x}^{ConMax},$$

$$P_{i,grid}^{Min} \le P_{i,grid}(t) \le P_{i,grid}^{Max},$$

$$P_{i,j}^{MGMin} \le P_{i,j}^{MG}(t) \le P_{i,j}^{MGMax},$$

$$P_{i,k}^{ESSMin} \le P_{i,k}^{ESS}(t) \le P_{i,k}^{ESSMax}.$$

The ramp rate constraints of the i-th microgrid's x-th controllable generating unit are given by

$$P_{i,x}^{Con}(t) - P_{i,x}^{Con}(t-1) \le R_{up,i,x}\Delta t,$$

$$P_{i,x}^{Con}(t-1) - P_{i,x}^{Con}(t) \le R_{down,i,x}\Delta t.$$

The constraint that ensures the state of charge of an energy storage system does not exceed its minimum and maximum limits is given by

$$SOC_{i,k}^{ESSMin} \le SOC_{i,k}^{ESS}(t) \le SOC_{i,k}^{ESSMax}.$$

A constraint is required to ensure that the initial and final state of charge of an energy storage system are equal. That constraint will ensure that an energy storage system can be used periodically and is given by

$$SOC_{i,k}^{ESS}(1) = SOC_{i,k}^{ESS}(T).$$

3. Case study

This case study considers a grid-connected multi-microgrid system, which consists of three microgrids. Each microgrid includes a number of generating units, storage units and a load demand as shown by Table 1 and Fig. 1. Each microgrid includes a 480 kWh lithium-ion battery with an initial state of charge of 70% and with a maximum and minimum state of charge of 100% and 10% [4], respectively. The upper and lower ramp rate limits of the micro-turbines are equal to 50% of their capacity [5]. The maximum amount of power that may flow between any microgrid and the main grid is 250 kW whereas the maximum amount of power that may flow between the microgrids is 100 kW.

Table 1. Characteristics of the distributed generating units and storage units within each microgrid [6].

Generating/storage unit	Fuel cost ($/kWh)	Fuel cost ($/h)	Operational and maintenance cost ($/kWh)	Start-up and shutdown cost ($)	Lower limit of the output power (kW)	Upper limit of the output power (kW)
Photo-voltaic in MG 1	n/a	n/a	0.0048	n/a	0	60
Wind turbine in MG 1	n/a	n/a	0.0095	n/a	0	40
Battery in MG 1	n/a	n/a	0.0133	n/a	-30	30
Micro-turbine in MG 1	0.0475	0.9667	0.0079	0.1109	3	40
Photo-voltaic in MG 2	n/a	n/a	0.0048	n/a	0	30
Wind turbine in MG 2	n/a	n/a	0.0095	n/a	0	75
Battery in MG 2	n/a	n/a	0.0133	n/a	-30	30
Micro-turbine in MG 2	0.0412	1.1094	0.0063	0.1426	5	50
Photo-voltaic in MG 3	n/a	n/a	0.0048	n/a	0	45
Wind turbine in MG 3	n/a	n/a	0.0095	n/a	0	50
Battery in MG 3	n/a	n/a	0.0133	n/a	-30	30
Micro-turbine in MG 3	0.0475	0.9667	0.0079	0.1109	3	35

The mathematical terms within the first objective function can be derived through the use of Table 1 and Fig 2. Similarly, the mathematical terms within the second objective function can be derived through the use of Table 2.

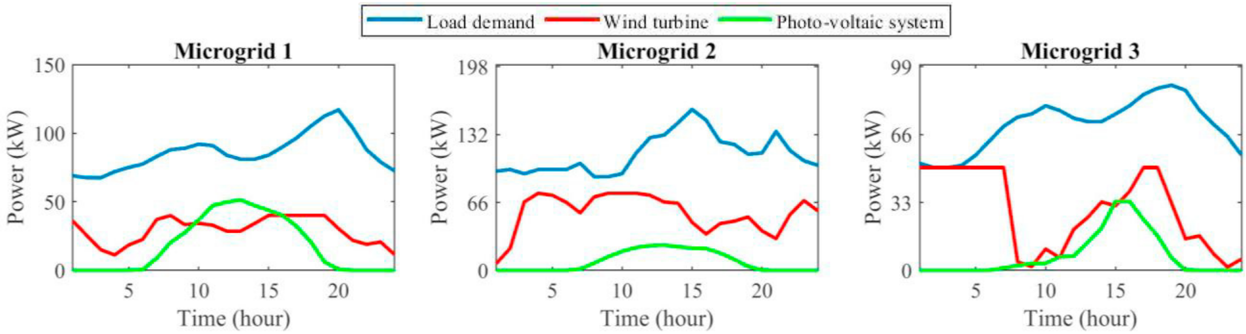

Fig. 1. Output power of the photo-voltaic system and wind turbine as well as the load demand within each microgrid [6], [7].

Fig. 2. Main grid and microgrid tariffs [6].

Table 2. Emission rates of various generating units [8].

	Photo-voltaic system	Wind turbine	Micro-turbine	Main grid (coal power plant)
NO_x (g/kWh)	0	0	0.1996	2.54
CO_2 (g/kWh)	0	0	0.7239	959.35
SO_2 (g/kWh)	0	0	0.0036	6.08

4. Results

4.1. Evaluating the performance of the proposed optimization model

Performance of the proposed optimization model is evaluated by comparing its results to the results provided by an existing optimization model developed in [6]. The model in [6] is one of the best models for a multi-microgrid system; however, it does not minimize the emissions, neither does it consider the ramp rate limits of the controllable generating units. The existing and proposed models were applied twenty times on the case study and solved through the use of hybrid functions between Matlab's genetic algorithm, fmincon and fgoalattain [9]. The twenty unique solutions provided by each model are used to calculate the average, median, minimum and maximum solutions.

4.2. Evaluation of the results

Figure 3 indicates that the proposed model provided an average solution, which increases the operational cost by 19.4%; however, it decreases the emissions by 73.9%. There is an increase in the operational cost because during the off-peak period (21:00 to 6:00) the optimization model will try to minimize the operational cost by purchasing power from the main grid ($0.027/kWh) as it is less expensive in comparison to the fuel cost of the micro-turbines ($0.04/kWh). However, at the same time the optimization model will try to utilize the micro-turbines as much as possible to minimize the emissions. This trade-off between the micro-turbines and the main grid during the off-peak period causes the increase in the operational cost when trying to reduce the emissions.

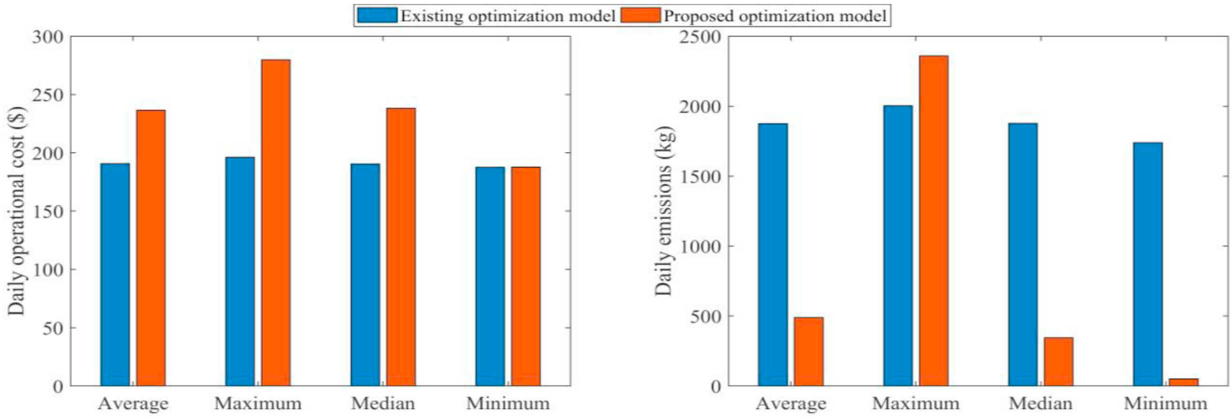

Fig. 3. Results provided by the existing optimization model and proposed optimization model.

5. Conclusion

Previous optimization models only minimized the operational cost of a multi-microgrid system. However, a new optimization model has been proposed, which not only minimizes the operational cost but also the emissions. The average solution provided by the proposed optimization model increases the operational cost by 19.4%; however, it decreases the emissions by 73.9%. This suggests that the proposed model should definitely be considered if an environmentally friendly energy management plan needs to be identified for a multi-microgrid system.

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