International Conference on Applied Energy 2020
Dec. 1 - Dec. 10, 2020, Bangkok / Virtual
Paper ID: 192

Optimal Power Component Sizing of Vehicle-borne Mobile Microgrids for Military Applications†

Saad Bin Arshad, Jiangfeng Zhang*, Beshah Ayalew, and Pierluigi Pisu

Department of Automotive Engineering, Clemson University, SC, USA

ABSTRACT

Remote and temporary military installations often do not have grid power connectivity despite the large electrical loads they have to support. In order to ensure adequate power supply for such needs, microgrids (MGs) composed of a variety of mobile power sources are often utilized. This paper studies the component sizing problem for such microgrids by formulating an optimization model with various budgetary, power, and packaging constraints. The optimization problem is solved to obtain a design that minimizes the operating cost of the MG while meeting all the microgrid design objectives and operational constraints.

Keywords: military microgrid, optimal sizing, vehicle-loaded microgrid

1. INTRODUCTION

Many temporary military forward operating bases are often located in remote locations without grid access. Thus, these temporary forward bases may use mobile vehicle-borne microgrids [1] as their primary source of power. Microgrids (MGs) may be powered by a combination [2] of diesel generators (gensets) on host vehicles, small size or micro combined heat and power (CHP), fuel cells, bi-directional (plug-in hybrid electric vehicles) PHEVs [3], portable photovoltaic (PV) systems, supercapacitors [4], small wind turbines, battery packs, etc. The loads on the MG may include communication systems, hospitals, surveillance, and reconnaissance equipment, and unmanned/manned electric vehicles.

This paper models the optimal power component sizing problem for such an MG as a mixed-integer nonlinear programming (MINP) problem. The optimal design will minimize the operating cost (OPEX) of the MG while meeting budget and various energy security constraints. For example, such an MG formed around tactical vehicles can maintain the backup power supply of a command center or critical loads at a forward operating base for up to 48 hours [5] without relying on the main grid power supply. Compared to usual commercial microgrid designs, the military MG investigated here has special requirements on the physical sizes of the power components due to the limited loading capacity of available vehicles. To solve this problem, special packaging constraints are introduced in the aforementioned optimization formulation. Furthermore, since the resulting MINP is computationally challenging, we propose a priority-based operating strategy that accelerates the speed of solution at some potential loss of optimality. To illustrate the main modeling ideas and solution approach for a multi-option military microgrid, a case study is provided.

2. MODELING

2.1 Optimization Problem Setup

For use in vehicle-loaded MGs, the portability of the power-producing components is vital. To this end, a total of four different types of power sources and storage systems are divided into nine categories. These are selected in order to simulate a wide variety of possible types of DC and AC power sources that may be available to forward military bases. Since this is an optimal design on a higher level of abstraction, for simplicity only component power in and outflows are considered instead of voltages and currents.

Out of the nine categories, four are considered mobile and the rest are considered movable. 'Mobile' components are defined as those that are installed in a truck and available to supply power without setting up (i.e. simply plug-and-play) while 'movable' components

*: Corresponding author, Email: jiangfz@clemson.edu
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are ones that are installed in a truck as well but need simple connections and setup and/or assembly (e.g. to set up the PV panels on the field next to a truck). It is assumed that the total demand of the MG is split into separate demand profiles for the mobile and the movable components.

The table below lists each category considered:

Category (Cat)	Component Type
1	Mobile Diesel genset
2	Mobile solar PV system
3	Mobile Diesel CHP genset
4	Mobile Li-Ion battery pack
5	Movable Diesel genset
6	Movable solar PV system
7	Movable Diesel CHP genset
8	Movable Li-Ion battery pack
9	Movable wind turbine generator

2.2 Optimization Variables and Objective Function

The optimization variables or inputs (or 'decision variables') to the mixed-integer non-linear optimization problem considered include the choices of the component chosen from each of the nine categories as well as the instantaneous power outflows from each component. We collect the optimization variable in the vector x given as follows:

$$x = (u_{1,1},\ \ldots,\ u_{J_1,1}, u_{1,2},\ \ldots,\ u_{J_2,2},\ \ldots,\ u_{1,n},\ \ldots,\ u_{J_j,n}, P_{1,1}(1), \ldots, P_{j,n}(T))$$

where:

- $u_{i,j}$ is equal to 1 when the component i from category j is chosen and is equal to zero otherwise
- n is the total number of component categories considered
- J_j is the maximum number of components in category j
- $P_{i,j}(\mathrm{T})$ is the power outflow from component i from category j at time T

The objective function is to minimize the OPEX of the microgrid over a demand profile of time T. The OPEX consists of the fuel cost of any gensets in the MG while the OPEX resulting from the batteries and renewable power sources (i.e. solar PV and wind turbines) is considered zero. Hence the objective function is given in the equation below:

$$\min f(x) = FC(\$)$$

where:

- $FC = \sum_{j=1,3,5,7} FCon_{Cat-j_T}(gal) \times \mathrm{Pr}_{Fuel}(\$/gal)$
- FC is the fuel cost consumed in time T
- $FCon_{Cat-j_T}$ is the quantity of fuel consumed by chosen component from category j in time T
- Pr_{Fuel} is the price of fuel per unit in USD

2.3 Optimization Constraints

There is a multitude of linear as well as non-linear constraints placed on the decision variables. Since only one component is allowed to be chosen from each category, we have the following exclusivity integer constraint:

$$\sum_{i=1}^{J_j} u_{i,j} \leq 1,\ \forall\, j = 1,\ \ldots,\ n$$

The capital expense (CAPEX) of the MG should not exceed a pre-defined budget hence the following budget constraint applies:

$$\sum_{j=1}^{n} \sum_{i=1}^{J_j} u_{i,j} \times c_{i,j}\ (\$) = CT_{Fuel}(\$) + CT_{Cont}\ (\$) \leq B(\$)$$

where:

- $c_{i,j}$ is the component CAPEX in USD
- CT_{Fuel} is the capital cost of tanker truck(s) for carrying fuel
- CT_{Cont} is the capital cost of container truck(s) for carrying MG components
- B is the total budget for the MG in USD

The nine categories of components considered contain both renewable as well as non-renewable power generation sources. Since renewables such as solar and wind turbines have relatively unreliable power output due to dependence on weather conditions, the MG is constrained to meet a minimum percentage of power demand from more consistent and predictable non-renewable power sources especially for mission-critical loads present in the MG. The gensets are an example of consistent/predictable power sources. Thus, the power supply security constraints are as follows (including batteries):

$$\sum_{j=1,3,4} \sum_{i=1}^{J_j} u_{i,j} * P_{i,j}^{c} \geq P_{crit,\,mob,\,max}$$

$$\sum_{j=5,7,8,10} \sum_{i=1}^{J_j} u_{i,j} * P_{i,j}^{c} \geq P_{crit,\,mov,\,max}$$

where:

- $P_{i,j}^{c}$ is the component rated power output in kW
- $P_{crit,\,mob,\,max}$ and $P_{crit,\,mov,\,max}$ are the minimum total critical power outputs required from the mobile and movable components, respectively

To provide an extra level of redundancy, the gensets alone (excluding batteries) are sized to meet a minimum level of power requirement that may be less than or equal to the critical requirement as follows:

$$\sum_{j=1,3}\sum_{i=1}^{J_j} u_{i,j} * P_{i,j}^{c} \geq P_{max,1}$$

$$\sum_{j=5,7,10}\sum_{i=1}^{J_j} u_{i,j} * P_{i,j}^{c} \geq P_{max,2}$$

where $P_{max,1}$ and $P_{max,2}$ are the minimum total power outputs required from the mobile and movable components, respectively.

The battery state-of-charge (SOC) is calculated and constrained by the non-linear functions as follows:

$$SOC_j(t) = SOC_j(t-1) - \frac{\sum_{i=1}^{J_j} u_{i,j} * P_{i,j}(t)\Delta t}{P_{i,j}^{C}}$$

$$for\ j = 4\ and\ 8;$$

$$SOC_j^{min} \leq SOC_j(t) \leq SOC_j^{max},\ j = 4\ and\ 8$$

Solar PV sets' and wind turbine generators' power output will vary in accordance with the instantaneous solar insolation and the wind speed at each time interval t for total time T thus the instantaneous power output for these will vary. For the other components, their instantaneous power output is assumed to equal their power ratings.

$$P_{i,j}(t) = F\left(P_{i,j}^{C},\ t\right),\ \forall\, j = 2,6,9$$

$$P_{i,j}(t) = P_{i,j}^{C},\ \forall\, j \neq 2,6,9$$

In terms of packaging, it is assumed that two different types of trucks are available for mobile and movable components. For the mobile components, it is assumed only a single truck (smaller size than that for movable components) is available and the solar panels are mounted on the exterior surface of the truck on movable fittings that can be adjusted according to the solar irradiance angle. The constraint is as follows:

$$P_{i,2}^{c} \leq P_{allowed}$$

The packaging in itself is quite a complicated optimization problem as there is a huge variation in the packaging possibilities. Thus, some simplifying assumptions have been made, for example, all components encapsulated within a rectangular prism-shaped 'bounding box', and for irregular objects, we take the maximum length, maximum width and maximum height into consideration. Thus, the constraints become:

$$\mathrm{h}_{i,j} \leq \mathrm{h}_{mob},\ \forall\, i, \forall\ j = 1, \dots, 4$$

$$\mathrm{h}_{i,j} \leq \mathrm{h}_{mov},\ \forall\, \mathrm{i}, \forall\ j = 5, \dots, 10$$

$$\mathrm{w}_{i,j} \leq \mathrm{w}_{mob},\ \forall\, i, \forall\ j = 1, \dots, 4$$

$$\mathrm{w}_{i,j} \leq \mathrm{w}_{mov},\ \forall\, \mathrm{i}, \forall\ \mathrm{j} = 5, \dots, 10$$

$$\sum \mathrm{ftp}_{i,j} \leq \mathrm{ftp}_{mob},\ \forall\, i, \forall\ j = 1, \dots, 4$$

$$\sum \mathrm{ftp}_{i,j} \leq \mathrm{ftp}_{mov},\ \forall\, i, \forall\ j = 5, \dots, 10$$

$$\sum \mathrm{W}_{i,j} \leq \mathrm{W}_{mob},\ \forall\, i, \forall\ j = 1, \dots, 4$$

$$\sum \mathrm{W_{i,j}} \leq \mathrm{W_{mov}},\ \forall\, \mathrm{i}, \forall\ \mathrm{j} = 5, \dots, 10$$

where:

- $\mathrm{h}_{i,j}$, $\mathrm{w}_{i,j}$, and $\mathrm{l}_{i,j}$ are the height, width, and the length of the bounding boxes of each component
- h_{mob}, w_{mob} and l_{mob} are the height, width, and the length of the total truck storage space for the mobile components
- h_{mov}, w_{mov} and l_{mov} are the height, width, and the length of the total truck storage space for the movable components
- $\mathrm{ftp}_{i,j} = \mathrm{l}_{i,j} * \mathrm{w}_{i,j}$ is the footprint area
- $\mathrm{W}_{i,j}$ are the weights of each component
- ftp_{mob}, ftp_{mov}, W_{mob} and W_{mov} are the total interior floor areas and weight capacities of the trucks for the mobile and movable components

In order to have a truly optimal design with the lowest possible OPEX, the power instantaneous power outflows from each component should exactly equal the power demand. The instantaneous power demand can be met by an infinitely large combination of relative component power outflows, one of which would result in the least OPEX. This approach, though optimal, would entail finding this optimal combination for each MG design and that would become prohibitively expensive computation-wise.

Thus, in order to aid quick convergence to a feasible design and minimize the computational cost, a priority-based operating strategy is employed. It is assumed that in order to ensure the cleanest operation, the renewables are fully utilized first to meet the power demand, then the gensets, and finally the batteries.

3. CASE STUDY

An extensive internet search is carried out to catalog multiple commercially available components for each category. A total of 69 components are listed each with its rated power output, purchase cost, dimensions, and weight data. Only one 20-ft container truck for mobile components and two 40-ft container trucks for the movable ones were considered.

Arbitrary power demand profiles are generated to simulate and MG of 300kW total peak demand with 40% coming from mobile components and the rest from movable components. Fig. 1 shows how the original demand is met using the various optimally selected

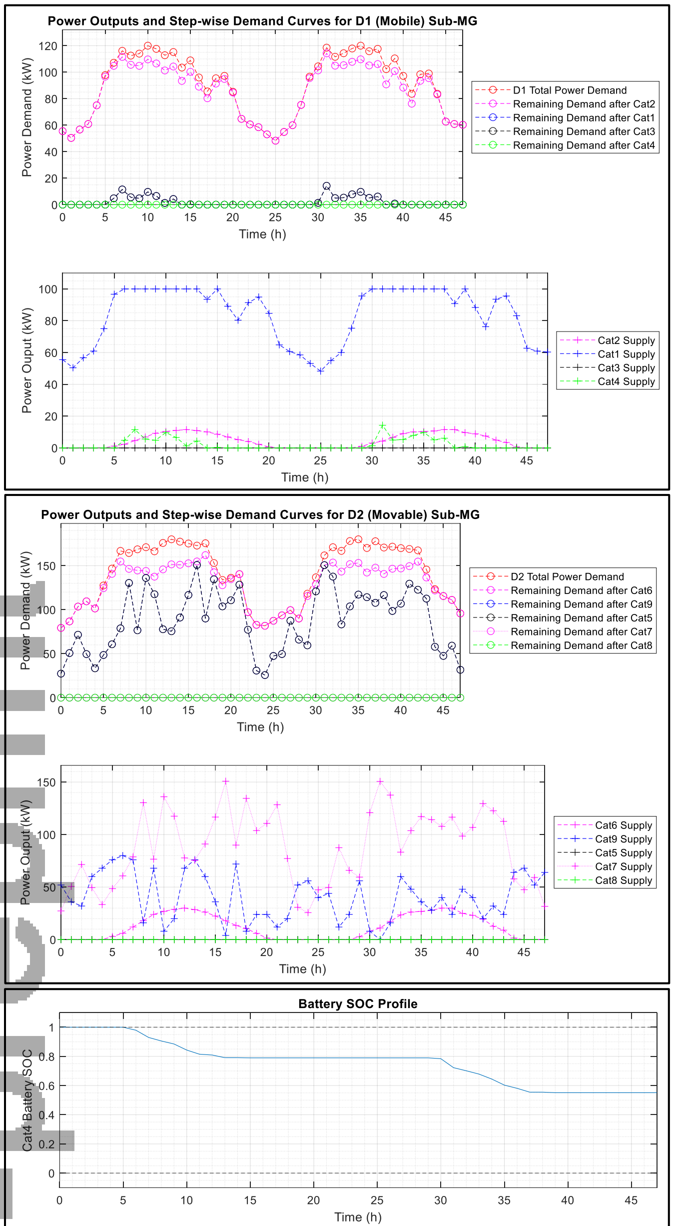

Fig. 1 Demand, Power Flow and Battery SOC Profiles

components. In this particular case, a single component from each of Cat1 (100kW), Cat2 (11.5kW) and Cat4 (232kW) (assuming 100% initial SOC and 1C discharge rate thus capacity is 232 kWh) are required to meet D1 demand. Similarly, for the case for the D2 demand, the choices are Cat6 (30kW), Cat7 (165kW), and Cat9 (80kW). No components are selected from Cat3, Cat5 and Cat8. Note that Cat2, Cat6 and Cat9 power outputs are calculated assuming a certain solar insolation and wind speed profile at the location. The instantaneous genset power is normalized to its rated capacity to find engine load which is then used to compute the instantaneous fuel consumption using a 2D lookup with inputs of power rating and engine load.

A budget limit of \$3.50M is set and the total resulting OPEX is \$1,372.63 for a demand profile of 48 hours with hourly increments.

The genetic algorithm from MATLAB is used to solve this MINP optimization problem. The results above show an optimal selection of components that meet the power demand with a minimum OPEX while satisfying all the power, energy security, and packaging constraints.

CONCLUSION

This paper presents an optimal design model for vehicle-loaded microgrid for the purpose of military applications, and a relatively computationally inexpensive algorithm is applied to solve the obtained problem. The designed microgrid is able to meet the needs of a forward operating base using two vehicle loaded generation facilities while minimizing the relevant OPEX while staying within budget. Future work will focus on the operational problem of this microgrid.

ACKNOWLEDGEMENT

Clemson University, Department of Automotive Engineering and the authors acknowledge the technical and financial support of the Automotive Research Center (ARC) in accordance with Cooperative Agreement W56HZV-19-2-0001 U.S. Army CCDC Ground Vehicle Systems Center (GVSC) Warren, MI. The time allotment on the Clemson University Palmetto Supercomputing Cluster is also acknowledged.

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