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Optimal Operation of Islanded Vehicle-Borne Microgrid under a Limited Fuel Constraint†

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ABSTRACT

The operation of microgrids (MGs) has garnered much attention in recent years due to their potential for leveraging renewable and non-renewable energy sources in a well-integrated system. One MG configuration which has not been extensively studied is the islanded vehicle-borne MG (VBMG). Optimizing the operation of any MG is important to ensure power security, resilience, and cost. The main factor considered in this paper is an operational condition in which additional fuel supply cannot reach an islanded VBMG. This paper discusses the optimal operation a VBMG while maximizing the amount of time given finite fuel constraints. The result can be key to ensuring successful power supply for critical tasks in applications such as disaster rescue and recovery, mobile medical services, and military applications.

Keywords: mobile microgrid, optimal operation, vehicle-borne microgrid

1. INTRODUCTION

Microgrids (MGs) are inherently versatile, which allows them to be used in many applications. MGs are powered by micro-sources, which could be comprised of renewable sources such as wind turbines and solar panels, or non-renewables such as diesel generators and storge systems such as batteries, to collectively meet a system load. Many systems have been considered for loads including EV charging stations [1], hospitals [2], and forward operating bases (FOBs) for military applications [3]. [1] and [2] consider stationary, grid-connected architectures, while [3] considers a stationary, islanded architecture for the MG. Although [1] includes some extensive parameters to calculate load, EV charging applications may not be useful when considering limited fuel resources. Meanwhile, [2] takes a data-driven approach, much of it used to design the MG, which is not the focus here. In fact, this paper will consider a mobile vehicle-borne microgrid (VBMG) with envisaged applications in the power supply of disaster rescue and recovery, mobile medical services, railway repair, remote construction, etc. The design optimization of such an MG structure has also been discussed in [4]. Such a mobile MG is often operated in islanded mode, similar to [3], due to the requirements of these rescue or mobile missions. Moreover, stationary architectures typically consider the micro-sources to be housed inside buildings or tents [1]-[3], while the mobile VBMG considered here houses the micro-sources in a container which can be towed and transported.

Some papers focus on optimizing MG operation in terms of cost [5]. In [5], this is accomplished by considering the costs of energy production, start-up and shut-down decisions, and earnings from selling power to consumers which is acquired from the utility grid. Then, these costs are combined to either maximize profit or minimize loss. Other papers focus on optimizing in terms of fuel consumption. An example of this can be seen in [6], where the fuel consumption of diesel generators is minimized while also minimizing the number of supercapacitors used, thus making the problem multi-objective. Similarly, [3] aims to optimize the operation of an islanded military MG by minimizing fuel consumption. Although in [3], this is done in part by optimally sizing and managing the BESS. However, an operational scenario which has not been considered in literature is how to maximize the power supply time duration for critical loads when additional fuel supply is not available and the fuel storage within the microgrid is limited. This could be prevalent for urgent scenarios such as disaster rescue and recovery, where critical loads need to be met as long

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as possible. This paper will use a VBMG architecture presented in Section 2 and mixed-integer nonlinear programming (MINLP) to optimize the operation of the VBMG for this scenario.

2. VBMG ARCHITECTURE

The physical description of this architecture can be explained as follows. In this VBMG, the micro-sources are housed in a container, or mounted on the exterior in the case of the PV, which is towed by a truck. This is what allows the VBMG to operate while stationary or mobile. The loads will consist of anything critical for operation. For example, in the case of a disaster rescue from a flood, this could include pumps or lighting systems. Pumps must be powered to evacuate any flood water from buildings or low elevation areas. Lighting systems are critical to workers while operating in dark places which have lost power. Fig. 1 shows this VBMG architecture.

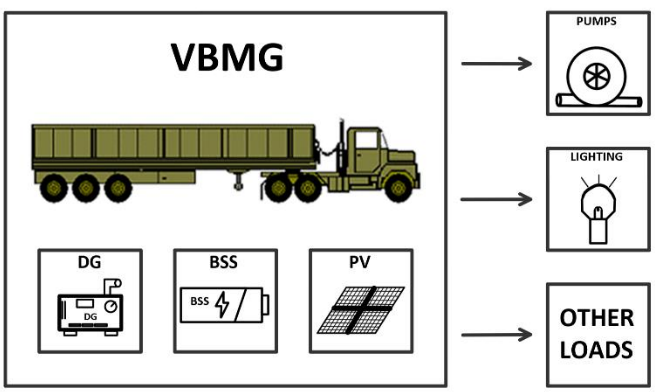

Fig. 1: VBMG Architecture

3. MG MODEL

3.1 Micro-sources

There are three components, or micro-sources, which are used in the VBMG. First, the DG is used due to its reliability and its power output capability relative to size and cost compared to renewable sources and storage components. Next, the PV was chosen due to its negligible operational cost and the fact that it takes up no space inside the container. The PV is mounted to the exterior of the container, which means it can be used while the VBMG is mobile, and it does not take up any interior space in the container. A BESS is also chosen because energy storage is critical since it can supply power from stored energy in the case that other components are having reliability issues. Additionally, energy storage can help with demand smoothing in the case there is a large fluctuation in load.

First, we discuss the system constraints on the DG. In this model, the ON/OFF status of the DG, u_{DG}, is considered at each time, t, as shown in Eqn. (1). The power limits of the DG are given by Eqn. (2), where the output power at each time, $P_{DG}(t)$, must be greater than or equal to the minimum power output, P_{DG}^{min}, and less than or equal to the maximum power output, P_{DG}^{max}. Additionally, the fluctuation in power output from one time step to the next is constrained to maintain DG resiliency. This is represented by Eqns. (3) through (5), where $P_{DG}^{min}(t)$ is the minimum power output at each time, β_0 is the maximum downward fluctuation, $P_{DG}^{max}(t)$ is the maximum power output at each time, and β_1 is the maximum upward fluctuation. The DG fuel consumption at each time, $FC_{DG}(t)$, is calculated using Eqn. (6) via quadratic approximation where α_0, α_1, and α_2 are consumption coefficients. The DG fuel cost at each time, $C_{DG}(t)$, is found by multiplying the fuel cost, C_{fuel}, with the fuel consumption at each time as seen in Eqn. (7). Finally, due to the operational scenario considered in this problem, the fuel supply, FS, is limited. The total fuel consumption, then, must be less than or equal to the fuel supply, which is depicted in Eqn. (8).

$$u_{DG}(t) = \begin{cases} 0, & \text{if DG is off} \\ 1, & \text{if DG is on} \end{cases} \tag{1}$$

$$P_{DG}^{min} \le P_{DG}(t) \le P_{DG}^{max} \tag{2}$$

$$P_{DG}^{min}(t) = P_{DG}(t-1) - \beta_0 \tag{3}$$

$$P_{DG}^{max}(t) = P_{DG}(t-1) + \beta_1 \tag{4}$$

$$P_{DG}^{min}(t) \le P_{DG}(t) \le P_{DG}^{max}(t) \tag{5}$$

$$FC_{DG}(t) = (\alpha_0 P_{DG}(t)^2 + \alpha_1 P_{DG}(t) + \alpha_2)\Delta t \tag{6}$$

$$C_{DG}(t) = C_{fuel} FC_{DG}(t) \tag{7}$$

$$\sum_{t=0}^{T} FC_{DG}(t) \le FS \tag{8}$$

Next, we discuss the constraints for the PV source. In this paper, the PV output at each time, $P_{PV}(t)$, is a function of the maximum output, P_{PV}^{max} and time. This is a simplified, data-driven approach to directly calculate the PV power output instead of relying on instantaneous solar irradiance and temperature. This relationship is represented with the function f_{PV} in Eqn. (9) below.

$$P_{PV}(t) = f_{PV}(P_{PV}^{max}, t) \tag{9}$$

The BESS is the final micro-source in the VBMG. The power output at each time, $P_{BESS}(t)$, is constrained by battery ratings, so the power limits are similar to those of the DG and are shown in Eqn. (10). The state-of-charge at each time, $SOC(t)$, can be calculated using Eqn. (11) where E_{BESS} is the energy capacity of the BESS. Note that this requires an initial SOC value to be known. There are some constraints on the SOC of the BESS as well.

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First, the SOC is constrained in a certain range, SOC_{min} and SOC_{max}, as given in Eqn. (12). Second, the final SOC at the end of the operational time, T, is constrained to be above or equal to a certain value, SOC_{final}, as depicted in Eqn. (13). Additionally, battery degradation is also considered in this paper. The model from [7] is used, which approximates the degradation primarily based on the limited number of life cycles inherent to the battery. The battery degradation cost can be approximated using Eqn. (14), where $C_{BESS}(t)$ is the degradation cost at each time, $C_{BESS}^{expense}$ is the capital expense of the BESS, and n_{cycles} is the number of lifetime cycles for the BESS.

$$P_{BESS}^{min} \leq P_{BESS}(t) \leq P_{BESS}^{max} \quad (10)$$

$$SOC(t) = SOC(t-1) - \frac{P_{BESS}(t-1)\Delta t}{E_{BESS}} \quad (11)$$

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad (12)$$

$$SOC(T) \geq SOC_{final} \quad (13)$$

$$C_{BESS}(t) = \frac{C_{BESS}^{expense}|P_{BESS}(t)|\Delta t}{n_{cycles}E_{BESS}} \quad (14)$$

3.2 Loads

The various loads on the system were mentioned briefly in the introduction. The total load at each time, $D(t)$, is approximated by summing the demand at each time for each load. For example, pump loads can be approximated as a function of the flooded area (A_{flood}) and elevation (e_{area}). Meanwhile, loads from lighting systems can be approximated by a function considering time-of-day and the number of lights required. These are shown in Eqns. (15) and (16). The total load at each time can then be calculated using Eqn. (17). Finally, the power balance constraint is formulated in Eqn. (18), which constrains the entire system to ensure all the critical loads are being met at all times.

$$D_p(t) = g(A_{flood}, e_{area}) \quad (15)$$

$$D_L(t) = h(t, n_L) \quad (16)$$

$$D(t) = D_p(t) + D_L(t) \quad (17)$$

$$u_{DG}(t)P_{DG}(t) + P_{PV}(t) + P_{BESS}(t) = D(t), \quad \forall t \quad (18)$$

3.3 Optimization problem formulation

The optimization objective is to maximize the operational time, T, subject to all the constraints mentioned in Section 3. The optimization should therefore also minimize DG usage since the operational time is primarily dependent on fuel supply. The objective function is compactly written as:

$$\max_{x} f(x) \quad (19)$$

where $f(x) = T$. As aforementioned, this is subject to constraints which are listed as Eqns. (1) through (18).

The optimization variable, x, is defined below and includes the total operation time, T, the DG status, $u_{DG}(t)$, the DG output, $P_{DG}(t)$, the PV output, $P_{PV}(t)$, and the BESS output, $P_{BESS}(t)$, at all times $t \leq T$.

$$x = (T, u_{DG}(1), \dots, u_{DG}(T), P_{DG}(1), \dots, P_{DG}(T), P_{PV}(1), \dots, P_{PV}(T), P_{BESS}(1), \dots, P_{BESS}(T))$$

This optimization problem is a nonlinear mixed-integer problem with nonlinear constraints. One major challenge for solving this problem was including the operational time as a variable when many of the other values were dependent on the operational time (i.e., operational time typically needs to be a preset value to solve the problem). To solve this challenge, an indicator variable was utilized to maximize the time duration while ensuring all constraints could be met, and an upper bound was implemented on the time duration in order for the model to be solvable.

Maximizing the total operational time allows the VBMG to optimize operations for sustained success in the mission. In many of the example missions, the importance of success must be emphasized since the situation may be life or death for some. Furthermore, the problem solution will have large implications on decisions, such as whether to carry out a disaster rescue and recovery mission, in all applications.

4. CASE STUDY

The optimization process was simulated using Gurobi Optimization [8] in conjunction with Python. A time step of one hour is used in this case study. The micro-source parameters used for the DG, PV, and BESS are summarized in Table 1.

The 24-hr load was approximated using parameters mentioned in Section 3.2 and the resulting load profile is shown in Fig. 2. Note that the load profile is based on expectations for a VBMG with the components chosen, and it is simply an example.

Table 1: Micro-source Parameters

Parameter	Value	**Parameter**	Value
P_{DG}^{min}	27 kW	P_{BESS}^{min}	-20 kW
P_{DG}^{max}	90 kW	P_{BESS}^{max}	20 kW
β_0	10 kW	E_{BESS}	46 kWh
β_1	10 kW	SOC_{min}	25%
α_0	-8.229(10^{-4})	SOC_{max}	90%
α_1	3.951(10^{-1})	$SOC_{initial}$	90%
α_2	-4.857(10^{-2})	SOC_{final}	25%
C_{fuel}	0.547 $/L	$CAPEX_{BESS}$	$24,700
FS	757.08 L	n_{cycles}	5,000
P_{PV}^{max}	10.3 kW		

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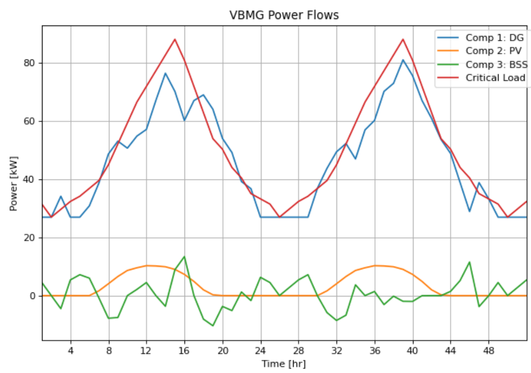

Fig. 2. Power Flow Results

Finally, the optimization results are summarized in Table 2. Along with the complete system, results are also shown if only the DG is included. The tabulated results show the operational costs as they may be of significance, although they were not directly minimized in the optimization. The corresponding power flow graph is depicted in Fig. 2. The power flow graph shows some interesting behavior. First, the PV only outputs power during the day when sunlight is present, and it follows a smooth ramp up and ramp down process. Also, due to the DG output change from one time step to the next being constrained, the BESS fluctuates in quite a peculiar fashion. The BESS fluctuations could also be caused, in part, by the SOC constraints. Overall, we see that the DG is responsible for meeting a large portion of the load over the time horizon.

Table 2: Optimization Results

Parameter	All Components	DG Only
Operational Time	52 h	47 h
Total DG Cost	$416.38	$416.92
Total BESS Degradation Cost	$21.54	$0.00
Total Operational Cost	$437.92	$416.92

5. CONCLUSION

The results for the maximum operational time for the given system show that it could operate for 52 hours. After this time, there is not enough fuel supply to continue operation. This means that it is critical for the disaster rescue to be completed in 52 hours or less, otherwise the mission will fail. However, the possible operational time would be reduced by five hours if only the DG is used in the system, which proves the benefit of storage and renewable components. There are also compromises made when solving the problem in this fashion. For instance, if a mission can be accomplished in less time, then it may be possible to use the DG more and therefore not be as reliant on the other sources which may be less reliable. Additionally, the total operational cost, which is $437.92, is presented which can be useful to decide on the financial feasibility of the disaster rescue. If the operational cost is deemed infeasible, then it may be decided to cancel the disaster rescue.

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