

Management of Mobile Energy Generation and Storage System

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Abstract - As the global demand for energy increases, new technologies are needed to satisfy the necessity for the electrical network growth. Smart grids' operational and energy measures are targeted by most developed countries to enhance the efficiency of their systems, and reduce their carbon dioxide footprint. As part of a Smart Grid (SG), Distributed Generation (DG) has been adapted by grid operators and planners to enhance the efficiency, the stability, the reliability, and the power quality of the electric grid, in addition to, deferring the need for network upgrades. The purpose of this paper is to propose a Mobile Energy Generation and Storage System (MEGSS) that can serve a number of customers using an optimal dispatch approach. Applying day-ahead scheduling for customer's profiles, mixed integer non-linear programming (MINLP) will be used for optimization to maximize the number of customers served. An Energy Management System (EMS) will be used to control the different power generation units on the truck. The costs and revenue of the system will be calculated to realize the efficiency and success of the proposed system.

Keywords - energy storage, energy management, mobile generation, optimization

I. INTRODUCTION

Due to the increase in the global population and cities' expansion, as well as technological advancement, the dependency on electricity is rapidly increasing. Future power grids will witness a shift in focus to Energy Storage Systems (ESS) to accommodate the expansion requirements of power without compromising on the minimization of CO₂ emissions. The State of California has placed a mandate to have more than 1300 MW of its power from storage units [1]. Due to multiple beneficial factors, the use of lithium-ion batteries as a type of ESS (BESS) has significantly increased, lowering its prices [2], making it more attractive for utilities to incorporate such technologies in their system. The importance of ESS units has arisen from the increased penetration of Renewable Energy Sources (RES) to the grid. Due to their intermittent nature, RES units can be problematic to the stability and reliability of the network. The installation of ESS at the same busses as RES will 1) provide an efficient way to store energy while it is not being used, 2) contribute to an almost stable power output, and 3) provide voltage support through VAR compensation [3].

To satisfy a diverse generation grid, without compromising on the stability or reliability of the system, Mobile Energy Storage Systems, in the form of Electric Vehicles, has been the focus of study in a lot of countries and energy sectors. To use EV's as MESS units, the vehicle would participate in grid activities where it would supply power to the grid in times of on-peak selling prices, while charging its batteries during off-peak hours, thus minimizing power drawn from the grid, and capitalizing on

the storage capacity of the EV [4]. This concept, however, known as V2G, is not the focus of this thesis. Alternatively, the work done for this thesis has been motivated by the lack of research on MESS units fully dedicated for the purpose of generation, storage, and providing power to multiple locations.

The need for such units has stemmed from the increased black-outs caused by various reasons: operational faults, natural disasters, events of war or terrorist attacks [5]. During those unfortunate events, parts of or the entire grid might be compromised, leaving people disconnected for days. In the presence of vital facilities, such as hospitals, having a power supply is an essential factor in the survival of human beings and the welfare of the community. On the other hand, the advantage of mobility has proven its worth during such events, as well as during normal operation hours. To have an ESS unit that is capable of being transported from one bus to the other, supplying multiple loads throughout a short period of time has its benefits to the grid, as well as to the environment through the reduced power drawn from the grid. Furthermore, due to short-time peak demand power, typically for industrial customers, utilities often implement very high charges on consumers, requiring them to look for an economically lucrative alternative source of power. The Mobile Energy Generation and Storage System discussed in this paper is an ideal solution for the various events mentioned earlier. The aim of this paper is to design and model the MEGSS unit and optimize the power transactions required for a maximum profit generation.

II. PROPOSED MEGSS

A. Problem Statement

The purpose of the proposed system is achieved through two parts of the solution:

- Modeling a Mobile Energy Generation and Storage System (MEGSS) that can perform energy transactions to multiple customers or locations over the day.
- Developing an optimal scheduling approach to maximize the number of customers served while using low- or zero-emission resources.

B. System Components

The proposed system consists of various power generation methods. To maximize on the reduction of CO₂ emissions, an electric truck was chosen for the MEGSS at hand. The truck can tow a shipping container that contains the system components, which include:

- A diesel generator with its fuel tank

- Lithium-Ion battery array
- PV panels
- Bi-directional inverter

During the movement of the truck, the PV panels mounted on the top of the shipping container will be charging the batteries. During serving time, the diesel generator will be serving the demand of the customers as well as charging the battery pack if required. The batteries will be used to provide the energy required by the movement of the truck, as well as serving part of the customers' demand when possible. As shown in Figure 1, the truck has enough room for personnel to provide required maintenance to the system components if required, and most importantly allows space for ventilation.

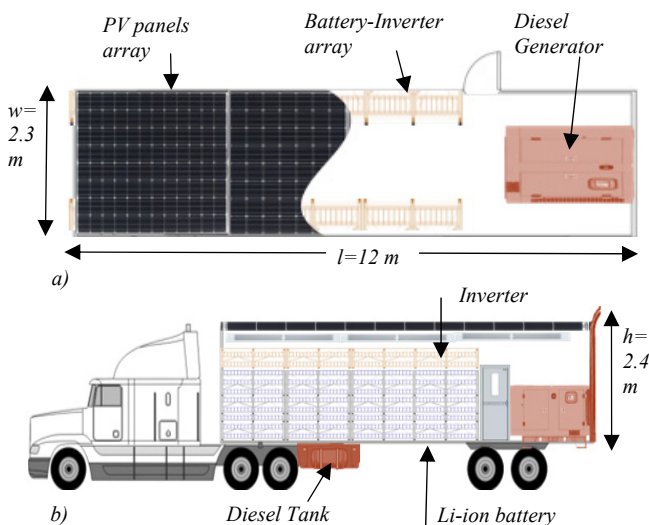


Figure 1 a) Top view and b) side view of suggested MEGSS

The bi-directional inverter is used as DC/AC to convert the power generated from the PV panels and the batteries into AC power to be served to the customers. A representation of the system components and the power flow is modelled in Figure 2. The proposed system consists of a dispatch unit or hub, the MEGSS truck, and an Energy Management System. The flow of operation of the proposed system starts when several customers send their power requirement and their profiles to the hub. The customers' profiles contain the amount of power required, as well as the time and duration of the required service. Based on day-ahead scheduling, the optimizer decides which customers are chosen for service. Using cellular network as a communication medium, the dispatch unit sends all the required information to the MEGSS truck. The Energy Management System in the truck runs the power flow calculations and decides how to control the power, keeping in consideration a set of constraints that involve the behavior of every component in the system.

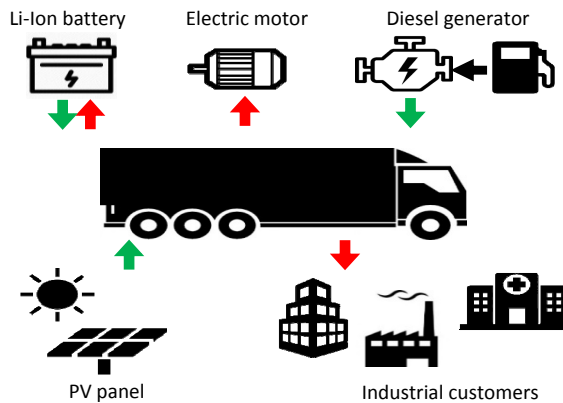


Figure 2 MEGSS components

C. Assumptions

Certain assumptions were considered while designing and modeling the proposed system:

- PV panels output and Traffic data are forecasted day-ahead.
- No overlapping can occur: 1 truck can serve one customer at a time.
- Customers' requirements are received day-ahead.

The proposed system's components and data are combined to optimize the customers' selection based on the profit generated.

III. PROBLEM FORMULATION

To model the problem at hand, based on day-ahead prediction, we define a time step, Δ_t of a few minutes. Modelling the problem using a time-step of 1 hour will not be very efficient due to travelling times, connecting and disconnecting times being provided in minutes. On the other hand, modelling it as 1 minute will require more computational time for a real-time problem similar to the one we are trying to solve. The time-step scheduling is a trade-off between accuracy and computational time, and. Although in a real-time problem like the one at hand, a 1-minute time-step can be solved, it would take a lot of computational time, especially if the problem can be expanded to include more variables. The overall period of modelling the system components will be calculated using $N_t = (60/\Delta_t) \times 24$, and represented as a set $t = \{1,2,3, \dots, N_t\}$. The number of customers requesting service is presented in the set $i = \{1,2,3, \dots, N_c\}$ where N_c is the maximum number of customers to be served is. The set i includes $N_c - 1$ customers as well as the hub as the first element, $i(1)$. In addition, the distance between customers, as well as the time required for travelling between the customers are known and defined as $D_s(i, j)$ and $T_m(i, j)$ respectively. Since the customers requesting service will be in contact with the dispatch center, their profiles will be known.

Using mixed integer non-linear programming (MINLP), an optimizer is used to maximize the number of customers served, as shown in (1)

$$\max \sum C_{served} \quad (1)$$

where C_{served} refers to the customer chosen to be served, based on the time constraint (2)

$$T_s(i) + T_p(i) + T_c(i) + T_d(i) + T_m(i, j) \leq T_s(j) \quad (2)$$

where $T_s(i)$ is the start of serving time, $T_p(i)$ is the serving duration time of each customer, $T_c(i)$ and $T_d(i)$ are the time required to connect the system to each consumer to start serving, and the time required to disconnect the system after supplying, respectively, given in time slots.

The MEGSS unit uses power stored from the batteries for its consumption. Based on (3), the energy consumed by the truck can be calculated

$$E_{move}(i, j) = E_{truck} * D_s(i, j) \quad (3)$$

where E_{truck} is the amount of energy consumed while moving given in kWh/km. To convert this to the power consumed by the truck at every time segment, the energy is divided by the total time travelled by the truck in time slots, The power consumed by the movement of the truck can then be calculated from the energy, as per (4)

$$P_{move}(t) = \frac{E_{move}(i, j)}{T_m(i, j) * \frac{\Delta_t}{60}} \quad (4)$$

To model the output power of the PV panel, the data of solar irradiance for a period of 24 hours was collected and used to measure the voltage and current, and thus, the real power as per (5)

$$T_{cell} = T_A + S_{IR} \frac{(NOCT - 20)}{0.8} \quad (5)$$

where T_{cell} is cell temperature ($^{\circ}C$), T_A is ambient temperature, and S is solar insolation (kW/m^2). To find the current and voltage outputs, I_{PV} and V_{PV} of the panel, (6) and (7) are used as follows

$$I_{PV} = S_{IR} I_{sc} (1 + k_i (T_{cell} - 25)) \quad (6)$$

where I_{sc} is the short circuit current of the PV module, and k_i is the temperature coefficient of I_{sc} .

$$V_{PV} = V_{oc} (1 + k_v (T_{cell} - 25)) \quad (7)$$

where V_{oc} is the open circuit voltage of the PV module, and k_v is the temperature coefficient of V_{oc} . This yields to the calculation of the fill factor required to find the output power of the PV. This is shown in (8), respectively.

$$FF = V_{mpp} \frac{I_{mpp}}{V_{oc} I_{sc}} \quad (8)$$

$$P_{PV} = N_{cells} \times FF \times V_{PV} \times I_{PV} \quad (9)$$

where N_{cells} is the number of solar cells in the chosen module [6].

To model the diesel generator and the charging and discharging behavior of the battery, the Energy Management System will control the power flow during serving times. The diesel generator will be running only while the truck is serving customers. It will be used to supply the power required by the customers, and to charge the batteries if required. The batteries discharge rate will be related to the truck consumption. Though the major contributor of power while serving the customers is the diesel generator, the PV panels contribute at times when $P_{PV} = 0$, thus reducing the use of diesel fuel. The behavior of the diesel generator is governed by the equation shown in (10)

$$P_{dg}(t) = P_i(t) + P_{ch}(t) \quad (10)$$

where P_i is the power required of customer i . The charging behavior of the lithium-ion batteries is described as per (11). The battery will be charged most of the day using the solar panels on the rooftop of the truck. However, the EMS will decide if the battery has enough energy to make the trips of the day, and thus direct the PV power to the customers, who are mainly supplied by the diesel generator, as discussed earlier.

$$P_{ch}(t) = P_{PV}(t) + (P_{dg}(t) - P_i(t)) \quad (11)$$

The discharging behavior of the battery occurs when the truck is moving and can be represented as (12) suggests and then used to find the total battery power as in (13)

$$P_{dis}(t) = P_{move}(t) \quad (12)$$

$$P_{bat}(t) = P_{ch}(t) + P_{dis}(t) \quad (13)$$

The discussed equations are used for a case study to optimize customers chosen and provide an insight on cost and revenue calculations. The final step required to calculate the profit of the system is to use P_{dg} to calculate the cost, and $P(i)$ to calculate the revenue, and eventually, the profit as (14), (15), and (16) suggest

$$Cost = \sum_t Price_{fuel} * FR * P_{dg}(t) * \frac{\Delta_t}{60} \quad (14)$$

where $Price_{fuel}$ is fixed amount of the price of 1 liter of diesel in $\$/L$, and FR is the amount of fuel burned to produce 1 kWh in L/kWh.

$$Revenue_{kW} = \sum_t Price_{kW} * P_i \quad (15)$$

$$Revenue_{kWh} = \sum_t Price_{kWh} * P_i * \frac{\Delta_t}{60} \quad (16)$$

where $Price_{kw}$ is the price of power sold to customers in \$/kW, and $Price_{kWh}$ is the price of energy sold to customers in \$/kWh.

IV. CASE STUDY AND RESULTS

The case study modeled to analyze the power behavior of the various components of the system consists of a time-based optimization of 20 locations, 19 customers and the starting point as the hub. The time step Δ_t is considered to be 5 minutes and is used to cover a period of one full day. The optimizer will ensure that the maximum number of customers is served while maintaining enough time for travelling between the customers, as well as the connecting and disconnecting times required at each customer, as per the constraint in (2). The customers chosen by the optimizer, and their respective profiles, are shown in TABLE I.

The rooftop PV panel chosen for this design is SunPower E20-327, which has an efficiency of 20.4% and an output power of 327 W for a 95 solar cells per module. This gives a maximum output power of approximately 6 kW and thus is considered one of most efficient residential PV module [7].

TABLE I
OPTIMIZED CUSTOMERS AND THEIR POWER PROFILES

Customer No.	T_s	T_{end}	T_p	P (kW)
1 (Hub)	0	1	1	0
20	12	36	24	195
14	96	132	36	160
18	156	168	12	195
12	186	216	30	175
10	234	252	18	185
8	276	287	12	160

To plot P_{dg} , P_{ch} and P_{dis} certain assumptions were made:

- The diesel generator rated power is 200 kW.
- The battery has a capacity of 480 kWh and starts the day with SOC of 35%.

When comparing the plots shown in Figure 3 and Figure 4, it can be noticed the power withdrawn from the battery during discharge seems to be slightly higher than the power consumed by the truck. This is due to the discharging efficiency factor, $Eff_d = 0.9$, and can be considered as power loss. A charging efficiency factor also effects the charging power and it is assumed to be $Eff_c = 0.87$.

Figure 3 shows the total consumption of real power in the proposed system in three categories: truck consumption, customers' consumption, and battery charging. Figure 4 represents the power generated in the system. It can be seen from comparing those two graphs that the PV panels charge the batteries while the truck is idle. On the other hand, at certain times of the day, the PV panels will also provide some of the power required by the customers, in addition to the diesel generated power and battery discharge power. The diesel generator will run only during times of serving, and in this case doesn't need to charge the batteries to

suffice the consumption of the system till the end of the day. However, this will differ in case the initial SOC was different. Losses should also be counted for, just as in the previous case and they are due to the charging and discharging efficiencies of the battery.

Assuming $Price_{kw} = 0.5$ \$/kW, $Price_{kWh} = 0.3$ \$/kWh, and $Price_{fuel} = 0.87$ \$/L, the cost, revenue, and profit of the system during the course of the day were calculated and resulted in a total profit of 327 \$/day.

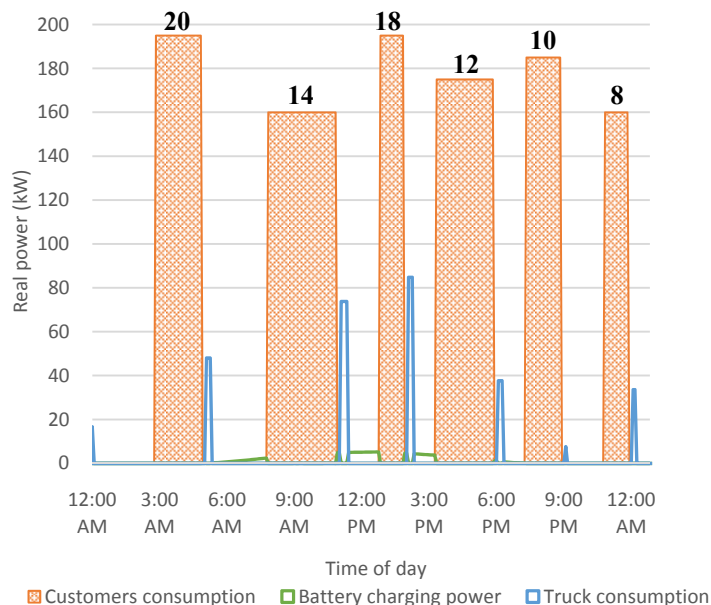


Figure 3 Power consumption of MEGSS unit

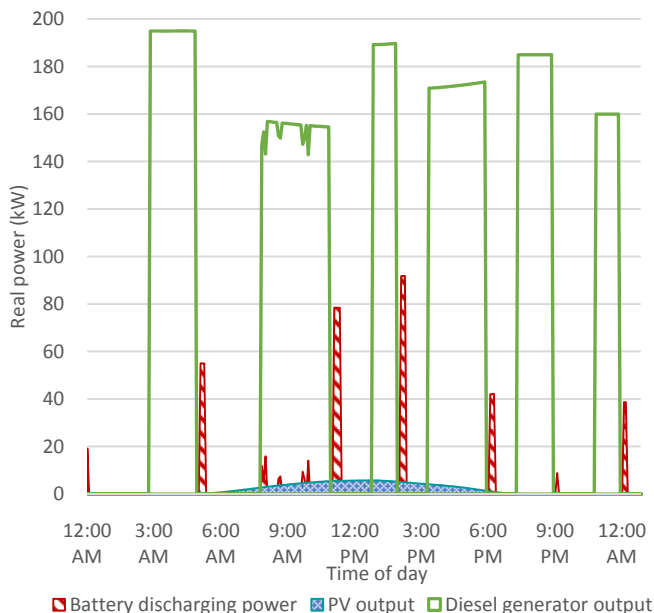


Figure 4 Power generated in MEGSS unit

V. CONCLUSION

This paper discusses a MEGSS that was proposed to optimally dispatch the truck from a hub to serve 19 customers during the period of 24 hours. The problem was solved based on day-ahead forecasting of the demand

requested by the customers. An Energy Management System was designed to control behavior of the generation components of the system: a diesel generator, a PV array, and a Lithium-Ion battery pack. The system generated profit at the end of the day and was successful in reducing the amount of diesel fuel used, and thus contributed to reducing CO₂ emissions.

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