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Discrete Logic vs Optimized Dispatch for Energy Storage in a Microgrid

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***Abstract*—Forward operating base (FOB) microgrids typically use diesel generators with discrete logic control to supply power. However, emerging energy storage systems can be added as spinning reserves and to increase the PV hosting capacity of microgrids to significantly reduce diesel consumption if resources are controlled appropriately. Discrete logic controllers use if/else statements to determine resource dispatch based on inputs such as net load and generator run times but do not account for the capabilities of energy storage systems explicitly. Optimal dispatch controllers could improve upon this architecture by optimizing dispatch based on forecasts of load and generation. However, optimal dispatch controllers are far less intuitive, require more processing power, and the level of potential improvement is unclear.**

This work seeks to address three points with regards to FOB microgrid operations. Firstly, the impact of energy storage systems on the adoption of solar generation in microgrids is discussed. Secondly, logic is added to the typical discrete controller decision tree to account for energy storage resources. Lastly, fuel savings with energy storage and solar generation using the new discrete control logic and optimal dispatch are compared based on load data measured from a real FOB. The results of these analyses show the potential impact of energy storage on fuel consumption in FOBs and gives guidance as to the appropriate control architecture for management of integrated resource microgrids.

***Index Terms*—energy storage,discrete dispatch, optimized dispatch, microgrid**

I. Introduction

Microgrids are being deployed around the nation to increase resiliency during power disruptions and generate revenue when operating in parallel with the electrical grid. Military operational energy has adopted this architecture for forward operating bases (FOBs) because it has been proven to reduce fossil fuel consumption by 49% or more as compared to individually pairing generators with electrical loads [5], [6]. Decreasing FOB fuel consumption leads to fewer fuel convoys, which saves money and reduces the risk of casualties.

Given recent advancements in the industry, energy storage systems can now be deployed in conjunction with fossil fuel generation sources to reduce fuel consumption. Firstly, the presence of energy storage systems can allow for fossil fuel generators to operate more consistently at their optimal point while the energy storage systems handle more of the fluctuations in demand. Secondly, energy storage can greatly increase the amount of alternative generation resources, such as photovoltaics, that can be reliably integrated with the system and thereby reduce fuel consumption further. However, to capture these benefits, the systems would need to be integrated and controlled appropriately.

Most FOB microgrid systems in operation use discrete logic controllers (DLCs) to manage the dispatch of resources [7]. These controllers have been used by industrial and manufacturing entities for many years because of their simple programming, digital and analog input and outputs, widespread vendor support, and low costs. Alternatively, optimal dispatch controllers (ODCs) are now being deployed throughout the microgrid industry and are touted as being superior to DLCs. An ODC uses a forecast of future energy needs and generation, the current status of the system, and objective functions specific to the situation to determine the best resource dispatch schedule. The objective of the controller varies depending on the application and can be economic or technical in nature. In the case of a FOB microgrid, the objective is to minimize fossil fuel consumption. This form of operation has the potential to improve upon DLCs but are more complex, less intuitive, and in practice the potential is highly dependent on the forecast method [11].

This paper addresses three issues concerning the integration of energy storage systems with microgrids through a case study of a FOB measured by the Army Base Camp Integration Laboratory (BCIL) [1]–[4]. Firstly, an analysis of the impact of energy storage on the maximum PV capacity within a FOB microgrid is presented. Secondly, an updated DLC including considerations for the capabilities and limitations of the associated energy storage system is developed. Lastly, FOB fuel savings using DLC and ODC with perfect foresight are compared to show the maximum benefit of optimal dispatch to FOB operations. The results of this work show the impact of energy storage on fuel consumption in FOBs and gives guidance as to the appropriate control architecture for the management of integrated resource microgrids.

II. FOB Microgrid Configuration

For this case study, a FOB with the following attributes was modeled:

- 600 person reconnaissance FOB in the middle east
- 6 diesel Tactical Quiet Generator (TQG) units
- 180-day deployment from March to August

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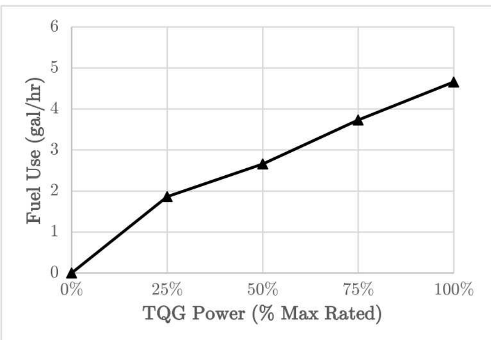
Integration of PV and energy storage will also be explored. Descriptions of the major FOB components follow.

A. Diesel Generation Units

The diesel units modeled here are 60kW TQG. The TQGs are located ∼10 feet apart and connected in a ring bus configuration through electric SO cords. The TQGs can be dispatched separately or in parallel by the energy management system. The relationship between TQG power output and fuel usage as measured at the Army BCIL is specified as shown in Fig. 1. This piecewise linear relationship was used for both of the control methods described below.



TQG Power	Fuel Use (gal/hr)
0%	0.00
25%	1.86
50%	2.66
75%	3.73
100%	4.66

Fig. 1. TQG Fuel use versus power output

B. FOB Energy Storage Systems

Sandia evaluated energy storage systems designed for FOB deployments in collaboration with the Army's BCIL. Systems from four companies (Raytheon/Ktech, GYuasa, Princeton Power and Milspray) were evaluated given their ability to meet military deployment needs. Tests were performed at the Distributed Energy Technology Laboratory in Albuquerque, New Mexico to determine parameters such as capacity and roundtrip efficiency at various power levels, response times to commands, frequency droop control, and voltage droop control. Evaluation results are shown in Table I.

Company	Technology	Rating	Capacity @ Max Power	AC Round Trip Efficiency
GSYuasa	VRLA	60kW/66kWh	58.67kWh	76.87%
Milspray	VRLA	15kW/32kWh	34.90kWh	62.00%
Princeton Power	Li-ion	60kW/60kWh	65.00kWh	78.70%
Ktech/Raytheon	ZnBr Flow	30kW/120kWh	104.00kWh	48.10%

TABLE I
TEST RESULTS FOR FOB ENERGY STORAGE SYSTEMS

These results were used to parameterize models to determine how much fuel could be saved with energy storage and PV generation in a FOB.

C. Photovoltaic Penetration in FOBs

The amount of PV that can be reliably managed is limited by the operating constraints of the TQGs and interconnection equipment. Integration of PV resources with energy storage can significantly increase the solar hosting capacity without violating operating constraints. The essential system constraints pertinent to PV integration are as follows:

1) The minimum generator output is 30% of the full rated power to prevent wet stacking
2) Generation from solar resources cannot be curtailed
   - Solar power conditioning systems (PCSs) are not controlled by the energy management system
   - Solar resources are tied to the microgrid through voltage control current source PCSs
3) If an energy storage system is installed, PV can support the full load so long as the system is not fully charged

To determine the maximum amount of PV generation that could be supported with the addition of energy storage, the following optimization was performed:

$$\begin{aligned} \max_{P_C,P_D} \quad & C_{sol} \\ s.t. \quad & P_{load,t} = P_{D,t} - P_{C,t} + p_{sol,t} \cdot C_{sol} + P_{G,t} \\ & S_t = S_{t-1} + (\eta_{RT} P_{C,t} - P_{D,t})\, \Delta t \end{aligned} \tag{1}$$

where C_{sol} is the installed solar capacity, $p_{sol,t}$ is the per kW generation profile for the modeled location, $P_{D,t}$ is the battery discharge power, $P_{C,t}$ is the battery charge power, $P_{G,t}$ is the power from all TQGs, S_t is the battery state-of-charge at time t, and η_{RT} is the battery roundtrip efficiency. Beyond the basic requirements for power balance and state-of-charge, additional constraints were necessary to ensure that the dispatch reflected realistic operation. Firstly, the following constraints ensure that the battery could not charge and discharge simultaneously:

$$P_{D,t} - P_{\max} \cdot \alpha_{D,t} \leq 0 \tag{2a}$$

$$P_{C,t} - P_{\max} \cdot \alpha_{C,t} \leq 0 \tag{2b}$$

$$\alpha_C + \alpha_D \leq 1 \tag{2c}$$

where α_C and α_D are binary variables that equal one during charge and discharges steps, respectively. As battery operations do not appear in the objective function, some configurations could be made to seem plausible by "curtailing" power by charging and discharging in the same time step if this is not explicitly disallowed.

Constraints were also imposed to reflect the limitations of the TQGs in the system.

$$P_{g,t} \geq K_{low} P_{\max} \cdot \alpha_{g,t} \tag{3a}$$

$$P_{g,t} \leq K_{high} P_{\max} \cdot \alpha_{g,t} \tag{3b}$$

where $\alpha_{g,t}$ is a binary variable indicating that generator g is on at time t, and P_{max} is the maximum generator output. This ensures that the output of each generator is between K_{low} and K_{high} percent of the rated power while operational. For this case, P_{max} is 360kW, the power rating of all six TQGs, K_{low} is 5% (30% output from a single TQG), and K_{high} is 80%. The results of the analysis are shown in Fig. 2.

Even moderate amounts of energy storage greatly increase the potential for PV installation. Just 5kWh of energy storage nearly triples the peak PV capacity. However, increases in energy capacity do not increase PV hosting capabilities

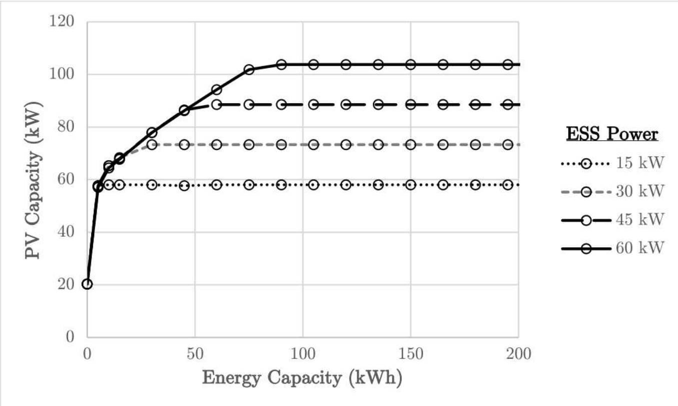


Fig. 2. Microgrid maximum PV capacity versus ESS energy capacity

indefinitely as the power rating of the energy storage system (i.e. the maximum charge/discharge rates) eventually becomes a limiting constraint. As increasing PV capacity greatly reduces the fuel requirements, some energy storage should be considered to increase the range of reliable configurations.

III. FOB Energy Management Methods

An energy management system capable scheduling dispatch of the TQGs and batteries in response to the net demand of the system would be needed to maximize benefits. In this section, the DLC and ODC energy management methods are analyzed for FOB operations. For this case study, the Force Provider FOB designed by the Army BCIL was simulated.

A. Discrete Logic Control (DLC)

As mentioned previously, DLC is the prevailing mode of control for microgrids only with fossil fuel generation. This control method uses if/else statements to determine when and which resources to engage at any given time. A discrete controller managing fossil fuel generation resources uses information on the system demand, total generator output, generator run time, and generator availability to dispatch resources.

For example, in the Force Provider FOB, when the power output of all the TQGs providing power is greater than 80% of the name plate rating (48kW per TQG), another TQG is brought online (i.e. increasing TQG Tier). Similarly, if power output from all active TQGs is less than 40% of the name plate rating, a generator is shut down (i.e. decreasing TQG Tier). The TQG availability and run time information is used to determine which TQGs to turn on to balance wear on the generators. However, current DLC systems are not equipped to integrate energy storage systems as well.

Here, we describe how the DLC method can be extended to incorporate an energy storage system to reduce diesel consumption. The integrated discrete control decision process begins by determining the availability of the battery:

$$AV_t = \begin{cases} 1, & \text{if } S_t > S_L \ \& \ AV_{t-1} = 1 \\ 1, & \text{if } S_t \geq S_P \\ 0, & \text{if } S_t = S_L \\ 0, & \text{if } S_t < S_P \ \& \ AV_{t-1} = 0 \end{cases} \tag{4}$$

If the energy storage system can discharge, $AV = 1$ and if the system can only charge then $AV = 0$. At each time step (t), AV is determined based on the previous availability (AV_{t-1}) , and current state of charge (S_t). If the energy storage system is charged or discharged during a time step, the S_t is updated for the next time step:

$$S_t = \begin{cases} AV_t = 0, & S_{t-1} + \frac{PE_{CMD} \cdot \eta_{RT}}{J_{RATE} \cdot \Delta t} \\ \\ AV_t = 1, & S_{t-1} - \frac{PE_{CMD}}{J_{RATE} \cdot \eta_{RT} \cdot \Delta t} \end{cases} \tag{5}$$

Each manufacturer recommends bounds on the state-of-charge of their systems that should be observed. The system is allowed to discharge until it reaches the lower bound, S_L at which time the system is required to charge ($AV = 0$). It will remain in the charge state until the state-of-charge reaches a prescribed state-of-charge, S_P. This forms a dead-band to prevent the battery from only charging a short period of time before discharging, which speeds degradation.

The FOB demand, battery availability, and state-of-charge at each time step is then used to determine the TQG Tier that is required. At Tier 1, the load is below 40% of the rated power for a single TQG. If the battery is available, all TQGs can be turned off and the battery can support the load. If the battery is not available, a single TQG will support the demand and charge the energy storage system. On the other end of the spectrum at Tier 6, the demand is such that all 6 TQGs need to be dispatched.

Operation in Tiers 2 -5 is based on the Force Provider DLC described in Fig. III-A with additional logic for the energy storage system. Before an additional TQG is dispatched to cover an increase in demand, the energy storage system will be discharged if $AV = 1$. In addition, the energy storage is only charged if $AV = 0$ and the demand is less than 80% of the maximum rated power of all the active TQGs. Charging the energy storage system when the TQGs are lightly loaded pushes the TQGs into a higher power output where they are more efficient, which ultimately reduces fuel consumption.

The simulation tracks fossil fuel consumption at each time step in gallons (6) as well as the number of cycles on the energy storage system (7). Here, a cycle is defined as the total energy throughput of the energy storage system divided by its energy rating.

$$\text{Fuel use} = \sum_{t=1}^{T} \sum_{g=1}^{6} F_{g,t} \tag{6}$$

$$\text{ESS cycles} = \frac{\sum_{t=1}^{T} \frac{P_{D,t} \cdot \Delta t}{60}}{ESS_{kWh}} \tag{7}$$

The DLC method was simulated in Matlab with 1-minute FOB load data from BCIL to determine how much diesel could be saved with DLC management of TQG and energy storage resources during a 180-day deployment.

B. Optimized Dispatch Control

An estimate of the maximum benefit that could be gained with ODC can be made by performing an optimization of resource dispatch assuming perfect foresight. For this analysis, historical FOB load data is used as a "perfect forecast" for the optimization algorithm to determine the best resource dispatch schedule subject to the constraints on the system and resource availability. This analysis gives a useful upper bound on the benefit of ODC in the given situation by showing the maximum potential to FOB operations.

To do this, a linear program describing the FOB generation system and load was created. The overall objective of the optimization routine was to minimize the fuel consumption from the TQGs in the system while meeting the FOB load and satisfying the SOC constraints on the energy storage system:

$$\begin{aligned} \min_{P_C, P_D} \quad & \sum_{t=1}^{T} \sum_{g=1}^{G} F_{g,t} \\ subject\ to \quad & P_{load,t} = P_{sol,t} + P_{D,t} + \sum_{g=1}^{G} P_{g,t} - P_{C,t} \\ & S_t = S_{t-1} + (\eta_{RT} P_{C,t} - P_{D,t}) \Delta t \end{aligned} \tag{8}$$

where P denotes power, t is time, C is battery charge, D is battery discharge, and g is the TQG index.

Beyond the basic requirements for power balance and the battery state-of-charge, constraints 2 and 3 were again necessary to ensure that the dispatch reflected realistic operation of the FOB resources. For this analysis, Eqn. 3 was applied to each TQG with $K_{low} = 40\%$ and $K_{high} = 80\%$.

Furthermore, the TQG power to fuel usage relationship was modeled with the piecewise linear approximation from measured fuel consumption rates at the 0%, 25%, 50%, 75% and 100% rated power breakpoints as shown in 1. This was integrated into the optimization framework with type 2 special ordered sets (SOS2):

$$\begin{aligned} P_{g,t} &= \sum_{k=1}^{B} b_k \cdot x_{k,g,t} \\ F_{g,t} &= \sum_{k=1}^{B} f_k \cdot x_{k,g,t} \\ 1 &= \sum_{k=1}^{B} x_{k,g,t} \\ x_{k,g,t} &\leq \gamma_{k,g,t} \end{aligned} \tag{9}$$

where k denotes the break points in the piecewise linear approximation, b_k is the power at breakpoint k, f_k is the associated fuel usage at breakpoint k, x_k's are continuous variables introduced by the SOS2 representation for interpolation between break points, and γ_k's are binary variables for which only consecutive values can be non-zero. With this, the fuel consumption of the TQGs could be minimized by optimizing the charge and discharge schedule of the energy storage system. This optimization framework was modeled in Python using Pyomo [8], [9] and optimization was performed using Gurobi [10]. Given the computational intensity of the ODC method, optimization was performed over a shorter time frame (48 days) and with a coarser time step (5-minutes) than the DLC method and results were scaled to represent the full 180-day FOB deployment. Note that a preliminary test over shorter timeframes was performed to compare results with a 1-min interval and 5-min interval with ODC and it was found that the difference in fuel savings was with each time interval in the analysis was insignificant.

IV. Results and Discussion

A. Energy Storage Integration

A baseline was modeled using the Force Provider microgrid control logic to determine the fossil fuel consumption without energy storage. The baseline was compared to a case using a GSYuasa VRLA energy storage system with DLC and ODC management to reduce fuel consumption. Both control methods were modeled with the same load profile. Comparison of the results are shown in Table II. Fuel consumption was

TABLE II
SANDIA TEST RESULTS FOR FOB ENERGY STORAGE SYSTEMS

Dispatch Method	**Fuel Consumed (gal)**	**TQG Runtime (hours)**	**ESS Cycles**
Baseline	27,018.19	8,659.12	0.00
Discrete	26,132.28	7,082.47	235.35
Optimized	25,978.98	6,643.50	290.32

reduced by 3.28% using DLC and 3.84% using ODC. The total TQG run time was also reduced by 18.21% and 23.28% for the discrete logic and optimized dispatch, respectively. The optimized dispatch out performed the discrete logic in terms of fuel consumption and TQG runtime, but at the expense of increased battery cycles.

B. Solar and Storage Integration

The power rating (60kW) and roundtrip efficiency (76.87%) of the GSYuasa VRLA system was assumed for both control methods. Each control algorithm was implemented with energy storage capacities of 0, 30, 60, 120, 180, and 240 kWh. Solar generation capacities of 0 to 100kW were simulated in 25kW increments. The fuel savings that could be obtained with each method of control is shown in Fig. 3.

Increasing the size of the energy storage system does very little to reduce fuel consumption directly. With 30kWh of energy storage, fuel consumption can be reduced by 3-4% without PV generation. Increasing the energy storage capacity beyond this point can save more fuel, but the increases are minor; a 240kWh system would only lead to ∼0.2% less fuel consumption than a 30kWh system. This is largely because the power versus fuel consumption curve for the curve for the TQGs is nearly linear in the applicable range, which limits the value of having the TQGs run in a more efficient

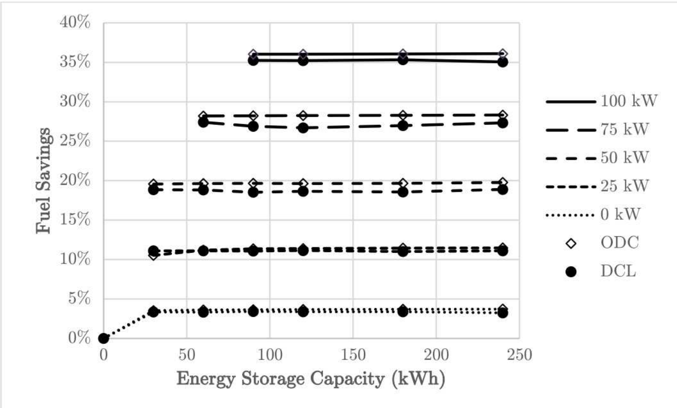


Fig. 3. Fuel Savings versus energy storage capacity with increasing solar generation capacity

range by charging and discharging the energy storage system. Generators with a less linear power-to-fuel curve could benefit more from larger energy storage systems.

The major benefit of energy storage is to increase the PV capacity that can be safely added to the microgrid, which significantly reduces fuel consumption. In this case, every additional 25kW of PV capacity reduces fuel consumption by 7-9%. Without energy storage, it was found that approximately 20kW of solar could be installed, but that can increase to nearly 100kW with a 60kW/60kWh battery. This would lead to fuel savings of $\sim$35% versus using TQGs alone. This benefit can be maximized with approximately 90kWh of energy storage for a 60kW system.

Lastly, Fig. 3 shows that the ODC and DLC energy management methods lead to nearly identical fuel savings. Though the ODC method consistently outperforms the DLC method, particularly as more PV is installed, the level of improvement is $\sim$1% at most for this application. This is true despite the fact that the ODC method analyzed here assumes a perfect forecast of the load and PV generation. In practice, the fallibility of the forecast would limit the ability to capture the full benefit of an optimized dispatch. As the DLC method does not rely on forecasting, a poor forecast could possibly make the use of ODC worst than DLC given the small margin of benefit.

V. Conclusion

Military operations are moving towards microgrid configurations for FOBs as this has been shown to greatly reduce fuel consumption. For FOB operations, reducing fuel consumption means fewer fuel convoys, lower costs, and, most importantly, a lower risk of casualties. Improvements in solar generation and energy storage technologies provide an opportunity to further reduce fuel consumption by servicing loads with other resources and allowing fossil fuel generators to operate in their optimal range. However, the potential benefit is highly dependent on the system configuration and the control method. This study investigated the potential for energy storage and PV generation on FOB operations and compared fuel savings that could be realized with two different resource management methods, discrete logic control (DLC) and optimized dispatch control (ODC).

The amount of solar resources that can be installed in a FOB is restricted by the technical limitations of the system. An analysis was performed to determine how much solar capacity could be increased with energy storage. This showed that energy storage can significantly increase the amount of solar that can be utilized reliably, leading to fuel savings up to $\sim$35% versus using TQGs alone.

Furthermore, analyses were performed to determine the difference in fuel consumption using DLC and ODC based energy management systems for TQG and energy storage dispatch. It was found that in this application, there was only a $\sim$1% increase in fuel savings going from DLC to ODC with perfect forecasts of the load and PV generation. Given the ease of implementation, intuitive nature, and near optimal performance of DLC for the FOB considered in this study, this energy management method is most likely the best option. This is particularly true as, in practice, the forecasts required to maximize the benefits of the ODC method will not be perfect.

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