Vehicle Supported Military Microgrids
Design, Scheduling, and Regulation for a Forward Operating Base

Case Study Team

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Motivation

- Reducing dependency on fossil fuel
- Increasing use of renewable energy resources on grid
- Increasing security, autonomy, and robustness of military and national grids
Motivation: Flexibility

Army energy requirements driven by mission requirements

Peacetime
- Combat Vehicles: 67%
- Combat Aircraft: 6%
- Tactical Vehicles: 16%
- Generators: 3%
- Non-Tactical Vehicles: 3%
- Facilities: 5%

Contingency Operations
- Combat Vehicles: 37%
- Combat Aircraft: 19%
- Tactical Vehicles: 11%
- Generators: 10%
- Non-Tactical Vehicles: 22%
- Facilities: 3%

Vehicle Supported Military Microgrid Example

- Installation of microgrid at Schofield Barracks, tied to critical infrastructure
  - Photovoltaic array
  - Dedicated electric vehicle charging
  - Grid connected
  - Conventional generator for extended backup power
  - Advanced stationary energy storage
  - Load management
- AC architecture
- Microgrid officially, fully operational as of March 2011
- Data collection and operational support for one year
"At or near the tactical edge, over 70% of fuel used by our military forces can be for power generation" [DARPA BAA-11-53]
**Case Study: Vehicle Supported FOB**

**Goal:** Developing an integrated tool for designing vehicle supported FOB

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**Design & Scheduling**
- Operating points, disturbance sizes
- Battery & APU power constraints
- Centralized control
  - Long time-scale

**Regulation**
- Decentralized control
  - Short time-scale
Literature

V2G

- Reduced Emissions [8, 10, 12, 16]

Economics [4, 9, 15, 17, 36]

- Impact on Renewable Power [5, 10, 12, 14, 15]

- V2G Technological Design Aspects [37]

- Economic Power [4, 9, 15, 17, 36]

- Microgrid Design [37, 40, 41]

- Microgrid modeling, controls, and practical implementation [38]

- Optimal dispatching of distributed energy resources [39]

- FOB Simulations [43]

Microgrid

- Regulation issues [1, 2]

- Droop control [1, 27-31]

- Inverter control [32]

- Regulation [33, 34, 35]

- Regulation for renewable energy [4, 5, 9, 14, 15, 17]

- Ancillary services [4, 5, 9, 14, 15, 17]

- Reduced Emissions [8, 10, 12, 16]

- V2G Design [0, 4, 40, 41]

- Today's Case Study

- Microgrid modeling, controls, and practical implementation [38]

- Optimal dispatching of distributed energy resources [39]

- FOB Simulations [43]
FOB with Solar + JLTVs with export power

~50 soldiers
120 kW peak power
67 kW average power
$6-8/gal fully-burdened cost of fuel
Radial network

Joint Light Tactical Vehicle with on-board auxiliary power unit and battery storage
• 30 kW export power
• 2 - 20 kWh Li-ion battery
Design & Scheduling

Operating points, disturbance sizes

Centralized control
Long time-scale

Battery & APU power constraints

Regulation

Decentralized control
Short time-scale
Design + Scheduling Goal

Optimization

- Minimizing Fuel and Capital Cost
- Operational Constraints
- Component Sizes and Scheduling
- Uncertainties
- Military Requirements
Design + Scheduling: FOB with Solar + JLTVs

1) Solar Panel Peak Power

2) Number of JLTVs

3) Battery pack size
   (Export power fixed: 30 kW)
Solar Supply
Hourly solar irradiance taken from NASA data for area near Kabul.

Design and Scheduling optimization used variable, but deterministic solar input.

Solar Error Modeling
An error variable created for non-linear model predictive control algorithm of the solar panel output power.
Non-Linear APU Model
Surrogate model constructed for generator from Cummins diesel generator data (50 generators in data set)

Model Inputs and Outputs
APU efficiency calculated as a function of APU rated power and percent load
Model Inputs: Power Load w/ Error

Known
2kW/soldier

Power Load Profile

(Part 1) Diurnal power load modeled with radial basis functions based on 5 key parameters.

(Part 2) Seasonal power load modeled with average daily temperature sine function to model change in HVAC needs based on published ECU's power load based on temperature.
Diurnal Power Load

Parameters:

\[ P_{\text{base}}, \sigma_{\text{high}}, \mu_{\text{high}}, \sigma_{\text{low}}, \mu_{\text{low}} \]

\[ P_{\text{peak}} = xP_{\text{base}} \]

\[ P_{\text{low}} = yP_{\text{base}} \]

Power Load (kW/soldier)

Time of Day (hour)
Adding Seasonal Variations

Used our Temperature model and HVAC model from N. C. McCaskey, “Renewable Energy Systems for Forward Operating Bases: A Simulations-Based Optimization Approach” *Colorado State University, 2010*
Power Load used in this Case Study.
Sample FOB Case to Compare

Electronic Power Control and Conditioning (EPCC)

LSA Warrior, NTC, Fort Irwin, CA

NEXTENERGY
Example of CONUS FOB Demand Data with UM Interpretation

**EB Output Controlled & Conditioned**

- $\mu_{\text{low-time}} = 5\text{hr}$
- $\sigma_{\text{low-width}} = 2\text{hr}$
- $\mu_{\text{peak-time}} = 15\text{hr}$
- $\sigma_{\text{peak-width}} = 5\text{hr}$

One, 24 Hour Period In August 2010

- $P_{\text{base}} = 80\text{kW}$
- $x = \frac{P_{\text{base}}}{P_{\text{peak}}} = \frac{80}{120} = 66\%$
- $\epsilon_1 = 1.5P_{\text{base}}$
- $\epsilon_1 = 20\text{kW} (25\%)$

- Data collected in support of NetZero+ JCTD at Ft. Irwin
Hub-based energy network [Geidl]

\[ L = CP - SE \]

Model Inputs
- Individual hub layouts
- Component sub-models
- Power loads vs. time
- Solar supply

Optimal design of a microgrid requires balancing capital costs of equipment with expected operation costs

→ requires solving a nested optimal scheduling problem for each design
→ could also consider other costs (e.g., transportation, maintenance)

**Optimal Design Problem**

minimize: capital + operation costs

variables: component sizes

constraints:
- operational limits
- backup req’ts
- reliability
- volume/footprint limits
- silent watch req’ts
- other military req’ts

**Optimal Scheduling Problem**

minimize: operation costs (e.g., over 1 year)

variables: energy generation / storage scheduling

constraints: operational limits
Initial Results: Design + Scheduling

Assumes $7/gallon fully-burdened cost of fuel

**89 kW Solar Panel**
(\~4,100 ft^2\) rigid PV or (\~14,400 ft^2\) of flexible PV)

Plug-in JLTVs: 4
Battery Capacity: **2.1 kWh**
Added Weight: 35 kg

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<table>
<thead>
<tr>
<th><strong>“Business as Usual” – Two generators</strong></th>
<th><strong>PV panel + JLTV w/ export power</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cap Cost (annualized): $4,400</td>
<td>Cap Cost (annualized): $91,500</td>
</tr>
<tr>
<td>Fuel Use (annual): 53,600 gallons</td>
<td>Fuel Use (annual): 38,000 gallons</td>
</tr>
<tr>
<td></td>
<td><strong>Change in Fuel Use: -29%</strong></td>
</tr>
</tbody>
</table>
Optimal scheduling on a time horizon results in strategic energy storage use.
Design & Scheduling

Operating points, disturbance sizes

Centralized control
Long time-scale
Transient power disturbances can cause power loss and equipment damage. Regulation problem can show design limitations and suggest improvements.

Drop in Solar Power of 50 kW
Design & Scheduling

Operating points, disturbance sizes

Regulation

Centralized control
Long time-scale

Decentralized control
Short time-scale
What is the regulation problem?

**Frequency regulation**
Keep rotational speed constant

**Voltage regulation**
Keep length constant
Significance of regulation

Frequency Variation

60 Hz

Voltage Variation

110V

LOW

HIGH

Speed

Temperature

Efficiency

Power

Impedance goes down. Current goes up and cooling goes down. May burn out earlier than designed.

Voltage exceeds the limitation. Current to the devices increases too much.
Frequency and power balance

Power Generation < Power Demand

\[ \sum_{i} P_{iG} = \sum_{i} P_{iL} + P_{\text{line loss}} + P_{\text{stored}} \]

Generated = Consumed + Lost + Stored
Frequency regulation framework

Performance Goal
- Frequency: 60Hz ± 0.5Hz
- Voltage: 110V ± 5%

\[
\dot{\omega} = A\omega + B \begin{bmatrix} p_1 \\ p_2 \end{bmatrix} + B_d d
\]

Battery Pack
- Fast Actuator
  - Unlimited Energy Capacity

APU
- Slow Actuator
  - Limited Energy Capacity

\[
p_1 = \frac{1}{1 + \tau_1 s} u_1
\]

\[
p_2 = \frac{1}{1 + \tau_2 s} u_2
\]
Simple vs. full model

Simple Model for Control Design
Linear
Focus on frequency

Full Model for Validation
Nonlinear
Focus on frequency and voltage
Includes battery model
Battery model

T.K. Lee and Zoran Filipi based on
Controllers

\[ C_1 : PI \text{ control}, \quad u_1 = -(k_{1P}\omega + k_{1I}p_1 + k_{1I}\int \omega dt) \]
\[ C_2 : P \text{ control}, \quad u_2 = -(k_{2P}\omega + k_{2I}p_2) \]

Requirements

\[ |\omega| < 0.5 \text{Hz}, \]
\[ |u_1| < \text{Gen power margin (120kW)}, \]
\[ |u_2| < \text{Batt power margin (19.3kW)} \quad \text{Assuming 2.3C max rate} \]
Frequency Control Result

Required Battery Power

Power (kW)

Frequency (Hz)

Time (s)
Simple vs. full model

- **Simple Model for Control Design**
  - Linear
  - Focus on frequency

- **Full Model for Validation**
  - Nonlinear
  - Focus on frequency and voltage
  - Includes battery model
Simulation with full model

Battery assumed constant voltage source

Microgrid frequency

Voltage at solar terminal

Frequency (Hz)

Time (s)

Voltage (V)

Time (s)
Simulation with full model

19kWh Battery with diffusion dynamics

No solution!
Physical explanation

- Current
- Voltage

Voltage drop limits AC power
One solution

Add more cells in parallel
Simulation with full model

38 kWh Battery with diffusion dynamics

Microgrid frequency

Voltage at solar terminal

Frequency (Hz)

Voltage (V)

Time (s)

Time (s)
Simulation with full model

53.8kWh Battery with diffusion dynamics

Microgrid frequency

Voltage at solar terminal

Frequency (Hz)

Voltage (V)

Time (s)
Evolution of battery sizing

- After **design and scheduling considerations**: 8.4 kWh
- After **regulation considerations**: 19 kWh
- After considering **battery dynamics**: 53.8 kWh
Design & Scheduling

- Operating points, disturbance sizes
- Centralized control
  - Long time-scale

Regulation

- Battery & APU power constraints
- Decentralized control
  - Short time-scale

Additional constraint from Regulation problem: at least **53.8 kWh** battery capacity

**87 kW** Solar Panel
(\(~4,000 \text{ ft}^2\) rigid PV (1.9x tennis courts) or \(~14,000 \text{ ft}^2\) of flexible PV (6.6x tennis courts))

Plug-in JLTVs: 4
Battery Capacity: **14.3 kWh**
Added Weight: 240 kg

28% saving in fuel compared to “business as usual”

<table>
<thead>
<tr>
<th>Original Design</th>
<th>New Design</th>
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<tbody>
<tr>
<td>Cap Cost (annualized): $91,500</td>
<td>Cap Cost (annualized): $94,100</td>
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<td>Fuel Use (annual): 38,000 gallons</td>
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</tr>
</tbody>
</table>
• Critical coupling exists between short and long time scale system behavior
• Proposed integrated approach can take this coupling into account
• Smart energy management strategies can reduce fuel use
• Battery voltage fluctuations may impose additional design considerations
Next steps

- Develop and incorporate models for additional components (e.g., hybridized vehicles)
- Develop framework for designing and analyzing reconfigurable topology
- Analyze interplay between prediction errors and horizon
- Develop flexible and scalable controllers
- Validation of proposed methods and tools
Our integrated methods and tools can help achieve this power and energy vision.