Flexible Design and Operation of a Smart Charging Microgrid

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Introduction

A microgrid is a controllable group of interconnected loads and distributed energy sources, including renewables, for grid-connected or island mode operation.

Wheeler Army Airfield Installation in Hawaii
Motivation
Designing a Reliable Microgrid
Repairable Systems
Microgrid and V2G Overview
Case Study
Optimization Problem and Results
Conclusions and Future Work
Reliability and Cost Efficiency Contributors

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

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

Microgrid as a Flexible System

• A microgrid is a repairable system that needs to accommodate varying operating conditions.
  – A deterministic design tends to be not feasible
  – Robust design can still become suboptimal as operating conditions change
  – A flexible design accommodates changes in operating conditions and is preferred

• Design of a microgrid involves multiple conflicting objectives such as: reliability, cost and planning horizon.

• To calculate these long-term metrics the computational effort becomes excessive.

• This work aims at flexible design that simultaneously attacks the computational effort.
Determine **optimal** microgrid architecture (number, size, and type of energy sources including hybrid vehicles) and **source dispatching** initial plus inventory to minimize acquisition and operation cost fuel, repairs for readiness (e.g. MFFP) and maximize performance (reliable service of a time-dependent and uncertain load), considering maintainability, repair strategy, inventory, reset, and energy storage. Incorporate **flexible approach** to microgrid design that “learns” from its behavior (loads and sources) and responds accordingly.
What is a Reliable Microgrid?

- Failure is the inability of the microgrid to meet load requirements.
  - Load exceeds maximum capacity of energy sources with no component failures (load shedding is required).
  - Load exceeds available capacity of energy sources due to component failures.
- Failures are expected because of the stochasticity regardless of how well the loads are modeled.
- Microgrid is treated as a repairable system.
Repairable and Non-repairable Systems

Reliability of a non-repairable system is the probability that a system has not failed at any time before the time of interest.

What is the reliability of a repairable system?

The diagram shows the reliability function $R(t)$, with three failure times $t_1$, $t_2$, and $t_3$, indicating partial repairs at $t_1$ and $t_2$, and a full repair at $t_3$. The reliability resets after each repair.
Metrics for Repairable Systems

• In classical reliability theory:
  – MTBF, which only reports the mean of the time to failure distribution, is used.
  – Availability may be misleading if system can be repaired quickly.

• We propose a set of metrics useful in capturing different aspects of performance of a repairable system and then select a minimal set (e.g. cost, MFFP, number of failures).

• A small set of metrics can be used to represent system performance using a Pareto front so that the best design can be chosen.
Microgrid and V2G Overview

- Integrates power from multiple sources without loss of power quality
  - 2 x Solar PV (50 kW)
  - 2 x Diesel generators (200 kW)
  - Hybrid vehicles EV batteries (60 kWh @ max discharge rate of 10kW)
- Capable of peak-shaving and load-shedding if required
- Islanded
- Provides power to variable loads
  - Building loads
  - Other miscellaneous loads
Load and Source Dispatching

![Graph showing load and supply over time](image-url)
Load and Source Dispatching
Load and Source Dispatching

Dispatching is performed for 1 year using 1-hour increment.
Optimization Problem

\[ \min_{x} \{ -T_{0.8}, N_f, C \} \]

- **MFFP with 80% probability**
- **Number of failures**
- **Cost**

\[ x = \{ s_{ls}, s_{so}, s_{lo}, s_{ss}, n_{gen}, n_{contacts} \}^T \]

\[ T_{0.8} = F_{T_{\text{working}}}^{-1}(0.2) \]

\[ C = C_{\text{initial}} + C_{\text{repair}} + C_{\text{running}} \]

subject to:

\[ g_1(x): P = 8760, \]
\[ g_2(x): p_{gen} = 0.25, \quad g_3(x): \eta_{\text{repair}} = 0.1 \]

\[ n_{gen}, n_{contacts} \in N \]
\[ s_{ls}, s_{so}, s_{lo}, s_{ss} \in [0, 100] \]

NSGA-II Algorithm

Ruled-based set points (decision variables)

Planning horizon
Issues with Classical Approach

- **Incorrect extrapolations:** Unless done properly, what is learned in a short simulation time may not be applicable to the entire planning horizon.

- **Coarse time scales:** Many transient effects are not captured properly because they happen within seconds. The flip-side is that fine time scale simulations are computationally prohibitive.

- **Uncertainty:** The effect of uncertainty cannot be fully captured. For example, we may encounter a chance failure and assume that the microgrid is unreliable or alternatively by luck, we may not see any failure in a short period even if the microgrid is unreliable.
Flexible Microgrid

- We are envisioning a flexible approach to microgrid design that “learns” from its behavior (loads and sources) and responds accordingly.
- Load follows a stochastic process and in response so does the supply.
- Failures are expected because of the stochasticity regardless of how well the loads are modeled.
- The dynamic microgrid system must be simulated with a very short time interval for months at a time in order to fully characterize its operation. This is computationally impractical.
- Our methodology proposes to “learn” the characteristics of the load profile $L(t)$ and the resulting supply profile $S(t)$, as enacted by an intelligent power management protocol.
The correlation between $L(t)$ and $S(t)$ is also determined.

A short period of a few days can be used to “learn” the process.

The quantified stochastic behavior of $L(t)$ and $S(t)$ is used to extrapolate for the system performance metrics at later times.
AR* time series models the load and source processes

\[ L(t_i) = 150 + 100\sin \left( \frac{2\pi t_i}{24} \right) + 50(0.0345\varepsilon_{i-1} + 0.1552\varepsilon_{i-2} + 0.2069\varepsilon_{i-3} + 0.2586\varepsilon_{i-4} + 0.3448\varepsilon_{i}) \]

Source can be modeled in two ways:

\[ S(t_i) = (1 + \phi) \left( 150 + 100\sin \left( \frac{2\pi t_i}{24} \right) \right) + 50(0.0345\omega_{i-1} + 0.1552\omega_{i-2} + 0.2069\omega_{i-3} + 0.2586\omega_{i-4} + 0.3448\omega_{i}) \]

\[ S(t_i) = \delta + 150 + 100\sin \left( \frac{2\pi t_i}{24} \right) + 50(0.0345\omega_{i-1} + 0.1552\omega_{i-2} + 0.2069\omega_{i-3} + 0.2586\omega_{i-4} + 0.3448\omega_{i}) \]

The white noise terms \( \omega_i \) and \( \varepsilon_i \) are highly (but not perfectly) correlated because we never have a perfect model of the load.

The first approach multiplies the load model by a factor while the second adds a fixed excess capacity.

Our preliminary results show that the second approach is better.

*Auto-Regressive
Realization of Load and Sources
Comparison of Strategies

- We assume that the electricity price is 10 cents per KWh.
- Realizations of the microgrid load and supply random processes are generated for 8760 hours.
- For comparison purposes, we fixed the number of failures.
- **Strategy 1** generates 328,695.3 kWh of excess energy over the course of the year. This amounts to $32,869.53 in money spent for insurance against chance failures.
- **Strategy 2** with an excess power of 20kW generates only 176,917.5 kWh of extra energy, which amounts to $17,691.75.
Comparison of Strategies

- As a result, we use Strategy 2 for further analysis.
- Building extra supply capacity as a percentage of load is wasteful because when the load is high, there is less likelihood of it increasing substantially anymore while the opposite is true when the load is low.
- Strategy 2 also gives an easier way to predict cost.
- We also propose that one should only look at the cost incurred in providing excess power as the microgrid running cost.
Sensitivity To The Correlation Between Load and Source

- The failures fall to zero when the supply is perfectly correlated with the load.
  - Good modeling of the load and responding with a supply that will meet that load quickly are essential.
  - Cost does not decrease much if correlation increases.
Pareto Front over Cost and Number of Failures
Design Details

- If the decision maker selects the design shown:
  - Strategy 2 to provide excess supply
  - Cost = $21,602 in excess power
  - Number of failures = 8
  - $\delta = 25 \text{ kW}$
  - $\text{MFFP} = 97.4$ hours
  - Correlation $\rho = 0.9$. 
Conclusions

- An optimal microgrid architecture can be obtained, considering performance, reliability and lifecycle cost.
- The overall system must be treated as a repairable system.
- This work proposes a flexible approach to microgrid design that “learns” from its behavior (loads and sources) and responds accordingly. This approach allows for significant reduction in computational effort.
- Our results showed the proper modeling of load is critical, so is responding with a highly correlated supply.
- Two strategies were compared, our results showed that to account for variability in load, one should respond with a supply that is fixed kW above the expected load.
- Other scenarios were also investigated such as: effect of correlation between load and source, as well as tradeoff between the attributes of cost and number of failures (Pareto front).
Thanks for your attention

Q & A