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Microgrid Design Analysis Using Technology Management Optimization and the Performance Reliability Model

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Abstract

Microgrids are a focus of localized energy production that support resiliency, security, local control, and increased access to renewable resources (among other potential benefits). The Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) Joint Capability Technology Demonstration (JCTD) program between the Department of Defense (DOD), Department of Energy (DOE), and Department of Homeland Security (DHS) resulted in the preliminary design and deployment of three microgrids at military installations. This paper is focused on the analysis process and supporting software used to determine optimal designs for energy surety microgrids (ESMs) in the SPIDERS project. There are two key pieces of software, an existing software application developed by Sandia National Laboratories (SNL) called Technology Management Optimization (TMO) and a new simulation developed for SPIDERS called the performance reliability model (PRM). TMO is a decision support tool that performs multi-objective optimization over a mixed discrete/continuous search space for which the performance measures

are unrestricted in form. The PRM is able to statistically quantify the performance and reliability of a microgrid operating in islanded mode (disconnected from any utility power source). Together, these two software applications were used as part of the ESM process to generate the preliminary designs presented by SNL-led DOE team to the DOD.

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Abbreviations and Acronyms

AE abnormal emergency

ATS automatic transfer switch

CLNS critical load not served

DBT design basis threat

DER distributed energy resource

DER-CAM Distributed Energy Resources Customer Adoption Model

DHS Department of Homeland Security

DOD Department of Defense

DOE Department of Energy

EMS energy management system

ES energy storage

ESM energy surety microgrid

FC fuel cell

FEMA Federal Emergency Management Agency

GAA generation adequacy assessment

GTC Grid Tied Controller

ICS industrial control system

IEE Institution of Electrical Engineers

IEEE Institute of Electrical and Electronics Engineers

JCTD Joint Capability Technology Demonstration

LBNL Lawrence Berkeley National Laboratory

LV low voltage

MC Monte Carlo

MDT Microgrid Design Toolset

MMC microgrid mode controller

MSC microgrid startup controller

MV medium voltage

NPV net present value

NRC Nuclear Regulatory Commission

PCC point of common coupling

PDF probability density function

PES Power Engineering Society

PPD predicted power deficit

PPE predicted power excess

PRM performance reliability model

PV photovoltaic

RE renewable energy

RFP request-for-proposal

SAA system adequacy assessment

SDT summary design table

SNL Sandia National Laboratories

SPIDERS Smart Power Infrastructure Demonstration for Energy Reliability and Security

TE typical emergency

TMO Technology Management Optimization

UPS uninterruptible power supply

Chapter 1

Introduction and Rationale

An energy surety microgrid (ESM) [1, 2] is an approach for energy system design that was developed at SNL to support Department of Defense (DOD) installation energy. An ESM includes the following six key attributes: *safety*, *reliability*, *security* (resilient to various cyber and physical threats), *sustainability*, *resiliency*, and *cost effectiveness*. Thus far, the ESM approach has been used to develop preliminary design reports which are used for soliciting requests-for-proposal (RFPs), including for all three phases of the joint DOD/Department of Energy (DOE) Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) program [3].

An ESM analysis quantifies energy resiliency, reliability, and the risk exposure of specific kinds of loads. The work also presents the trade-space among several microgrid designs that, while meeting needed criteria, all offer different levels of performance at different project costs. Efficient solutions are narrowed down to a specific one that best fits the site's needs.

The ESM definition includes a microgrid that can operate either grid-tied or in islanded (standalone) mode. Every ESM comprises the following types of loads and/or buildings:

- **Type C:** loads / buildings that are critical to the mission or function of the facility; these loads usually have dedicated backup generators. Some Type C loads are non-interruptible and will include an uninterruptible power supply (UPS) while other Type C loads can endure short term losses of electrical power (C_U and C_I respectively).
- **Type P:** loads / buildings that are of high priority ("nice to have"), but that can be switched on or off of microgrids at the discretion of the designated emergency authorities.
- **Type O:** other loads/buildings that will not be powered during islanded microgrid operations.

The approach is very strongly focused on quantitative, repeatable analysis, suited to the technical nature of the design problem. That said, the work does depend on assumptions, so the results need to be considered carefully. The analysis includes probabilistic elements to maintain a realistic perspective. Each of its constituent elements has a specific function:

- **PRM:** performs probabilistic calculations for microgrid performance metrics according to specific design options.
- **TMO:** develops a Pareto-optimal set of design options using PRM for calculations.

Chapter 2

Energy Surety Microgrid Operations and the Design Basis Threat

The concept of a design basis threat (DBT) [4] is borrowed from the nuclear industry, where it documents threats that a facility must withstand. For an ESM, a DBT defines the most conditions (threats) that must be met by the design. The threats may be environmental (like a hurricane) or man-made (a cyber or physical attack or simple misoperation), and is one of the first decisions for analysts and ESM stakeholders.

A key concept for an ESM is that energy surety investments are intended primarily to improve performance for the DBT. However, investments in energy surety can also provide improvement during normal periods, or more conventional emergencies (not to the level of the DBT). The three operating conditions are defined as:

- **Normal:** No emergency conditions.
- **Typical emergency (TE):** Abnormal conditions that fall under the purview of good planning/engineering (utility outages in line with historical reliability figures, etc.).
- **Abnormal emergency (AE):** High impact, low frequency (HILF) events, which may be included in the DBT.

The PRM is focused on the DBT/AE conditions, while the overall ESM design can evaluate tradeoffs between all three.

Timeframes are a key investment issue, particularly since normal conditions dominate as a fraction of operating time, and microgrids may allow for revenue generation/cost avoidance (through site energy or demand reduction, peak shaving/shifting, energy contracts with the local utility, participation in local markets, etc.). Conceptually, *the investment in energy surety – performance during AE intervals – is amortized by the improved performance that the investment provides during normal (grid-connected) and TE conditions.* That is a fundamental design perspective, since the DBT is frequently without any good quantification of its frequency or likelihood of occurrence, which makes it difficult to compare to investment criteria. Conversely, the normal and TE conditions are well-established, and so the value of the ESM investments in improving those can be easily expressed succinctly, perhaps as a net present value (NPV). The stakeholders for an ESM can compare the difference of the NPV of the ESM costs and the NPV of the benefits during normal and TE conditions to the expected, quantified benefits calculated by the PRM for AE conditions (which are not expressed financially). This represents their investment in energy surety and resiliency for the planned microgrid site. Obviously, if the NPV of non-DBT benefits are greater than the overall project cost, then the DBT performance is "free" and the project is very easy to justify (in SNL's experience, this is not the case).

For prior ESM work by SNL, DBTs have included:

- Regional electrical blackout lasting 72 hours
- Regional electrical blackout lasting 24 hours at 40% probability, 72 hours at 30%, 1 week at 20%, and 1 month at 10% (used for SPIDERS)
- Flood level at the Federal Emergency Management Agency (FEMA) 100 year flood plain plus 2.5 feet [5]
- Active cyber security threats against microgrid industrial control system (ICS) of specified characteristics [6]

Chapter 3

Design Analysis and Optimization Approach

In formulating the approach, it is necessary to define decision variables, response functions (metrics, objectives, constraints, etc.), and solution technique. Throughout the SNL experience using this process, variables and response functions have changed substantially from project to project. They are not rigidly dictated by the process but instead are specialized for the situation. Examples of decision variables include:

- **Type and sizing of distributed energy resources (DERs) and energy storage (ES):** This includes diesel and natural gas generators, photovoltaic (PV), wind, batteries, etc. including whether or not new DERs were necessary and if so, the type and size needed.
- **Placement of DER and ES in the microgrid:** Similar to type and sizing, the location of DER can be variable. In the past, this has been implemented by specifying reasonable locations to receive DER and allowing the optimizer to choose type, size, etc. for each.
- **Operational modes of DER and ES:** This has been of particular interest to determine how best to utilize large ES assets, and once to determine the desired operation of a hydrogen fuel cell (FC).
- **Microgrid topology:** Topology-related questions have included whether or not to connect certain buildings to the microgrid, add redundant feeders, buildings to house additional generation, etc.

Examples of response functions in ESM efforts include:

- **Variable Cost:** The cost associated with all decision variables (included in the optimization); consequently, this does not include the cost of aspects of the microgrid design that are not under the control of the optimizer.
- **Generator Efficiency:** The efficiency of controllable, fossil-based generators such as diesel and natural gas units is calculated by the PRM and the optimizer has been given the goal of improving this result in past projects.

- **Power Reliability:** Power reliability has been quantified in several ways but generally includes measures of the frequency, duration, and magnitude of load loss or service on a type-by-type basis. Examples include the frequency of occurrence of critical load not served (CLNS) outages (type C_U, C_I, or both) on a per-hour-of-DBT basis, the amount of CLNS energy not served on a per-hour-of-DBT basis, or the energy supplied to type P load during an outage. The optimizer has the goal of minimizing unserved type C and improving type P service.

- **Renewable Penetration:** The percentage of total generation present on the microgrid at any given time that is provided by renewables can be limited as a constraint.

Beyond these core response functions, occasionally the need to compute specialized values for specific questions have come up. As an example, during the SPIDERS project a metric was formulated to count the number of times that generators were started during utility outages. The purpose of measuring this was to help quantify the effect of peak shaving while islanded using ES to avoid frequent generator starts.

Chapter 4

Microgrid Performance-Reliability Model

The PRM is a simulation code (written in C++) used to statistically quantify performance and reliability of a microgrid operating in islanded mode (disconnected from the utility grid). The genesis of the PRM was as an analyzer used to assess candidate microgrid designs generated during a preliminary design phase. PRM has since been adapted to provide calculations to decision support software used to explore the cost versus performance trade-space of investment options in a microgrid design effort.

The PRM allows the performance of a microgrid to be quantified in terms of metrics for response functions (described in section 3) like fuel efficiency, fuel usage, renewable energy (RE) utilization, dispatch statistics, and other operational characteristics of the system. Microgrid reliability can be quantified in terms of frequency and magnitude of load lost on a tier-by-tier, load-by-load, or bus-by-bus basis, or on an aggregated basis over the microgrid. PRM also supports calculation and reporting of individual equipment reliability statistics.

4.1 PRM Approach

One well-accepted method for calculating the performance of an engineered system is Monte Carlo (MC) sampling. The process has been used extensively for power system planning, with formulations for both generation adequacy assessment (GAA) and system adequacy assessment (SAA) (the latter includes the electrical network, while the former is more about simple generator capacity). The desired analysis will leverage existing SAA formulations [7, 8, 9].

The PRM is used as the SAA engine to calculate performance metrics. It includes a few specific characteristics:

- The DBT is expressed as a probability density function (PDF) of expected utility outages.
- Instead of a bulk power system, the analysis was for microgrids, which share similarities. PRM supports multiple energy islands and connections between them.
- A sequential MC was used, modeling the entire outage interval; this allowed modeling for operational characteristics (like different ES management schemes).

- The PRM requires the complete microgrid topology, including buildings, load types, buses, lines, DER/ES, transformers, UPS, switches, inverters, fuel consumption curves and storage, etc. (either existing or a possible design selection).

- Other inputs include equipment outage rates, recovery rates, start probabilities, RE output characterization, load characterization, and fuel usage rates/storage capacities for existing fossil-fuel generators at the site.

The PRM operates as a discrete event simulation, which is a means of modeling a systems behavior as a discrete sequence of events in time. At each event, appropriate logic is executed which may result in the scheduling of more events. The simulation proceeds until all events have been executed or until some explicit stopping criterion is satisfied. This type of simulation is minimalistic in the sense that logic is only executed in response to a known event. There are many possible events in the PRM, but some examples include:

- The failure or repair of the utility or a piece of equipment,

- A change to a bus's load condition,

- The start or stop of a fossil generator,

- A change to a renewable output, or

- The emptying of a fuel tank.

4.2 Grid-Tied Microgrid Simulation

The PRM simulation relies on a representation of an unreliable power utility through the definition of failure modes per the DBT. The PRM typically simulates thousands of utility outages to ensure that calculated statistics are meaningful (i.e., stable). Although the PRM is focused on DBT conditions, it does perform minimal analysis while grid connected (since equipment may fail outside of an occurrence of a DBT, and its potential lack of availability may extend through the beginning of a DBT, which will affect the islanded ESM performance). Therefore, the PRM includes operational logic called the Grid Tied Controller (GTC) for the time leading up to the start of utility outages. The GTC's only job is to manage the failures and repairs of those pieces of equipment that operate during normal operations (including components such as lines, transformers, and renewable generators, but excluding components such as backup diesel generators as these do not operate during normal operations). The GTC completes its work at the beginning of the next sampled DBT outage where the PRM microgrid startup controller (MSC) is entered.

4.3 Microgrid Startup Simulation

The MSC is quite different from sustained microgrid operations. For example, the MSC does no generator dispatch beyond the simplistic strategy of starting them all, which it does immediately in order to simulate the planned initial interval of backup generator/UPS operations (thus far, all SNL-designed microgrids have not required immediate transition – seamless or otherwise – into microgrid mode for unexpected utility outages, as this has been seen as not financially justifiable by stakeholders given existing UPS). The MSC necessarily has some control over the interconnection of buses, in order to accurately simulate the action of UPSs and automatic transfer switches (ATSs). Each generator may have a spin-up delay associated with it before it can be connected. Next, the MSC examines all inverters on the system, and if any are not capable of maintaining connection through a utility outage, then it is disconnected. (These can be reconnected once the microgrid formation is complete and the anti-islanding delay has passed.)

At this point, no time has passed. The logic associated with the previous actions will have resulted in the scheduling of events. The PRM begins to execute them as simulated time passes. While generators are spinning up, UPSs provide power to connected Tier C_U loads. When ready, generators are connected. If the load bus is not yet energized, then the generator can be immediately connected; otherwise, if the bus is energized (i.e. another generator is already connected), then a synchronization delay is added before connection of the second generator. All of the generator connection logic requires a functioning path between the generator and the bus and also the availability of fuel. At this point, both Tier C_U and Tier C_I loads are receiving energy.

The MSC will begin the transition to microgrid mode after a delay, which is used because the majority of outages in the US are too short to employ the microgrid immediately. The delay may be shortened (if a key generator fails) and is user controllable. The microgrid is formed by carefully energizing branches – transformers and lines, probably medium voltage (MV) equipment – and synchronizing the generators bus-by-bus. As the MSC forms the microgrid, it follows certain rules:

- There must be a functioning path between buses.
- There is a synchronization delay for two energized buses.
- The resulting sub-grids must not be underpowered.
- Any non-microgrid-enabled generators are shut down upon the connection of their bus, and the power that they were supplying must be accounted in (subtracted from) the balance computed for the enlarging microgrid island.

In addition to all those considerations, the MSC manages equipment failure events as it goes about the job of forming the microgrid. It also accounts for load served/unserved statistics (as well as all other metrics). Also, special consideration must be given in the startup phase to the fact that equipment failures may result in isolated buses or a fractured grid. There is additional logic that manages these operations which mimics the expected behavior of a reasonable microgrid energy management system (EMS). After startup, control passes to the microgrid mode controller (MMC).

4.4 Microgrid Operation

The MMC schedules and reacts to all events and also rebalances the microgrid (acting as a dispatching EMS). Events include failures and repairs, load changes, RE output changes, fuel outages, refueling events, and so on. A substantial percentage of the MMC logic is devoted to determining when events occur and managing them, and the rest manages how much power is coming from which generation/storage assets. Several dispatchers have been developed for the PRM, and which dispatch strategy to use is potentially an interesting design variable. The dispatcher principally functions using rule-based logic; a representative summary is as follows:

1. Ensure a minimum number of running generators and spinning reserve based on load.

2. Calculate system load, effective load (which is system load reduced by any power from RE sources), and a short-term load estimate using simple load forecasting.

3. Account for all currently running dispatchable generation (a complication here is that the MMC must account currently producing generators as well as others in the startup phase but not yet connected to the microgrid.

4. Calculate any predicted power deficit (PPD) or predicted power excess (PPE); a PPD occurs if load is expected to rise above generation plus spinning reserve and a PPE occurs if the load is expected to drop enough that a generator may try to operate below its minimum.

5. Determine whether or not it would like to start generators, stop generators, or leave things the way they are (additional criteria help determine the best choices).

6. Given the probabilistic nature, if a generator fails to start then the dispatch simply re-enters the decision logic.

7. In a critical PPD situation where either enough generation is simply unavailable or a path to a load is insufficient/nonexistent, then the MMC sheds minimal load (priority load is shed first, and critical load only as a last resort) which is reconnected as soon as feasible.

Note that the dispatch scheme is not an economic dispatch model and justifiably so. The reasoning is that the PRM is doing analysis for AE operations where minimizing actual cost is a lesser concern than maximizing service over a long period of time, and backup generators have very fast start times so cycles do not have to be planned long in advance. Finally, since the system is islanded, there is no opportunity for arbitrage, providing ancillary services, impacting demand charges, etc. The MMC's job is complete when the utility power returns signaling the end of the outage. Control is passed back to the GTC until the next utility outage.

4.5 PRM Outputs

The primary outputs of the PRM are computed quantities and statistics. All unreliable entities gather statistics detailing the outages they suffer, their durations, and the amount of downtime attributable to each failure mode. All levels of the grid (site, microgrid, bus, area) for which it makes sense to express load service statistics track load served and not served (by type) for each of three categories:

- All simulated DBT occurrences
- Only post-startup operations (interesting because all C_I load is unserved and accrues statistics during startup)
- Only those outages for which any critical load is not served post-startup (called conditional CLNS outages)

All generator types have additional statistics computed for them, including runtime, utilization rate, energy production, and efficiency. Several additional statistics are computed for ES, including power output and state of charge (min, max, weighted mean, and 1^{st} moment). Overall microgrid statistics include the amount of diesel fuel /natural gas used, the amount of RE generated, the amount of RE that went unused (spilled), the number of times generators were dispatched, the number of times the dispatch logic was executed (executing the logic may not result in a change in generation), how long it takes to execute microgrid startup, and finally statistics on the time steps taken by the discrete event simulator. At the site level, load service statistics are tracked as are statistics similar to the microgrid statistics for diesel/natural gas used and RE generated and spilled.

Statistics generally include min, max, mean, variance, and a histogram where appropriate. The ESM design process has to date focused only on improving the mean of the expected performance, but the PRM easily allows for optimizing against any parameters of a resulting statistic; for example, reducing the likelihood of extremely poor results (extrema) in conjunction with improving mean expected performance.

Chapter 5

Iteratively Optimizing PRM Using Technology Management Optimization

TMO is an application that builds optimal roadmaps specifying what technologies should be in use and when. It was developed to allow proactive maintenance and update of technologies for high-valued, long-lived, technologically sophisticated systems. In the time since it was first developed, it has been used extensively for more general decision support problems not directly related to technology management.

TMO can perform a multi-objective search as represented in Figure 5.1 [10, 11] to develop analysis over several dimensions (e.g. cost, performance, reliability, risk, etc.) which themselves can represent multiple issues. Using a novel approach to metric aggregation, TMO can effectively handle many metrics and their goal settings to provide meaningful trade-off information.

The type of search space principally targeted by TMO is one of discrete categorical variables with metric calculations that are unrestricted in form. This level of flexibility allows for decision support on many problems of interest in which discrete selections of items or choices are being made that cannot be easily represented by variables with an inherent order and for which metrics cannot be easily calculated with simple analytic functions. TMO has been used on many high profile applications in the military, nuclear weapons, homeland security, and energy arenas.

5.1 TMO Metric Aggregation & Fitness Assessment

As mentioned above, TMO may aggregate an unlimited number of metrics into groupings that serve as dimensions in the multi-objective search. In order to aggregate over arbitrarily scaled metrics they must be normalized, which is the process of scaling raw metric values such that they can be compared and combined on an equal mathematical basis with the values of other metrics [12]. The process involves applying a mathematical transformation to the raw values. For TMO, that transformation is a function that has a shape similar to that shown in Figure 5.2 when maximizing a functional objective. Two characteristic values must be provided in order to specify the transformation function – the "limit" and the "objective." Limits are interpreted as the worst values that are still acceptable. Objectives be interpreted as target values; values which if obtained would provide a high level of satisfaction.

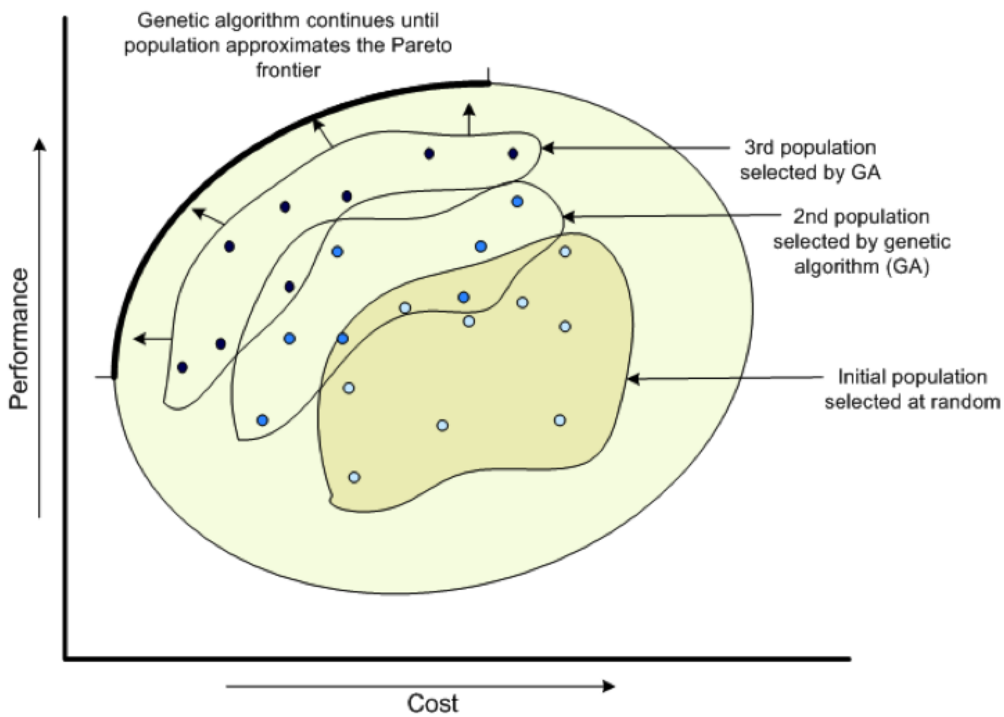

Figure 5.1. Representation of multi-objective genetic search.

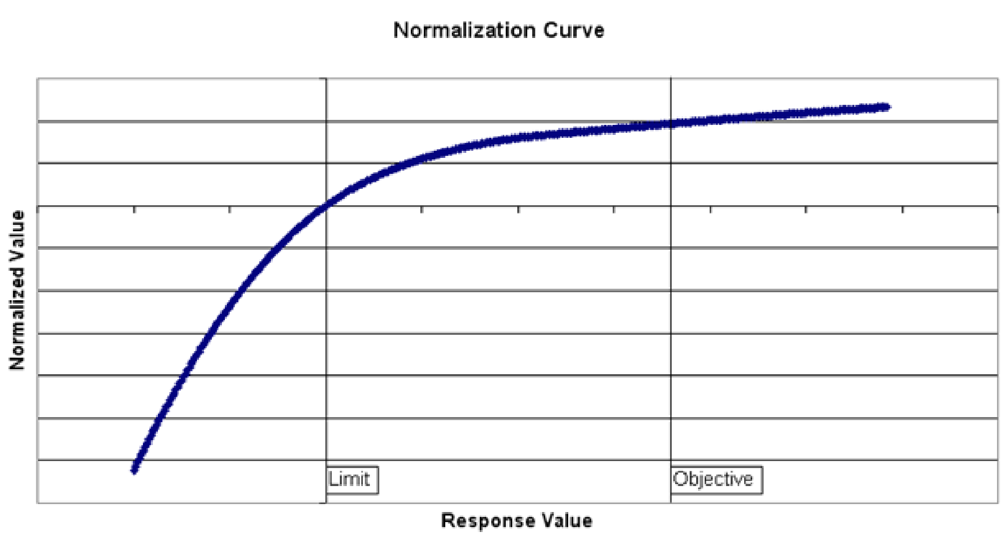

Figure 5.2. TMO normalization function.

This curve consists of 3 quadratic sections; the section below the limit, the section between the limit and objective, and the section above the objective. Each section is C0 and C1 constrained with any other section to which it joins. There are 4 parameters that can be adjusted to control the details of the shape of the curve (the equations and parameters for these curves are beyond the scope of this paper). If minimizing, then the curve is similar but mirrored such that its slope is opposite in sign to that shown. When the improvement type is seek-value, the curve is mirrored about the objective line such that it peaks in the middle and reduces on either side of the objective. Once normalized values have been computed, fitness values can be attained. In TMO, fitness is the weighed sum of normalized response values over all metrics.

5.2 TMO and PRM Linkage

The communication between TMO and the PRM is conceptually fairly simple. TMO repeatedly formulates candidate microgrid solutions and passes the information describing them to a custom PRM middleware application. The middleware translates the information into PRM inputs and executes the PRM simulation. The same middleware extracts the required results from the simulation and returns them to TMO. The process is repeated until TMO has completed the search. Figure 5.3 below serves as a conceptual diagram of the process.

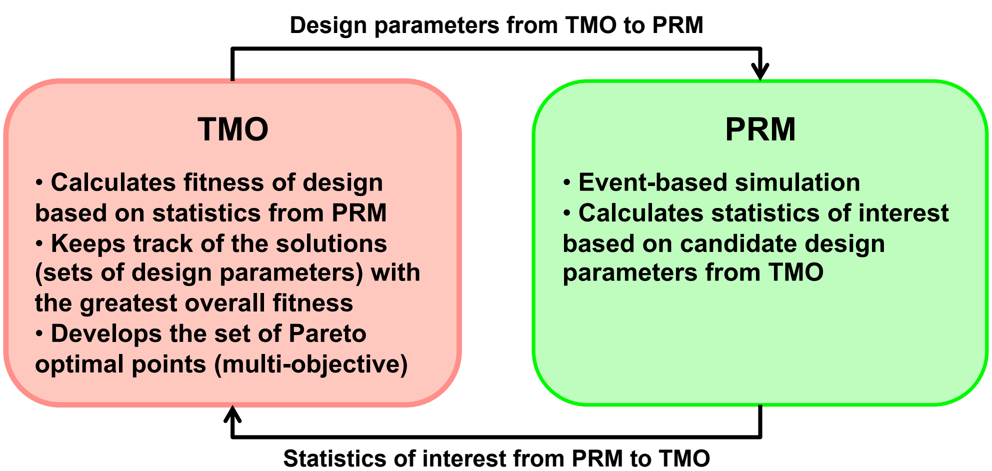

Figure 5.3. Coordination between TMO and the PRM.

Chapter 6

Representative Military Installation Example

The SPIDERS and other ESM experience was distilled to provide a representative example of the TMO/PRM approach. The given information is:

- Project budget is preferably no more than $11.35M
- Site includes PV generation available in 0, 1, 2 MW
- There are eight desired critical buildings A-H
- All include diesel generation of varying sizes
- There are four desired priority buildings W-Z
- Option to add diesel generation to buildings A, C, D, E
- Option to add fixed ES to allow integration of higher PV
- Existing system includes both pad-mount switches & taps
- Tier C_U & C_I were not differentiated (ignored UPS)
- DBT is 24-, 72-, and 168-hour outages (equal probability)

6.1 Initial Analysis and Fixed Costs

The first step in the ESM process is to summarize the design options and requirements. At any site, the stakeholders have a "wish list" and a concept of their budget (which may be resolutely fixed, or have wiggle room). After analysis and discussion, there are obvious requirements for any microgrid at the site that are conducive to the likely budget. These "core" microgrid decisions represent the project's fixed costs. Here, a key pre-optimization decision was to make maximum use of the existing MV system, as adding dedicated microgrid infrastructure would be financially infeasible.

One ESM requirement is to disconnect all Type *O* load using automated switches. This was facilitated by the layout at this site, which allowed for disconnection of most with existing MV switches (including one location where an entire lateral of Type *O* load can be disconnected by a single switch, thereby saving cost versus needing a switch per building). In a few cases, some taps needed to be upgraded to switches, and all existing and new switches in the microgrid footprint required remote control (motorization) and communications.

The critical buildings were parsed by the ESM design team and the stakeholders into two groups: some were designated as "mandatory," meaning they were located within the designated microgrid core, and others were "optional," since they would require incremental investment to extend the core microgrid reach to include them. All critical buildings require switching to manage their connection to the microgrid, so that the interconnection of the critical buildings during microgrid operations could be done in an orderly way (to ensure acceptable system dynamic performance and to isolate faults in case of a malfunction). Switching costs for the mandatory buildings added to the project's fixed costs. Type *P* buildings need automated switching, as they must be disconnected if generation runs short. As all four Type *P* buildings lay in the core area, switching for those was a fixed cost.

Finally, the site's existing PV was a mandatory feature. It lay far outside the core, but there was a feasible path via existing site MV lines that could be leveraged, given some reasonable investment in additional remote control MV switching. The PV site itself required remote connect/disconnect capability (regardless of the decision of 1 or 2 MW on the microgrid – even if only 1 MW is used, the other must be disconnected).

The ESM design team summarized the required improvements and tabulated the costs for the group of buildings and equipment that were definitely going to be on the microgrid. Other fixed costs included an allowance for networking and control systems, as well as placement of a point of common coupling (PCC) breaker and associated controls. The remaining funding was left to optimize the design against.

6.2 Site Design Optimization Setup

Of the eight critical buildings, A through E were already in the microgrid core, leaving F, G, and H as optional. To be included in the microgrid, the ESM design team tabulated the additional switching and control that would be necessary to extend the microgrid perimeter (which would include remote switching for the building itself, as well as adequate switching to remove all Type *O* load along the way). This added several possible options for the optimization (seven permutations: adding G would also add F, since F is along the path to G, and also the choice of none of the three).

Each of the critical buildings included an existing backup generator of a given size. The decision variable is which of these to convert to microgrid support capability (which would involve retrofitting advanced controls, communications, and a synchronization-supervised low voltage (LV) connection from the generator terminals across the ATS to the LV side of the building transformer). Three of the decisions are conditional, as including buildings F, G, and H are not certain. In each case, the cost estimate for microgrid inclusion was calculated individually, since generator conditions varied. Even if a generator was not included, it could still power critical load conventionally via its ATS, which would be beneficial if the microgrid suffered outages isolating a critical load.

In addition to the basic generator questions, the optimizer was given the opportunity to add diesel generation to any of the critical buildings. Each building was given four potential additional units, which would automatically be microgrid-enabled (the ones for buildings F, G, and H are allowed only if the buildings are in the microgrid).

TMO included variables about how much priority load could be served. Including them is beneficial, since they have perceived value during a DBT occurrence. However, the microgrid diesel generation requirements and fuel consumption will go up, so their service is uncertain.

The optimizer had the option of designating 1 or 2 MW of PV for microgrid operation. The algorithm has a constraint limiting RE penetration, in order to limit the possible power quality issues from very high RE ratios. However, this will depend on the load, which varies according to time of day and also which buildings have been included (both critical and priority). The response function for lower fuel usage against the penetration constraint – for a given building selection pattern – will settle whether the system can appropriately use 2 MW of PV, or if 1 MW is the best choice.

Finally, the site included options for ES that could help manage RE. It could either reduce short-term cycling of diesels (to cover swings in variable RE output) or limit the overall RE penetration. Since there was only one feasible location for the ES at the site, the variables in the optimization included a selection of reasonable power and energy ratings. All of the design variables are tabulated in the lower left of the project's summary design table (SDT) shown in Table 6.1.

6.3 Metrics

The optimization metrics are detailed in the upper left of the SDT. The large negative objective for the solar penetration value tricks TMO into effectively computing that any value in the range 0% to 50% is equally good but above 50% is poor (this is limited to ensure operational effectiveness by avoiding very high levels of RE). The base case values (no microgrid) are essential to setting limits and objectives for metrics (along with stakeholder input). "Short-term diesel use avoidance" represents machine runtimes of unacceptably short duration (often needed to maintain spinning reserve, particularly with wildly variable RE on the microgrid). The limits and objectives were set using stakeholder experience and data gathered during design screening, including prior load flow analysis and isolated PRM runs.

Table 6.1. Summary design table for the example application (values are per hour of outage unless otherwise noted).

Metric	Min/ Max	Limit	Obj- ective	Base Case	Results 1	2	3	4	5	6	7	8	9	10	11
Total project cost (million $)	Min	11.35	10.5	$0	10.300	10.639	11.093	11.186	11.279	11.372	11.512	11.662	11.756	12.035	12.455
Average diesel used (gallons)	Min	81	230	109.9	109.4	109.4	109.9	109.6	142.2	142.2	142.2	131.2	131.1	131.1	131.1
Average generator efficiency (unitless)	Max	0.30	0.37	0.282	0.365	0.366	0.361	0.360	0.367	0.367	0.367	0.364	0.365	0.365	0.365
Short-term diesel use avoidance (per hour)	Max	0.1	0.5	N/A	0	0	0.036	0.059	0.088	0.088	0.089	0.085	0.100	0.101	0.101
Rate of DBT with CLNS (percent)	Min	1.0	0	14.3	0.0465	0.0436	0.0405	0.0232	0.0465	0.0232	0.0465	0.0571	0.0675	0.0608	0.0608
Priority load served (kWh per hour)	Max	0	500	0	602.4	602.4	602.5	602.4	1078.4	1078.4	1078.4	919.8	919.7	919.7	919.7
Solar penetration (max % of load)	Min	0.50	-1000	0	28.6	28.6	28.6	28.6	22.3	22.3	22.3	24.5	24.5	24.5	24.5
TMO-calculated multi-objective Pareto-optimal values	Normalized cost (capital investment) fitness (unitless)				1.14	1.06	0.64	0.50	0.31	-0.26	-2.48	-5.47	-7.64	-15.61	-31.64
	Normalized performance fitness (unitless)				2.50	2.51	3.37	3.92	4.21	4.23	4.24	4.30	4.62	4.63	4.64
Battery power (kW)	Inverter size is 0, 250, 500, 750, 1000kW				0	0	250	500	750	1000	1000	500	750	750	1500
Battery energy (kWh)	Storage size is 0, 250, 500, 750, 1000kWh				0	0	250	250	250	250	500	250	250	750	1500
Existing diesel integration (location)	Choices are for which core critical buildings (A,C,D,E)				A,C,D	A,C,D	A,C,D	A,C,D	A,C,D	A,C,D	A,C,D	A,C,D	A,C,D	A,C,D	A,C,D
Type *P* load service (location)	Choices are for which core priority buildings (W-Z)				W,Y	W,Y	W,Y	W,Y	all	all	all	W,X,Z	W,X,Z	W,X,Z	W,X,Z
PV integration (MW)	From the existing field at the site: 0, 1, or 2MW				1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Crit. building F/G/H include? (location)	Each has a specified cost (one condition: adding G requires F)				none	none	none	none	none	none	none	none	none	none	none
Total additional fossil generation (kW)	0, 500, 1000, or 1500kW (only places with selected microgrid generators)				0	1000	0	0	0	0	0	1500	1500	1500	1500
Decision Variable	**Values Available To TMO**				**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
					Results										

6.4 Design Optimization Results

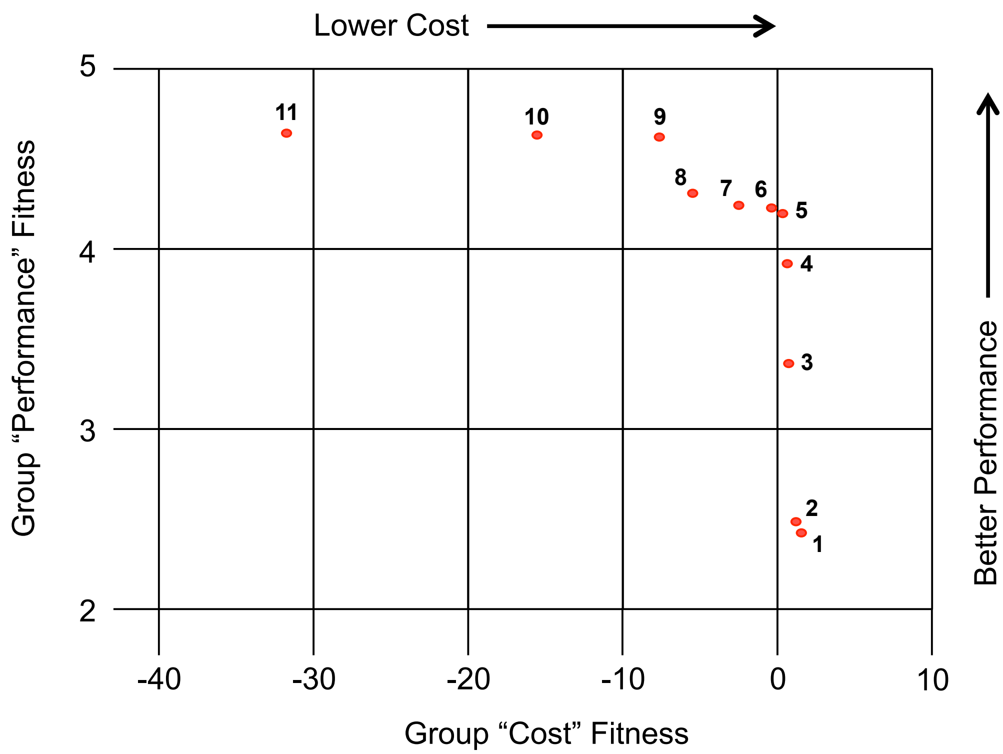

Figure 6.1. Pareto-optimal set for the example.

Figure 6.1 shows the Pareto solution set generated by TMO and PRM. The quantities along the axes are unitless fitness values. Since fitness is always maximized, the search algorithm is trying to move the solution set to the upper right of the plot. Therefore, solution 11 is the most expensive and highest-performing while solution 1 is the cheapest and lowest performing (solution numbers are labels only and do not indicate preference). Several trade-off solutions exist in between. The combined normalized results for all 11 solutions (plotted in Figure 6.1) are in the center horizontal band of the SDT, while the values for each metric are in the upper right and the corresponding design selections are in the lower right. Obviously, many solutions greatly exceeded the budget (the limit was represented as somewhat soft, in order to gain insight into potential solutions that may only slightly exceed resources) and were discarded. Solution 1 basically showed the benefit from a microgrid installation with minimal enhancements, and already suggests a many-fold improvement in CLNS performance. Other improvements included deferred emissions amounting to about 1.3 tons of CO_2 per outage (reduced on account of improved efficiency and integrated RE) and about a threefold reduction in conditional CLNS energy given an occurrence of unserved critical load (a measure of critical load outage severity).

The process carried out by SNL in order to choose a single, final recommended solution started by examining technology trends in the Pareto solutions. Choices that were overwhelmingly used in optimal solutions were selected and conversely, those never used were discarded. Here, the microgrid perimeter was never extended beyond the core, and three generators (in buildings A, C, and D) were always selected for microgrid integration. Some ES helped avoid short-term generator cycling, and contributed slightly to keeping the RE penetration fraction to a manageable level (although for the latter, no doubt Type *P* load service also played a role). With what remained, additional analyses (including power flow and dynamic modeling) and discussions about relative cost and performance thresholds were used to make determinations. Note that all solutions use as much or more fuel than the base case, which might impact the endurance of the site (diesel deliveries may be difficult under DBT conditions). This is a side effect of the desired Type *P* service. However, further analysis showed that – without type *P* service – the microgrid consumed approximately 20% less fuel per hour, so under dire conditions the site could elect to extend its onsite fuel using the microgrid. The final design result ended up strongly resembling a hybrid of solutions 4 and 5, with ES provided by distributed sources.

Chapter 7

Conclusions and Future Work

The ESM design methodology has been proven effective for microgrid investment analysis over a number of applications spanning both military and civilian use. It was a key capability for developing specifications for all three SPIDERS RFPs. The methodology successfully developed optimal preliminary designs, as well as providing a structural approach for soliciting and unifying stakeholder concerns and input.

Currently, TMO only includes response functions for the means of metrics calculated by PRM. The next logical step is to develop additional response functions to quantify ESM value for improving other properties of the statistics. One obvious idea is to assign improvement in reducing the magnitude and rate of occurrence of extremely poor performance within one or more metrics (attacking the extrema of the statistic). Another idea may be to value some combinations of mean and variance, such that a slightly poorer result for the mean of a metric may be preferred if its variance is greatly reduced compared to one with a slightly better mean. That way, the optimizer will value confidence in expected performance.

The work on ESM that uses TMO driving PRM has focused entirely on DBT performance. As noted in section 2, the ESM investment can be amortized by including the effects of the investment on grid-connected performance (for revenue generation or cost avoidance). To that end, SNL is funded by the DOE to expand the TMO optimization to include a second calculation for grid-connected financial performance. TMO will necessarily include the needed response functions to properly value the resulting metrics, and will optimize the tradeoffs for ESM investment, DBT performance (from PRM), and NPV of grid-connected performance. The project is funded (FY2013 through FY2015 planned) as the Microgrid Design Toolset (MDT) program. As of late 2013, TMO was calculating project costs as capital investments less the NPV of revenue/cost avoidance during grid-connected conditions by communicating with the Lawrence Berkeley National Laboratory (LBNL) Distributed Energy Resources Customer Adoption Model (DER-CAM) software [13].

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