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GLOBAL STRATEGIES FOR OPTIMIZING THE RELIABILITY AND PERFORMANCE OF U.S. ARMY MOBILE POWER TRANSFER SYSTEMS

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ABSTRACT

As the U.S. Army develops its 30-year science and technology strategy for ground systems, these systems are seen more as mobile power generation systems than just semi-autonomous mobile protection systems. As ground systems continue to have greater levels of electrification, they are perceived as key to providing power not only to the propulsion and mobility systems, but to protection systems, communications, information systems and a complex, ever-increasing suite of auxiliary power systems which are not limited to the vehicle platform itself, but to external systems and platforms. All power systems can be connected wirelessly, or through a microgrid. Therefore, optimizing the overall ground system along with an external suite of loads and sources through a power grid, as a system of systems, becomes crucial in vehicle design. This optimization problem for performance and reliability is complex when considering the outside grid and a mix of other sources and loads with uncertain power quality and availability. This paper proposes how this optimization problem can be formulated and solved, and attempts to change the perspective of the importance of the overall ground system as a power generation system on the battlefield, and for base operations, restoration and contingency operations. Because a microgrid is designed for a period of time, our optimization problem considers factors such as cost to operate, maintenance, reliability, repair time and logistics. This paper also focuses on optimizing the vehicle-microgrid system using these factors with emphasis on the vehicle to grid management where a vehicle is a mobile power generation system and a key part of the grid.

1. INTRODUCTION

Ground systems have become more electrified over time and their power needs and generation capabilities have increased. Considering how they support internal and external (outside the platform) electrical systems in an optimized way, is becoming more crucial. When vehicle systems link into other systems as a way to share power sources and loads, a vehicle-to-grid (V2G) system

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14. ABSTRACT

As the U.S. Army develops its 30-year science and technology strategy for ground systems, these systems are seen more as mobile power generation systems than just semi-autonomous mobile protection systems. As ground systems continue to have greater levels of electrification, they are perceived as key to providing power not only to the propulsion and mobility systems, but to protection systems, communications, information systems and a complex, ever-increasing suite of auxiliary power systems which are not limited to the vehicle platform itself, but to external systems and platforms. All power systems can be connected wirelessly, or through a microgrid. Therefore, optimizing the overall ground system along with an external suite of loads and sources through a power grid, as a system of systems, becomes crucial in vehicle design. This optimization problem for performance and reliability is complex when considering the outside grid and a mix of other sources and loads with uncertain power quality and availability. This paper proposes how this optimization problem can be formulated and solved, and attempts to change the perspective of the importance of the overall ground system as a power generation system on the battlefield, and for base operations, restoration and contingency operations. Because a microgrid is designed for a period of time, our optimization problem considers factors such as cost to operate, maintenance, reliability, repair time and logistics. This paper also focuses on optimizing the vehicle-microgrid system using these factors with emphasis on the vehicle to grid management where a vehicle is a mobile power generation system and a key part of the grid.

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is formed with vehicles connected to a microgrid. If the microgrid is not connected to a major city utility, as we assume in this paper, the microgrid is considered islanded, where it is likely part of a forward operating base or part of an emergency operation where a major utility is not available.

How vehicles connecting into and out of a microgrid, are managed, becomes a complex problem to optimize because the optimization problem must consider factors such as cost to operate, utility, vehicle state of charge, maintenance, reliability, repair time and logistics. This optimization is not trivial. Are vehicles sources or loads? How does the overall power system deal with it? This study focuses on optimizing the vehicle-microgrid system using these factors with emphasis on the vehicle-to-grid management, considering the vehicle as a mobile power generation system. Vehicle-to-grid can reduce dependencies on small expensive units in existing power systems as energy storage and can efficiently manage load fluctuation, peak load and increase reliability. Efficient vehicle-to-grid management can reduce power generation costs if “gridable” vehicles are charged from the grid at off-peak load and discharge to the grid at peak load. Vehicle-to-grid researchers for the most part have focused on interconnection energy storage issues between the vehicles and the grid [1-7]. Although the success of V2G depends on the efficient scheduling of “gridable” vehicles, many studies have focused on the environmental and economic benefits of V2G and on how these benefits can enhance the V2G product market. Understanding how to manage the grid with a number of vehicles being able to connect to the grid as sources or loads is the focus of the paper.

The microgrid system optimization problem involves multiple conflicting objectives. One objective is to maximize the reliability of the microgrid which is defined as the ability of the online sources to power the online loads without turning them off unexpectedly. Other objectives include cost and the number of failures encountered in the planning horizon. Since the microgrid is a repairable system (defined below), the classical notion of reliability is not directly available. For this reason, we use the Minimum Failure Free Period (MFFP) as a surrogate for reliability. The optimization is set up as a non-linear mixed integer problem because of the type of the objective function and the design variables which are both discrete and continuous. The strategy to manage the microgrid is based on turning on and off sources and loads if the load or source is above, or below a required point (set points).

Efficient vehicle-to-grid management can reduce generation costs if “gridable” vehicles are charged from the grid at off-peak load and discharge to the grid at peak load. This management matrix must be controlled through active communications between the mobile power generation systems and the other loads and sources on the grid. The set points can be optimized to keep sources off to reduce cost, or turned on to ensure loads are not turned off improving therefore, reliability. Sources and loads can also be prioritized. This helps ensure highly critical assets such as communications devices are turned off only in the worst case. A genetic-algorithm based stochastic optimization approach is applied to determine the global control strategy for the microgrid.

We build on the paper by Pandey, Skowronska et al. [8] by expanding the optimization approach to include the prioritization of loads and sources and mobile power generation (V2G). Also, generators are continuously dispatched by metering their output so that they run at their most efficient loads/speeds. An explicit model of fuel consumption as a function of generated power is used for the generators.

Most real-life engineering systems are repairable. The amount and frequency of repair affects how one perceives their reliability or more generally, their “performance.” The classical notion of reliability, defined as the probability that the system has not failed before a given time *t*, can be misleading because a repairable system may have failed before time *t*. The classical reliability definition can also impede decision making involving maintenance, availability and service cost of such systems. Although an appropriate maintenance strategy can make a system available most of the time, it cannot compensate for too many service interruptions and a potentially high service cost. The tradeoffs between performance, service interruptions and cost are hard to capture. Pandey and Mourelatos [9] have recently shown that we can systematically approach the design and maintenance of repairable systems using a minimal set of metrics (MSOM) to capture most of the information about the working conditions and reparability of such systems. In this paper, we extend and apply their method to a smart charging electric microgrid (SCMG) used by the US Army in remote installations with a focus on the vehicle-to-grid aspect.

The paper is organized as follows. Section 2 discusses and presents the minimal set of metrics. Section 3 describes the SCMG. Sections 4 and 5 present the problem formulation and the results, respectively. Finally, Section 6 summarizes, concludes and provides directions for future work.

2. PERFORMANCE OF REPAIRABLE SYSTEMS

Classical reliability theory uses metrics such as the Mean Time Between Failures (MTBF) and availability to assess the expected performance of a repairable system. These metrics are calculated using data on times between failures and system repair. However, the MTBF and availability metrics only capture one statistic of the time between failures [9]. The MTBF captures the mean, while the availability is simply the ratio of system up-time to the total duration considered. A system that has a skewed distribution of the time between failures will not have its performance well represented by the MTBF only (Figure 1). Similarly, a system that requires constant repair but can be repaired quickly has high availability, but such a system has little practical use, as it is hard to get any meaningful service out of it. Section 2.1 shows that we can describe the performance of a repairable system very effectively with a carefully chosen set of metrics.

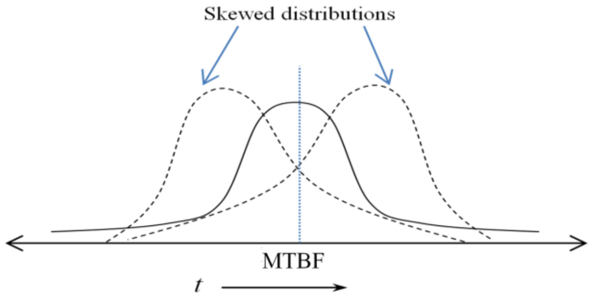

Figure 1. MTBF represents the expected time between failures correctly only for symmetric distributions (solid line)

2.1 Minimal Set of Metrics

To describe the performance of a repairable system, we define a minimal set of metrics (MSOM) which, individually or collectively, should cover most aspects of the system performance. To accomplish this, we use the following set of desirable properties (desiderata):

1. The MSOM should be able to describe the performance of a repairable system when it is first installed with all new components.
2. The MSOM should be able to describe the performance of a repairable system when it has undergone a few repair and installation cycles.
3. The MSOM should show how often repairs are required for the system.
4. The MSOM should be usable for a fleet of systems where the end-user selects one system from the fleet at an arbitrary time and expects a

certain performance level or a trouble-free mission length.

5. The MSOM should be able to quantify the tradeoff between performance and cost.
6. The MSOM should be able to account for technical obsolescence in addition to functional loss.
7. The MSOM should identify, to a fair degree of accuracy, the best repair strategy for system maintenance.
8. The MSOM should indicate how long the system will be in operation, even with constant repair, before being replaced by a new technology.

3. THE SMART CHARGING MICROGRID

A smart charging microgrid (SCMG) is used in remote locations to provide reliable power to critical installations. The SCMG we consider in this work, takes power from three distinct sources: generators, solar arrays and vehicle batteries. Figure 2 shows the schematic of the SCMG.

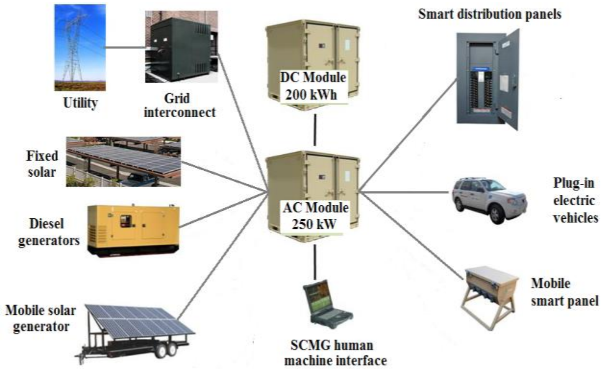

Figure 2. A smart charging microgrid

An intelligent power management is used to enable a robust and reliable operation with substantial fuel and maintenance economies over its service life. We developed a MATLAB simulation model which represents both continuous and discrete events, such as time varying loads and generator starts/stops and breaker trips or grid faults.

A protocol was developed to manage the sources, i.e. whether they are on or off and how much power they generate, using *self-dispatching*. We define self-dispatching as the ability of each source to interpret the supply-load condition of the microgrid and modify its power output accordingly. Under self-dispatching, a source autonomously increases its output in case of a supply deficit, and decreases it in case of a supply surplus, without a command from a central computer. Self-dispatching has benefits when the sources are incrementally added and removed. Also, it can easily conform to set priorities for different sources.

The SCMG source system is assumed to include the following components:

1. Two 100 kW diesel generators
2. Two 25 kW solar arrays,
3. Hybrid vehicles (n_v in number)
4. One contactor each for the above sources.

The generator, solar array and hybrid vehicle sources are connected in parallel and can provide power to the grid if their contactor is on. However, this parallel connection does not imply that they provide complete redundancy for each other. Simply because the sources are connected does not mean that the microgrid is operational. If the total power provided by the sources is not enough to power all loads, the system is considered failed. To avoid delay in repair and maintenance, spares of generators and contactors are used. This results in a tradeoff between easier upkeep, and procurement and inventory costs for these components. The solar panels have high enough MTBF that one can safely assume that they will not fail during our planning horizon of one year.

The sources are given priority numbers, which determine the order in which they self-dispatch. The generators have the highest priority, followed by the solar panels and the vehicles. The load side of the SCMG is not explicitly modeled. However, loads are shed and added depending on the system's excess capacity. Two loads are considered: building loads, and other miscellaneous loads. The vehicles act as loads when there is excess capacity and as sources when there is a supply deficit. They are not modeled as other loads because they self-dispatch. If there is a supply deficit they automatically stop drawing power from the grid and start supplying to it.

3.1 Source and Load Characteristics

Details for the power sources and loads are provided below in terms of their power generation/consumption.

Generators: The generators are 100 kilowatt units with an MTBF of 500 hours. Their replacement time is 8 hours if a generator is available in the inventory. Otherwise, it is 48 hours, including procurement from a remote location. A generator is replaced with a new one only after a major failure which is assumed to occur with a probability p_{gen} equal to 0.25 for the baseline case. Otherwise, for a minor failure, the generator is repaired at a much lower cost, which is a fraction of the cost of a new generator.

Solar arrays: The two solar arrays are 25 kilowatts each. They include batteries and an inverter unit. They are able therefore, to provide constant power during day and night. The commonly used arrays and inverter units have MTBFs in the range of decades. Thus, their reliability does not affect the reliability of the microgrid.

Hybrid vehicles: Hybrid vehicles power the microgrid if needed. At other times, they are either charged by the microgrid or are a passive element of the grid. The total capacity of the vehicles is 60 kWh and their rate of charge/discharge is 10 kW. The vehicles provide transportation and may not always be available for the microgrid. We assume that the vehicles leave the base only for short durations at most twice per day. Therefore, the vehicle availability is approximately equal to $1-\frac{2}{24}=0.92$. The number of available vehicles is denoted as n_v and is manually varied to find the minimum number of vehicles required. The baseline value is 2.

Building loads: The building is the main load to be serviced. The load is cyclic to represent the difference in power consumption during work hours and at night. The consumption is assumed to be a sine wave with a 40 kW amplitude and a period of one day.

Miscellaneous loads: Other miscellaneous loads may include powering of outside equipment and external lighting in the complex. We assume them to be normally distributed with a mean of 20 kW and a standard deviation of 4 kW.

Table 1 provides the baseline MTBF in hours of operation and the baseline cost for each component. The MTBF is an indicator of reliability but is not directly used in our simulation. The time between failures of each component is assumed to follow a Beta distribution with an upper limit equal to four times the MTBF.

Table 1. Mean Time Between Failures (MTBF) of the components used in the microgrid

Component	MTBF	Unit Cost
Contactor	2000 hours	$2,000
25 kW solar array	219,000 hours	$70,000
100 kW Diesel Generator	500 hours	$51,800

3.2 Power Management

As mentioned before, each unit in the SCMG modifies its power output by sensing power usage at various loads to bring the system to the desired state of operation. This entails switching contactors on or off. In our MATLAB simulation, the contactors are modeled as switches that respond to the state of a Boolean variable (0 = disable, 1 = enable).

When initiated, the grid starts at the system equilibrium and remains in this state unless/until the excess system capacity moves outside specified set points. Excess capacity is defined as the available power in excess of the current load, and is expressed as the following percentage

$$C_{excess} = \frac{(Source - Load)}{Load} \cdot 100\% \ . \qquad (1)$$

4. PROBLEM FORMULATION

This section demonstrates how our proposed minimal set of metrics can be used in decision making for the design and maintenance of the SCMG. We first discuss the mathematical formulation and then present results derived from running the model in Section 5. Table 2 provides our notation.

Table 2. Notation for microgrid optimization

Symbol	Description	Symbol	Description
P_{source}	Total power available from online sources	n_{gen}	Number of selected generators
P_{load}	Total power required by online loads	t_f	Time at which failure occurs
C_{excess}	Percentage of excess power available over load	$n_{breakers}$	Number of circuit breakers (installed plus backup)
ns_{total}	Total number of available sources	n_v	Number of hybrid vehicles
ns_{online}	Total number of online sources	P	Length of planning horizon
nl_{total}	Total number of available loads	N_f	Number of failures within planning horizon
nl_{online}	Total number of online loads	$T^i_{working}$	The i^{th} failure free period

The SCMG is maintained for 1 year; i.e. P=365x24 hours. During this period, the SCMG goes through many cycles of failure and repair. A failure is defined as the period where the online sources are not able to meet the load requirements. This can happen because of insufficient installed capacity or component failures. As discussed before, the loads are stochastic and as such, we do not know their exact value at a particular time. Even though loads are shed (in the reverse order of priority precluding thereby, a complete failure of the grid) any shedding is counted as a failure. Sources and loads are added and removed at other times also. If the load requirements are too low, some sources are shed to save fuel and also to increase reliability by decreasing up-time. We assume that the increase in reliability is more significant than the potential harm from frequent turning on and off the sources. In systems where the opposite is true, sources can be kept on all the time. We do not consider this scenario here.

If the overall load gets too close to the total supply, either sources are added or loads are shed or both. The following set points, acting as design variables, are used:

1. If the system excess capacity falls below s_{so}, any additional sources that are available are brought online.
2. If the system excess capacity increases beyond s_{ss}, sources are moved to 'standby' status according to their sequence ranking, to conserve fuel and minimize runtime, minimizing therefore, maintenance costs and downtime.
3. If the system excess capacity falls below s_{ls}, loads are shed in the reverse order of their ranking.
4. If the system excess capacity exceeds s_{lo}, loads that were taken offline before are brought back online.

Figure 3 shows the power management protocol based on the above four set points. The protocol enables the microgrid to revert to a state where all loads are powered if enough supply is available. This guarantees that given sufficient capacity, the operation of the microgrid regains equilibrium (all loads are online) starting from any state. It does not imply however, that failures will not happen. It only implies that if enough capacity is available, the protocol can bring the system back to an operational status from a failure.

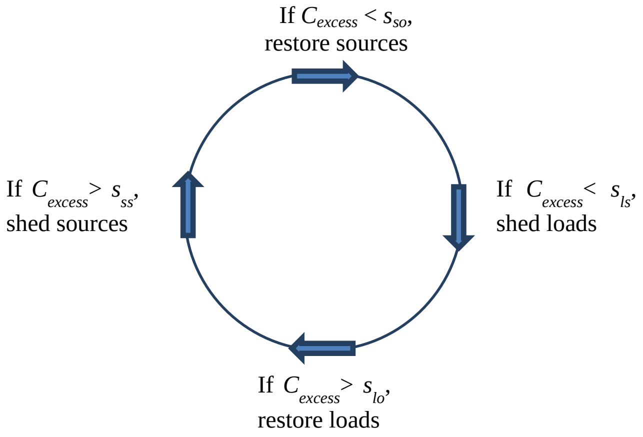

Figure 3. Power management protocol for microgrid

If all loads are online and are powered by available sources, the system is considered operational. Otherwise, it has failed. As mentioned before, failure occurs for two reasons:

1. The system does not have enough installed capacity to power all loads at all times.
2. Some or all of the components have failed and despite having enough capacity some loads are not being powered.

The first scenario requires waiting until the load requirements go down and the system starts working again. The second scenario requires repair of the malfunctioning components. We denote the online loads and total online sources with $P_{loads}(t)$ and $P_{sources}(t)$, respectively. Both are stochastic processes indexed in time. Failure happens at time t_f if

$$\{P_{source}(t_f) - P_{load}(t_f) < 0 \cup nl_{online}(t_f) < nl_{total}(t_f)\}. \quad (2)$$

The number of failures within the planning horizon (i.e., the number of *different* times $t = t_f$ failure has occurred) is given by N_f. A running repository of $T_{working}$ is also kept so that we calculate $T_{0.8}$ (see Table 1) using the CDF $F_{T_{working}}\left(t_{working}\right)$.

The following multiobjective optimization problem is solved using the NSGA-II multiattribute genetic algorithm [10] using many randomly generated starting points.

$$\underset{\mathbf{x}}{Min}\left\{-T_{0.8}, N_f, C\right\} \tag{3}$$

$$\text{where: } \mathbf{x} = \left\{s_{ls}, s_{so}, s_{lo}, s_{ss}, n_{gen}, n_{contacts}\right\}^T$$

$$T_{0.8} = F^{-1}_{T_{working}}(0.2)$$

$$C = C_{initial} + C_{repair} + C_{running}$$

subject to:

$$g_1(\mathbf{x}): P = 8760,$$

$$g_2(\mathbf{x}): p_{gen} = 0.25,\ g_3(\mathbf{x}): \eta_{repair} = 0.1$$

$$n_{gen}, n_{contacts} \in N$$

$$s_{ls}, s_{so}, s_{lo}, s_{ss}, \in [0,100]$$

The problem involves simultaneous maximization of the MFFP (represented by $T_{0.8}$) of the microgrid, and minimization of the number of failures, N_f and cost, C. Other metrics which affect the optimal solution are considered as constraints. The design variables include the set points $s_{so}, s_{ss}, s_{lo}, s_{ls}$ for restoring and shedding sources and loads as well as the number of sources and breakers $n_{gen}, n_{breakers}$ at the beginning of the installation. Sources and breakers that are not used are stored in the inventory. Thus, this formulation automatically accounts for the inventory size, repair time and their impact on the MSOM.

4.1 Implementation

A MATLAB suite of programs was developed comprising the optimization module and the simulation module. The former uses the NSGA-II multiattribute genetic algorithm to identify the best combinations of design variables to simultaneously optimize the three objectives of Equation (3). For each set of design variables, the simulation module tracks all loads for 8760 hours at one-hour interval. Then, the simulation module uses the values of s_{so}, s_{ss}, s_{lo} and s_{ls} of the design variable vector to decide whether to add or shed loads and/or sources. The simulation module keeps track of when failures occur and how long they last. If a particular failure requires replacement of a component, the module takes into account the replacement delay and the associated cost. The cost is then added to the initial cost of installation. The simulation module finally reports the cost, the 20th percentile of time between failures ($T_{0.8}$) and the number of failures within the planning horizon to the optimizer, which in turn compares it with other solutions and ranks it within the GA population. All solutions are evolved until a good approximation of the Pareto front over the three attributes is found.

5. RESULTS

Figure 4 shows the Pareto front generated over the three attributes of Mean Failure Free Period (MFFP) with 80% probability, the number of failures N_f, and the cost C. Each point on the front shows a different tradeoff between the three attributes.

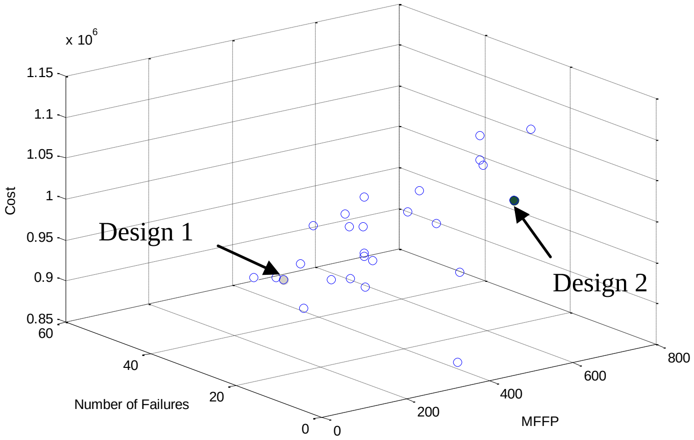

Figure 4. Pareto front over MFFP, number of failures and cost

The Pareto front is presented to a decision maker who chooses a design based on his/her tradeoff preferences. Table 3 shows the details of designs 1 and 2 indicated with filled circles on the Pareto front. The attribute values are averaged over many runs with the same design variables to account for the uncertainty in their calculation. The two designs correspond to different tradeoffs between the attributes. Design 1 runs for at least 71.7 hours without failure with 80% probability. The average number of encountered failures is 16 and the overall cost to acquire, repair and run the microgrid is $0.978 million. The corresponding numbers for design 2 are 516 hours, 5.5 and $1.046 million. The costs include the fuel cost for the generators. We observe that design 2 provides a much better performance for only a slight increase in cost.

Based on the optimal values of the design variables, the optimal set points are relatively aggressive for design 2 compared to design 1. For example, loads are shed when the excess capacity is only less than s_{ls} = 0.59%, versus s_{ls} = 2.71% for design 2. The other set points are also lower, except for s_{so} . This indicates that loads are kept online almost as long as possible for design 2 without wasting too much money to maintain excess capacity. While design 1 seems conservative by keeping large excess capacity it experiences more failures because loads are intentionally shut off when the excess capacity goes down, not because loads could not be met by the sources. The optimal solution for design 2 also calls for one less generator and one less contactor compared with design 1. This helps design 2 provide a higher reliability without incurring a high initial cost to acquire the equipment. This is achieved because of its more aggressive set points.

The optimal values of Table 3 correspond to an assumed stochastic behavior of the load. For a different system, the numbers will be different. If the decision maker does not “like” these numbers, he/she can choose a different point on the Pareto front with a higher MFFP and a higher cost.

Table 3. Decision variables and corresponding attributes for two designs on the Pareto front

Decision variables	**Design 1**	**Design 2**
s_{ls}	2.71%	0.59%
s_{so}	10.47%	17.88%
s_{lo}	14.59%	11.41%
s_{ss}	31.53%	22.35%
n_{gen}	5	4
$n_{contacts}$	18	17
Attributes		
$T_{0.8}$	71.7 hrs	516 hrs
N_f	16	5.5
C	$0.978 M	$1.046M

Note that Table 3 only shows the initial component count and not the count during the whole planning horizon after replacements. This initial count still leads to lower procurement delays (one less generator must be procured) and a higher MFFP.

The results of Figure 4 and Table 3 correspond to a microgrid with V2G capability using only two vehicles. We further analyzed the effect of bringing more vehicles to the grid. Table 4 shows the result of increasing the number of vehicles for the design 2 optimal solution of Table 3. Since the optimal solutions are calculated using a multiobjective optimization under uncertainty, they are not directly comparable because of the uncertainty. We observe however, that the solution tends to improve (e.g. higher MFFP and lower number of failures). Increasing the number of vehicles for example, improves the microgrid performance because of the power back-up they provide. This improvement results in either an increased MFFP (3 and 5 vehicle case) or decreased failures (5 vehicle case) or decreased cost (4 vehicle case).

Note that the actual solution from solving the optimization problem of Equation (3) with a higher number of vehicles may actually be better than that shown in Table 4 which simply increases the number of vehicles while using the optimal values of design 2.

Table 4. Attribute values as a function of the number of vehicles for the design 2 optimal solution of Table 3

Vehicles	MFFP	Failures	Cost ($)
2	516	5.5	1.04 M
3	863	6.2	1.11 M
4	406	8	0.985 M
5	653	3.6	1.08 M

Finally, we should note that the results from our method are not directly comparable with results from standard reliability engineering methods because of the fundamental challenges one faces when implementing classical reliability methods on repairable systems as outlined in Section 1.

6. SUMMARY, CONCLUSIONS AND FUTURE WORK

Ground systems are increasingly seen as mobile power generation systems rather than simply semi-autonomous mobile protection systems. This paradigm shift requires that microgrids be optimized using realistic load conditions using intelligent dispatching of available power sources. This paper presented a methodology to optimize the performance of a microgrid with V2G capability considering reliability specifications. The work also developed a protocol that can be used to run the microgrid over a pre-defined period of time.

We treated the microgrid as a repairable system where classical notions of reliability engineering do not apply. Instead, we performed multiobjective optimization over many attributes that measure different aspects of the microgrid's performance such as the Minimum Failure Free Period (MFFP), the number of failures within the planning horizon and the cost. A microgrid that uses generators, solar arrays as well as hybrid vehicles can be more reliable and at the same time cost effective as our results showed. We also showed that self-dispatching, where each source is able to dispatch itself depending on grid conditions, brings considerable value. The use of vehicles as load/sources was shown to improve the optimal solution for the microgrid . Finally a non-dominated Pareto front was generated over various attributes of concern so that the decision makers can choose the best solution.

Future work entails better modeling of the vehicle usage which will allow us to estimate the likelihood of a vehicle being available to connect to the microgrid when needed.

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