Systems Engineering Issues in Microgrids for Military Installations

Conference Paper *in* INCOSE International Symposium · July 2020

DOI: 10.1002/j.2334-5837.2020.00751.x

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30th Annual INCOSE international symposium
Virtual Event
July 20 - 22, 2020

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Abstract. This article investigates the systems engineering issues involved in the design of microgrid systems for military installations. A review of how microgrids function including major system elements is provided from a systems engineering perspective for non-microgrid experts. Specific issues that systems engineers are beginning to address and that remain to be addressed are highlighted. The activities of the INCOSE Critical Infrastructure Protection and Recovery (CIPR) Working Group demonstrate the growing importance of systems engineers to addressing microgrid issues. The increasing interest within the US Department of Defense in improving microgrids on installations shows the need to address issues that are specific to military microgrids.

Introduction

The U.S. Department of Defense (DoD) is the largest consumer of electricity in the United States (ODASD(IE) (2016)). The DoD relies on the uninterrupted delivery of electrical power to operate systems and installations to accomplish their national security mission. As reliable as the electricity grid is though, it is not perfect in its delivery of power. Outages still occur due to a variety of environmental, equipment, and human failures. In 2015 alone, DoD installations experienced 127 electricity outages due to weather and equipment failures that lasted eight hours or longer (DOE (2017)). The number of outages increased to 507 in FY2016, 1,205 outages in FY2017 ((ODASD(IE)) (2018)). In addition to outages caused by weather and failures, the DoD has many overseas bases dependent on local utilities for power making them vulnerable to power disruptions due to geo-political events. Finally, military bases must consider intentional attacks on the electrical grid, which no doubt are part of many adversaries' plans. DoD functions and activities depend on the availability of energy; consequently, the issue of energy security needs to be addressed in both a systematic and systemic way to assure mission accomplishment.

The U.S. Department of Energy defines microgrids as, "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode" (Ton and Smith (2012)). The IEEE defines characteristics of microgrids to include the above as well as identifying a microgrid as being intentionally designed as such (IEEE Standards Coordinating Committee 21 (2011)). The definitions of a microgrid define for us the system-of-interest as given by the electrical boundaries controlled by the installation. From the military perspective, the military organization generally controls the microgrid, which can function whether connected or not to the external provider. Two types of military installations exist: military installations connected to the public utility, and military installations on islands or other remote locations that provide 100% of their own power.

The U.S. Navy has been developing microgrids at Navy shore-side facilities with the objective of increasing energy security. Energy security can be thought of on multiple levels, from national strategy down to tactical [local] installation level. Energy security at the installation level has three components: reliability, resilience, and efficiency. Energy reliability is the percentage of time the energy delivery systems, external power grid plus microgrid, can supply stable, installation well-mannered electricity to its customers. Energy resilience refers to the electrical supply's ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions to the external energy supply or installation power disruptions and failures. Energy efficiency is the ability of the installation to minimize the energy demand of its operations without sacrificing operational performance. By public law (10 USC Ch. 173 section 2911), the Secretary of Defense (SECDEF) is required to "...ensure the readiness of the armed forces for their military missions by pursuing energy security and energy resilience." The SECDEF is given statutory authority to authorize the use of energy security and energy resilience as factors when conducting cost-benefit analysis for the procurement of energy, and to give favorable consideration to projects that will use renewable energy sources to provide power to military facilities or to an installation's electrical grid. Consequently, for military microgrids all decisions must consider tradeoffs between energy security and the cost of the energy.

The majority of research on microgrids deals with technical challenges in isolation without consideration of the operational context (see for example (Parhizi et al. (2015)) and (Salam et al. (2008))). Hence, we see a need for identifying microgrid research issues relevant to the systems engineering community and specifically to the concerns unique to military installations. The systems engineering perspective differs from many of the technological and discipline specific approaches to microgrid design because a systems engineering approach views microgrids as a whole system, considers both operational effectiveness and suitability of the microgrid design, and analyzes the microgrid in the context of the larger power grid and other systems it is a part of. Hence, a systems engineering perspective considers the integration of the many components of a microgrid and how they work together to deliver operational capabilities. This paper reviews the research issues concerning microgrids for military facilities from a systems engineering perspective. While our focus is on military bases, we believe almost all of the issues are relevant to microgrids in general. The intent is to provide guidance on where the systems engineering community needs to concentrate our efforts to advance the development and installation of microgrid solutions.

System Perspective of Microgrid Design and Operation

This section presents a systems engineering perspective of microgrid design and operation. Specifically, we consider:1) System Purpose, 2) Stakeholders, 3) System Boundaries, 4) Functional Requirements, 5) System Architecture, and 6) System Operating Modes.

One of the first questions to consider in designing a system is what is the purpose of the system? The answer to this question is usually documented in a problem statement which serves to focus the design, development, and integration effort. All systems are designed for one or more purposes, which guide the system development process. The second issue is to identify all of the stakeholders and their needs with respect to the system. To fulfill its purpose the system performs one or more functions which establish the basic requirements for the system. The system engineer is then involved with designing the system architecture, which shows the structure of the system elements and the relationships between the elements. Finally, the system engineering must be concerned with all the lifecycle issues encountered during acquisition through disposal of the microgrid.

System Purpose

The DoD's priority for microgrids is to ensure mission readiness through energy security ((ODASD(IE)) (2018)). Secondary goals for the DoD include percentage of renewable energy used for facility energy needs to meet policy guidance (DOD (2019)). The U.S. Navy defines energy security as consisting of three pillars: reliability, resilience, and efficiency (Savena et al. (2017)). Microgrids for shore-side installations must support all three. Of the three, resiliency is of the greatest interest because military bases must contend with the same disruptions as civilian infrastructure due to weather, failed equipment, changing loads, etc., but military bases must also consider additional threats due to malicious attacks. Malicious attacks may be physical attacks on the infrastructure or cyber-attacks on the communication and control system, or a combination of both.

The DoD defines energy resilience as "The ability to prepare for and recover from energy disruptions that impact mission assurance on military installations" (of Defense (2009)). The definition aligns with the larger literature in the domain. We describe resilience as four phases starting with (1) the baseline phase during which the system has normal performance, (2) the vulnerable phase when the system degrades following a disruption event, (3) the recovery phase during which the system improves its performance due to restorative efforts until it reaches (4) the recovered phase (Yodo and Wang (2015)).

Energy efficiency seeks to reduce waste and use the minimum amount of energy required for the operational mission. The DoD views energy efficiency as a potential force multiplier by extending the range and endurance of its forces, as well as reducing energy costs.

Consequently, military microgrids have the purpose to provide and distribute energy, provide energy security, and to do it as inexpensively as possible. The design decisions impacting the microgrid must take into consideration all these objectives.

Stakeholders

Identifying the relevant stakeholders is a first step towards establishing operational requirements for a microgrid. Military installations are often partitioned into a base (installation) command and one or more tenant commands. The base command is responsible for the acquisition, operation, and maintenance of the base, which includes the microgrid. Whereas the tenant commands are situated within the installation and are the users of the microgrid. Additionally, the local energy company the microgrid is connected to, the microgrid provider, and any organizations for the maintenance and upkeep of the microgrid are stakeholders. Each installation reports to a higher authority in the military chain of command, including key stakeholders who fund the microgrid and related energy security projects.

System Boundaries

A system has both physical boundaries and functional boundaries. The system engineering perspective views the entire system including the physical equipment, software, processes, and people as the system. Adopting this holistic perspective changes how we approach energy security of the microgrid. For example, recovery from a disruption depends on the availability of spares, ability to troubleshoot the problem, training of the maintenance crew, and so forth. Many existing research papers on resilience and energy security take a narrow view of the system as consisting of just the microgrid. Figure 1 depicts the context of a military facility microgrid from a systems engineering perspective.

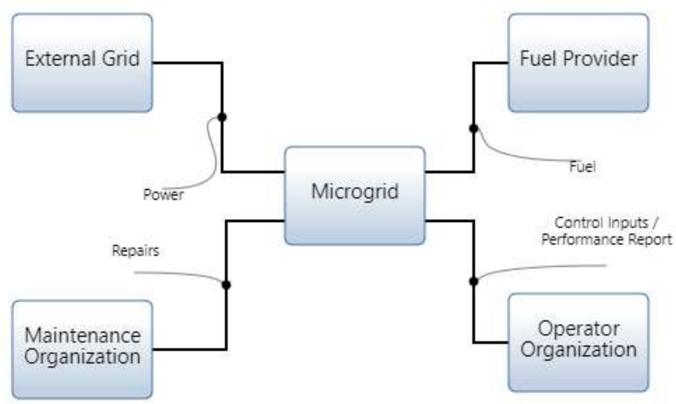

Figure 1: The Microgrid Context from a Systems Engineering Perspective.

The major external interface is between the microgrid and the external power grid.

Functional Requirements

The functional analysis of microgrids provides a means to organize and discuss microgrid requirements and design. Figure 2 shows the top-level functions of a microgrid. A microgrid provides the following minimum functionality: generate power, distribute power, control power distribution, and often a microgrid will also provide the function of storing power. Additional functionality might be required, here we only define the minimum. A microgrid needs to generate sufficient power to meet critical loads while in island mode. The microgrid must be able to distribute power to where it is required. Control is the most complex of the basic functionality and includes managing the microgrid so it can seamlessly connect and disconnect from the grid, load balancing, controlling frequency, controlling voltage, monitoring and controlling storage, and optimizing microgrid operations (Castillo et al. (2016)). The function to store energy is not absolutely required, but in any actual installation energy storage is necessary because the load and energy generation are almost never matched when operating in island mode. Moreover, energy storage aids some of the control functions and stability. Consequently, the system must store energy from when energy generation exceeds demand in order to meet requirements when demand exceeds generation.

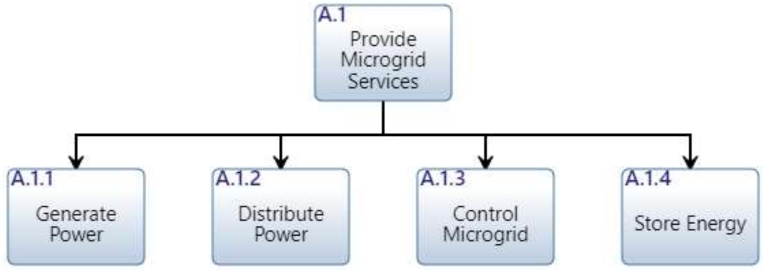

Figure 2: A High-Level Microgrid Functional Model.

Below is a breakdown of lower-level functions within the functional model:

1. Generate Power
   1.1. Generate Electrical Power
   1.2. Adjust Power Production
2. Distribute Power
   2.1. Transmit Power
   2.2. Control Power Flow
   2.3. Convert Power
3. Control Microgrid
   3.1. Measure Microgrid State
   3.2. Process Measurements (Make Control Decisions)
   3.3. Send Control Signals
4. Store Energy
   4.1. Store Power
   4.2. Release Power
   4.3. Adjust Power Flow

Generate Power: A variety of power generation sources can be used on microgrids. Many military microgrids use the external grid as their primary power source. Most microgrids also include one or more distributed energy resources (DER), which are local energy generation sources such as fossil-fuel based generators and power plants (gas turbine, oil plant, diesel generator, coal plant, etc.), renewable power sources (solar, wind, micro hydro, wave power, etc.), and other sources (fuel cells with a variety of fuel sources, garbage incinerator power plants, biomass plants, etc.). Occasionally, unconventional generation sources such as plug-in hybrid vehicles may be used to generate energy.

Microgrid power generation may be either peaking power generation, load following, base generation, or intermittent generation (DOE (2017), Kaplan (2008)). On some microgrids, a mixture of all four generation types may be found. For instance, a microgrid may have an oil-fired power plant providing base generation capacity, a solar array providing intermittent generation, and a fast start gas turbine generator that provides load following capability.

Distribute Power: Microgrids use several methods of transmitting energy between generation sources, the grid, energy storage systems, and loads. The most common are AC and DC power lines and buses. These usually take the form of overhead cables and wires (insulated or uninsulated) or underground cables (direct bury, in a conduit or wire race, or otherwise protected from the earth). In some systems, transformers may be used to step up and/or step down voltage. AC energy transmission is generally used when there are longer distances between nodes in the microgrid network. DC energy transmission is often found in specialized microgrid applications such as computer server farms or facilities with large quantities of sensitive electronics. DC energy transmission is also sometimes found in facilities with large amounts of DC power generated via renewable resources to reduce losses in the power distribution system from DC to AC power conversion (Shaver (2017)).

Control Microgrid: Microgrid control includes many sub-problems making it a complex problem. The control problem depends on the state of the microgrid, whether it is grid connected or islanded, as well as switching between these states. Microgrid control is further complicated by controlling different microgrid characteristics, simultaneously, at multiple timescales ranging from mili-seconds through minutes and hours.

Microgrid controls may also encompass load shedding through direct control of non-critical loads (Brooks et al. (2010)) such as heating and air conditioner loads. The microgrid control problem is often conceptualized as hierarchical control at three levels of authority. Primary controllers (sometimes referred to as droop controls) operate generators and storage sources to maintaining the stability of frequency and voltage within a predefined range of values in intervals measured in miliseconds. Secondary controllers coordinate generation and storage across the microgrid for power quality control, power flow control, and synchronization. Tertiary controllers operate the grid connect/disconnect switch and regulate if power is being taken from the grid or fed back to the grid. Tertiary control addresses the economics of operating the microgrid. Microgrid controls may perform load shedding through direct control of non-critical loads such as heating and air conditioner loads (Brooks et al. (2010)).

Several researchers are addressing various aspects of the microgrid control problem because microgrid control introduces many issues not present in control of the overall power grid. For example, the power supplied by solar and wind vary with the weather and consequently power is not assured from these sources [cite]. Additionally, there are advances in communication technologies and sensors to better manage the microgrid. Microgrid control can be achieved through central control or through a decentralized control architecture (Colson and Nehrir (2009), Lopes et al. (2006)).

Energy Storage: The storage of energy is not an essential microgrid function, but for microgrid performance, energy storage is generally needed to help balance energy generation and loads, aid in frequency and voltage control, and to increase microgrid resiliency. Military microgrids often contain energy storage systems such as batteries (lead acid, lithium, flow, etc.), mechanical storage (compressed air, flywheel, pump storage hydro, etc.), supercapacitors, thermal (cryogenic, ice storage, molten salt storage, etc.), and other storage methods (hydrogen storage, etc.) (US EPA (2015)). Site-specific constraints and microgrid requirements often dictate what energy storage technologies are implemented on a microgrid. For instance, some residential homes have battery storage (lithium-ion, lead acid, etc.) for electrical energy while some large buildings have a variety of thermal storage (primarily ice storage and some cryogenic) for building thermal management (EIA (2018)). In some cases, hybrid or electric vehicles can be tied into microgrids to provide battery storage capacity ((iea) (2014), Lu and Hossain (2015)).

System Architecture

A system architecture describes system elements and how they are related to each other. Figure 3 shows a typical military microgrid architecture. The microgrid has a power network that interconnects various types of distributed energy resources to the loads and an energy storage subsystem. The energy generation subsystems may be dispatchable, meaning the microgrid control system can control the generation of energy, or not dispatchable. Renewable energy sources such as wind and solar are non-dispatchable energy generators because there is little or no control of how much energy will be generated at any given time.

In an ideal situation on a military microgrid, loads are partitioned into critical loads, which must be served regardless of any disruptions, and all other loads termed non-critical loads which can be curtailed during a disruption. The definition of critical load depends on the installation's mission. The total energy required for the critical loads determines the necessary resilience of the microgrid because these are the loads that must be served if any disruption occurs to the connection to external power grid. In practice, critical loads and non-critical loads are not always partitioned on the power network in an easily dispatchable manner to enable load-shedding of non-critical loads while preserving power delivery to critical loads.

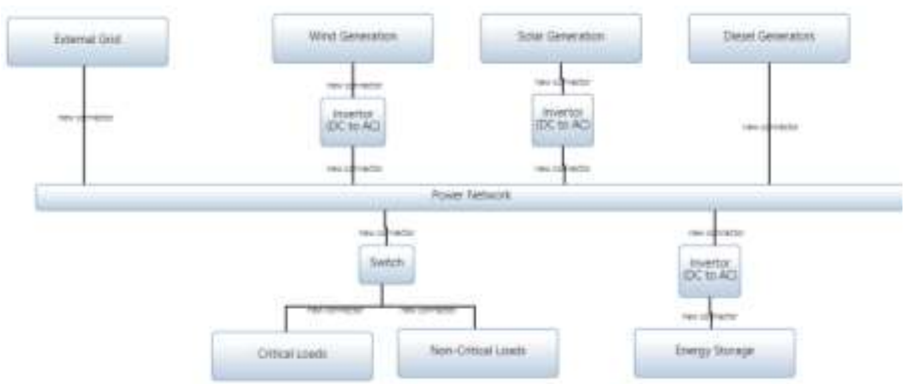

Figure 3: Microgrid Physical Architecture.

The energy storage system serves multiple purposes, but primarily from an energy security perspective, the energy storage enables the microgrid to balance supply and demand. The architecture also highlights the need for inverters between AC and DC because most loads will be AC, while many of the renewable energy sources generate DC power.

System Operating Modes

In addition to the functional perspective, it is also useful to consider microgrids from a state perspective. IEEE Standard 1547.4-2011 defines four normal operating modes for microgrids: grid-connected mode (or normal operating mode), transition-to-island mode, island mode, and reconnection mode. Figure 4 graphically shows the states that a microgrid operates in and how transitions between the states can be made.

Grid-connected Mode: This mode of operation is sometimes referred to as "normal parallel operation." During normal parallel operations, all the distributed resources in the microgrid (loads, generators, switches, MIC equipment) are operating within IEEE standards, or in conditions agreed to in advance with the local utility. Information from the microgrid must be provided to the microgrid controller device.

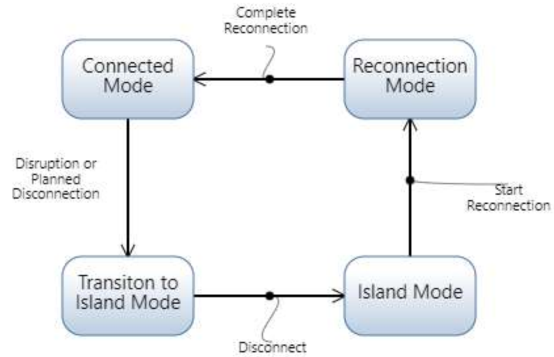

Figure 4: Microgrid States.

Transition-to-island Mode: The microgrid can transition from normal parallel operation to a transition-to-island mode as a result of either planned or unplanned events that cause a disruption to the power being delivered by the local utility. During transition-to-island there must be sufficient power generation or energy storage resources to provide stable voltage and frequency until a successful transition can be accomplished. Of particular concern in this operational mode is the dampening of transients produced in the microgrid quickly enough to avoid protective devices in the microgrid from tripping.

Island Mode: In island mode, the microgrid is isolated from the local utility and now assumes responsibility for actively maintaining the microgrid voltage and frequency within agreed upon ranges. If there are multiple participating power sources or energy storage devices in the microgrid, they must be controlled and synchronized to meet the needs of the microgrid stakeholders. In some cases, demand side control is also incorporated to maintain microgrid operation.

Reconnection Mode: Before a microgrid can be reconnected to the local utility, the microgrid control must determine that the local utility is stable and operating within acceptable parameters. In a system architecture that includes multiple microgrids, the reconnections may be intentionally staggered to aid synchronization. There are at least three ways to reconnect microgrids from island mode back to normal parallel operation (IEEE Standards Coordinating Committee 21 (2011)). The key issue is synchronization of voltage, frequency, and phase angle between the microgrid and the local utility. In active synchronization, the local utility and the microgrid system conditions are sensed and passed to a control mechanism that actively adjusts parameters until they are within acceptable limits. In passive synchronization, the microgrid's paralleling device is monitored until the local utility and microgrid are within acceptable limits before initiating reconnection. A third method is to use open-transition transfer, during which the microgrid load and any distributed resources in the microgrid are de-energized prior to reconnection. This approach has the advantage of not requiring system synchronization sensors, but is disruptive to the operations of the loads served within the microgrid.

Research Issues Concerning Systems Engineering of Microgrids

Microgrid Architecture Design

Systems engineering approaches system design in a top-down fashion of architecture design followed by system design. Systems engineers often further divide system architecture into operational, functional, and physical architectures. The architecture defines the structure of the elements and the relationships between them. Microgrid architecture design decisions include: 1) energy generation types and capacities, 2) microgrid configuration layout, 3) energy storage system (ESS) type, size, and location, 4) AC or DC grid, 5) control methods, 6) level of load shedding control, 7) protection, and 8) performance criteria. Liu, Gorgiadis, and Pistikopoulos (2013)find many microgrids are not realizing their potential benefits because the microgrids lack a suitable architecture or do not have a suitable operational strategy. These shortfalls lead Liu, Georgiadis, and Pistikopoulos to recommend a systems engineering approach.

Jones (Jones (2018)) discusses how engineering of microgrids is fragmented with engineers focused on their specialty and often not considering or fully appreciating how it will integrate with the other components of the microgrid. He traces this mentality to the design of the overall electric power grid in which each component can be designed in relative isolation because of the network architecture. Microgrids by contrast require tight coordination between generation and loads. Jones states, "The team tasked with engineering a microgrid needs to understand how the system will work as a whole, how the components work individually and how they must interact with another." This is a potential research area for systems engineering to develop the microgrid architecture to provide the basis for how the components are all intended to integrate together.

ESS is one element of microgrid architecture which is important to microgrid operations. ESS in microgrids serve multiple functional roles. Some microgrids use ESS for load-shifting in which the ESS stores energy during peak generation periods and then discharges the energy to the microgrid during peak demand periods. ESS also can provide power regulation. A common role of ESS is to provide for stand-by power loss. During the transition-to-island mode operation, ESS can maintain power to critical loads by meeting the momentary shortfall between generation and load until slower responding generation sources, such as diesel generators, can come online (Castillo et al. (2016)). Current backup power systems with diesel generator backup power use uninterruptible power supplies (UPS) to maintain power to those loads which cannot tolerate any power interruption (Stamp (2012)). We identify nine properties of ESS normally considered in architecture design as power capacity (MW), energy capacity (MWh), ramp rate, location, response granularity, response frequency, control and communication, response time, and implementation requirements.

The several existing design tools for microgrids primarily focus on economic optimization while not adequately considering issues of resilience and other topics of concern to DoD microgrids. DER-CAM is a design tool based on a mixed-integer programming model to determine the best distributed energy resources to minimize total operating costs. The Microgrid Design Toolkit (MDT) from Sandia develops the tradespace for multiple objectives although most implementations ignore many DoD microgrid concerns. HOMER is another microgrid tool that is based on a simulation model but cannot fully address DoD microgrid issues. XENDEE is a microgrid design tool that has seen recent traction within DoD although it is primarily sold as an economic analysis tool. An open area of research is the need for microgrid design tools that can support DoD microgrid issues and design objectives. Such a tool will need to span from the system architecture phase of system design through to maintenance and support, and will need to interface with existing electrical infrastructure modeling software packages through the detailed design phase.

Trade Studies

Much of the research on microgrids focuses on narrow questions suitable to optimization. Optimization techniques are less relevant however, when taking a broader, holistic perspective of the entire microgrid in the context of its environment. When you have multiple stakeholders, often with incommensurate goals, it is not possible to define a single overall system objective. Additionally, there is the tension between the short-term costs of many components such as solar panels or batteries compared to the long-term and often non-tangible benefits received. Consequently, a trade study to understand and support decisions seeking a balance between the many concerns becomes necessary. Framing and conducting trade studies is a core knowledge area of the systems engineering discipline.

Trade studies to analyze performance versus resiliency as well as other -ilities and cost must be performed because increases in resilience come at a cost beyond baseline operating costs. One significant research issue that systems engineers must address is the life-cycle costing of various energy technologies and system architectures, as well as determining the right mix of technologies. Another area of research with regards to trade studies is the military microgrid design problem of sizing energy storage. Most existing research focuses on optimize the economics of storage rather than other important factors such as resilience (Poonpun and Jewell (2008), Chen et al. (2011), Chen et al. (2011)). Determining the cost of resilience is important so decision makers can decide whether the investment is worthwhile. Guidance for DoD approving officials on the value of energy security is lacking (Rusco and Lepore (2016)), resulting in inconsistent approaches.

DoD 4170.11 Change 1 requires that projects for energy resiliency are life-cycle cost effective, and requires DoD Components to use National Institute of Standards and Technology (NIST) Handbook 135, Life Cycle Costing Manual to determine life-cycle cost effectiveness. It further provides guidance for a 10-year simple payback period when making decisions to reduce energy usage (of Defense (2009)). Castillo et al. provide guidance and tools for the DoD to use in making business case decisions on costs of difference strategies to reach resilience objectives (Castillo et al. (2016)).

Use of Renewable Power Generation Sources

The military's energy policy is driven by the need for ensuring energy security, resilience, and cost reduction. The National Defense Authorization Act of 2010 requires military installations in the US to be energy efficient and produce or buy 25% of the total DoD energy use from renewable resources by 2025. 10 U.S. Code § 2911 requires that 25% of DoD total facility energy from renewable resource by 2025 (DOD (2019)). Renewable energy sources provide diversification away from traditional fuel sources, which can decrease fossil fuel usage and CO2 generation, resiliency, and reduce lifecycle costs. For example, an installation might rely completely on the regional power grid with backup diesel generators. When a disruption occurs, the diesel generators are limited by the availability of fuel. Renewable sources such as solar or wind can provide an important source of power and diversify the installation away from a reliance on fuel in the event of a natural disaster or attack where resupply is constrained. Renewable energy provides point-of-use energy generation, smaller and decentralized power generation, free and inexhaustible source, and easy to rapidly install and deploy onsite. The contribution of renewable power generation sources to resiliency and the balance of peak shaving versus resiliency for military microgrids provides areas of interest for research.

System of Systems and Microgrids

The microgrid by itself is usually not a system of systems (SoS) because the microgrid authority almost always has managerial and operational control over all the component systems in the microgrid. However, a microgrid is almost always part of a larger power grid SoS. A microgrid will have multiple interactions with the larger SoS including electrical flows, information flows, control flows, as well as the flow of money. Many microgrids use the main grid as the main power source, which the microgrid supplements with their DER. Microgrids also must often coordinate their power generation and consumption with the larger grid. Kargarian, Falahati, and Fu (Kargarian et al. (2013)) illustrate the type of issues related to microgrids and SoS in which they model a distributed and connected set of microgrids as a SoS, and develop an optimization approach whereby each independent microgrid maximizes its profit, and then exchanges information with the distribution grid, which maximizes its profit. Ouammi, Dagdougui, and Sacile [31] have also looked at the issue of control flows when they analyzed the case of four microgrids that cooperate as well as interconnect to the larger power grid. The main research issues in this area are coordination of the microgrid with other energy systems such as the grid; understanding and modeling the interactions for failure analysis or other reasons since emergent behaviors may result; and developing control algorithms for the distributed energy network. Existing systems engineering research into how SoS can prevent failure of the entire SoS when constituent members fail (Van Bossuyt et al. ()) may be useful in the context of DoD microgrids.

Microgrid -ilities

Military installations require energy security from the microgrid. Energy security implies high reliability to meet critical loads, and it means resiliency to attacks as well as natural events. Most microgrid research on resilience studies how the microgrid responds to natural disasters. However, resilience with respect to attacks requires a different approach than resilience to natural disasters. Intentional attacks are not random events. An attacker seeks out weaknesses in the system and tries to exploit them. Attacks can come in the form of both physical attacks and cyberattacks, and as attacks to disrupt the incoming installation power or against the microgrid itself. Consequently, methods to increase resilience of microgrids must combine security analysis with the technical analysis of the microgrid.

The focus of microgrids to support energy security and resiliency in DoD applications also requires different analysis approaches and system control strategies versus civilian microgrid system applications. Civilian microgrids may have objectives to minimize energy costs. Maintaining high ESS charge levels to maximize the time the microgrid can supply critical loads in the event of a loss of utility power would be favorable to using the ESS to perform peak shaving. Trade-offs between the cost of energy and energy security need to be balanced.

Fathima and Palaniswamy (Fathima and Palanisamy (2015)) discuss the application of optimization to microgrid design and find most papers seek to minimize some aspect of costs or the optimal size of energy generation components. Khan (Khan et al. (2016)) extensively surveys papers on optimization of microgrids and overwhelmingly the objective is to minimize a cost function. We were unable to find any papers optimizing the resilience or energy security of a microgrid, which would be of interest to military installations.

Systems engineers can improve microgrid resilience by hardening the microgrid to avoid disruptions, designing the microgrid to minimize the effect of any disruptions, and designing the microgrid to recover as quickly as possible. Beyond the microgrid design issues to improve resiliency, there is the microgrid operational aspects of training personnel, having needed supplies and materials available, defining policies and procedures, and having the leadership to institute all the needed system and system operation aspects for resiliency (sometimes abbreviated as DOTLMPF). Another aspect of DoD microgrids that complicates understanding the resilience of a microgrid is identifying the critical loads and other power requirements that support critical base missions. Identifying critical loads is a non-trivial task often overlooked in the existing research literature.

Most DoD facilities have backup generators connected to critical loads to minimize the impact of any power disruptions (Castillo et al. (2016)). In the context of resilience engineering, failure of a system such as a microgrid is seen as the inability of the system to adapt to real-world conditions (Madni and Jackson (2009), Hollnagel et al. (2006), Jackson (2010)). In the context of DoD microgrids, resiliency encompasses not only issues associated with civilian microgrids such as storms, failed equipment, changing loads, etc., but also encompasses malicious attacks (both physical and cyber) and adverse environments (arctic, desert, tropical, ocean).

Utilities typically measure electric grid reliability using two indices of System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI) (Cepin (2011), Allan (1996)). In the presence of momentary faults due to severe weather events, utilities started to use the Momentary Interruptions Per Customer Index (MAIFI). An issue for a military microgrid is how to define suitable measures to guide the design decisions. SAIFI and SAIDI are likely not suitable measures for military microgrid reliability because a military installation does not serve customers in the same sense as a utility. Rather, the military installation likely has critical loads tied to its mission, and any measure must be tied to this objective. One such measure is the Mission Dependency Index (MDI) that was developed to better understand the inter-relation between microgrid reliability and the impact a microgrid's reliability has on completing the mission of a base (Command (2018)). However, MDI has a number of shortcomings as a useful measure.

Designers can improve system resilience by incorporating redundancy into the system, automating switching between elements of the architecture, hardening system elements, being able to sense issues and having a communication and control system to react quickly to potential problems, and including reconfigurable elements that can be used to bypass damaged or destroyed portions of a microgrid. Resilience can also be improved through system architectures which incorporate features such as decentralized controls (Colson et al. (2011), Danzi et al. (2018)), incorporation of demand response (Pourmousavi and Nehrir (2012)), and communication protocols which are less susceptible to attack (Danzi et al. (2018)). While civilian microgrid resiliency decisions are often strongly driven by cost considerations, DoD microgrid resiliency decisions may be more driven by mission considerations such as how critical it is to have a microgrid that can continue to supply power to critical loads under adverse conditions. Similarly, a rapidly reconfigurable microgrid may be desirable for DoD applications to quickly bypass damaged components or subsystems so that power delivery can resume rapidly.

Microgrid Acquisitions

The DoD can procure microgrids as part of traditional energy infrastructure acquisition methods with Congressional-appropriated Military Construction (MILCON) funds. The most flexible and widely used option is the Energy Resiliency and Conservation Investment Program (ERCIP) ((ODASD(IE)) (2018)). This program is authorized under 10 U.S.C. § 2914 and has $150M in annual funding planned for FY2020 for energy resilience, energy security, or energy conservation MILCON projects which improve mission assurance or provide payback.

Additional options use third-party financing which is paid back via the savings generated from the project. Utility Energy Service Contracts (UESCs) and Energy Savings Performance Contracts (ESPCs) are two options available to DoD ((ODASD(IE)) (2018)). However, a net positive payback for microgrids is often not achievable, and these acquisition alternatives may not support the acquisition of microgrids to support resiliency objectives. Changes in acquisition regulations and guidance on how to use third party financing to buy resiliency in a manner cost effective in comparison to buying other resiliency measures through MILCON would be an area worth researching.

The DoD is restricted to acquiring only U.S.-made (or allied nations-made) equipment for power distribution equipment and wire (48 CFR § 225.401-70), and for photovoltaic devices (48 CFR § 225.7017). These restrictions limit procurement options and can increase costs as compared to a civilian microgrid. Additional requirements and restrictions as part of the DoD and federal government acquisition process can lead to challenging acquisition situations. Existing research and civilian industry practice can indicate a better solution than DoD microgrid acquisitions; however, this is often because said industry practices and existing research don't have to address requirements that are more common to DoD applications than civilian applications. For instance, in addition to the above mentioned acquisition requirements, DoD microgrids must sometimes operate in what is termed an "expeditionary mode", i.e. be transportable and able to operate in potentially hostile locations in harsh environments (such as arctic regions, deserts, jungles, mountains, ocean environments) with a minimal amount of logistical support. In a fixed installation application, a microgrid is a type of infrastructure system that is almost never built from the ground up because military bases already have an electrical system to which the microgrid must interface. In an expeditionary mode, a microgrid may operate largely in an island mode due to the unreliability or nonexistence of host electric power infrastructure in the area of operations.

Conclusion

Many communities and industrial facilities are designing and deploying microgrids consisting of distributed energy generation, energy storage, and energy consumption. While electrical engineering research and industrial practice support civilian microgrid development, to date, the systems engineering community has not done much research directly related to military microgrids. Military microgrids share all the same issues and characteristics of civilian microgrids with the primary difference being military microgrids are more concerned with energy security, whereas civilian microgrids are more concerned with cost and environmental issues.

Much existing research on microgrids is narrowly focused on particular aspects such as energy storage or objectives such as cost minimization. A systems perspective necessarily considers multiple aspects and objectives simultaneously. This paper reviewed microgrids from a systems engineering perspective and identified the relevant research issues where the systems engineering community can contribute to this field. We urge the systems engineering community to become more involved in addressing DoD microgrid issues; we believe by addressing DoD microgrid issues, DoD microgrids will better serve their intended purposes and civilian microgrids will also see benefits.

References

Allan, R. (1996). *Reliability Evaluation of Power Systems*. Boston, MA: Springer US.

Brooks, A., E. Lu, D. Reicher, C. Spirakis, and B. Weihl (2010, May). Demand dispatch. *IEEE Power and Energy Magazine 8*(3), 20–29.

Castillo, A., S. V. Broekhoven, N. Judson, A. Pina, and E. Dydek (2016). Application of a resilience framework to military installations: A methodology for energy resilience business case decision. Technical Report TR-1216, Massachusetts Institute of Technology Lincoln Laboratory.

Cepin, M. (2011). *Distribution and Transmission System Reliability Measures*, pp. 215–226. London: Springer London.

Chen, C., S. Duan, T. Cai, B. Liu, and G. Hu (2011, Oct). Optimal allocation and economic analysis of energy storage system in microgrids. *IEEE Transactions on Power Electronics 26*(10), 2762–2773.

Chen, S., H. B. Gooi, and M. Wang (2011). Sizing of energy storage for microgrids. *IEEE Transactions on Smart Grid 3*(1), 142–151.

Colson, C. M. and M. H. Nehrir (2009). A review of challenges to real-time power management of microgrids. In *2009 IEEE Power & Energy Society General Meeting*, pp. 1–8. ID: 1.

Colson, C. M., M. H. Nehrir, and R. W. Gunderson (2011, Aug). Distributed multi-agent microgrids: a decentralized approach to resilient power system self-healing. In *2011 4th International Symposium on Resilient Control Systems*, pp. 83–88.

Command, N. I. (2018). Cnic instruction 11100.1a: Mission dependency index.

Danzi, P., M. Angjelichinoski, ÄŒedomir StefanoviÄ‡, T. DragiÄ• eviÄ‡, and P. Popovski (2018). Software-defined microgrid control for resilience against cyber attacks. *IEEE Transactions on Smart Grid.*. ID: arxiv1802.02936.

DOD (2019, January 26,). 10 u.s.c. Â§2911 energy policy of the department of defense.

DOE (2017). Valuation of energy security for the united states.

EIA (2018, May). U.s. battery storage market trends. Technical report, US Energy Information Agency.

Fathima, A. H. and K. Palanisamy (2015). Optimization in microgrids with hybrid energy systems–a review. *Renewable and Sustainable Energy Reviews 45*, 431–446.

Hollnagel, E., D. D. Woods, and N. Leveson (2006). *Resilience Engineering: Concepts and Precepts*. Ashgate Publishing, Ltd.

(iea), I. E. A. (2014). Technology roadmap energy storage. Technical report, International Energy Agency.

IEEE Standards Coordinating Committee 21 (2011). *IEEE Standard 1547.4-2011: Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems*. Institute of Electrical and Electronics Engineers.

Jackson, S. (2010). *Architecting Resilient Systems: Accident Avoidance and Survival and Recovery from Disruptions*. John Wiley and Sons, Inc.

Jones, D. (2018, April 13,). Microgrid engineering becoming a macro-profession.

Kaplan, S. (2008, Nov 13,). Power plants: Characteristics and costs. Technical report, Federation of American Scientists.

Kargarian, A., B. Falahati, and Y. Fu (2013). Optimal operation of distribution grids: A system of systems framework. In *2013 IEEE PES Innovative Smart Grid Technologies Conference (ISGT)*, pp. 1–6. IEEE.

Khan, A. A., M. Naeem, M. Iqbal, S. Qaisar, and A. Anpalagan (2016). A compendium of optimization objectives, constraints, tools and algorithms for energy management in microgrids. *Renewable and Sustainable Energy Reviews 58*, 1664 – 1683.

Lopes, J. A. P., C. L. Moreira, and A. G. Madureira (2006, May). Defining control strategies for microgrids islanded operation. *IEEE Transactions on Power Systems 21*(2), 916–924.

Lu, J. and J. Hossain (2015). *Vehicle-to-Grid: Linking Electric Vehicles to the Smart Grid*. London, England: The Institution of Engineering and Technology.

Madni, A. M. and S. Jackson (2009). Towards a conceptual framework for resiliency engineering. *IEEE Systems Journal 3*(2), 181–191.

ODASD(IE) (2016, June). Annual energy management and resilience report fy2015. Technical report, Department of Defense.

(ODASD(IE)) (2018, July). Annual energy management and resilience report fy2017. Technical report, Office of the Assistant Secretary of Defense for Energy, Installations, and Environment.

of Defense, U. D. (2009). Dod instruction 4170.11 installation energy management.

Parhizi, S., H. Lotfi, A. Khodaei, and S. Bahramirad (2015). State of the art in research on microgrids: A review. *IEEE Access 3*, 890–925.

Poonpun, P. and W. T. Jewell (2008). Analysis of the cost per kilowatt hour to store electricity. *IEEE Transactions on energy conversion 23*(2), 529–534.

Pourmousavi, S. A. and M. H. Nehrir (2012, Dec). Real-time central demand response for primary frequency regulation in microgrids. *IEEE Transactions on Smart Grid 3*(4), 1988–1996.

Rusco, F. and B. J. Lepore (2016, Sep 8,). Dod renewable energy projects: Improved guidance needed for analyzing and documenting costs and benefits. gao-16-487. Technical report, HT Media Ltd.

Salam, A., A. Mohamed, and M. A Hannan (2008, 01). Technical challenges of microgrids. *ARPN Journal of Engineering and Applied Sciences 3*, 64–69.

Savena, M., N. Judson, and A. Pina (November 16, 2017, November 16, 2017). The cost of energy security and resilience. In *FEDERAL UTILITY PARTNERSHIP WORKING GROUP SEMINAR*.

Shaver, L. (2017, May 30,). Implementation of a dc microgrid.

Stamp, J. (2012). The spiders project-smart power infrastructure demonstration for energy reliability and security at us military facilities. In *Innovative Smart Grid Technologies (ISGT), 2012 IEEE PES*, pp. 1. IEEE.

Ton, D. T. and M. A. Smith (2012). The U.S. Department of Energy's microgrid initiative. *The Electricity Journal 25*(8), 84–94.

US EPA (2015, 08). Electricity storage.

Van Bossuyt, D. L., B. M. O'Halloran, and R. M. Arlitt. A method of identifying and analyzing irrational system behavior in a system of systems. *Systems Engineering n/a*(n/a).

Yodo, N. and P. Wang (2015). Resilience analysis and allocation for complex systems using bayesian network;. In *ASME international Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pp. V02AT03A040. 10.1115/DETC2015-46999.

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