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MAXIMUM UTILIZATION OF ON-BASE EMERGENCY GENERATION AFTER SUSTAINED UTILITY OUTAGE

BY

BRYAN JOHN COOPER

B.S., Clarkson University, 2000

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Electrical Engineering
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Committee Member - *Committee Member -*

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ABSTRACT

The focus of this research will take advantage of the excess emergency generation capacity typically seen at any Air Force base and use it to backfeed the local distribution system to maximize the load supplied for sustained power outages. The model developed was intended to represent all Air Force bases and includes 2 distribution substations, 7 feeders, and 39 dispersed emergency generators. The generators range in size from 7.5 kW to 2.5 MW and provide a total of 13.9 MVA of potential capacity.

Four system states were simulated in this research. Power flow and short-circuit tests were performed for each state to verify and check solution feasibility. The base case modeled normal operating conditions with the utility supplying the entire load. The first scenario simulated the loss of utility so only critical loads were powered by their respective emergency generators. This created 39 electrical islands leaving an excess generating capacity of 8.23 MVA. The second scenario attempted to connect generators so power could be supplied to some noncritical loads. Through trial and error, while verifying feasibility, 22 electrical islands were created reducing the excess generating capacity to 4.07 MVA. The third scenario employed essential loading tactics to maximize the quantity of loads supplied. Here, 18 electrical islands were formed giving an excess generating capacity of 4.71 MVA.

There are several issues that may prohibit connecting generators to an existing distribution system. Transformers will need to act as step-up transformers for the generators, and may have adverse effects on short-circuit currents and harmonics, depending on their size, impedance rating, and configuration. Unintentional islanding may damage equipment and

cause harm to crews who maintain the system, and the coordination and existing protection scheme may become invalid as a result of adding distributed generators.

Special considerations should be made when identifying microgrids and determining which isolating devices remain open or closed. The generator size, excess capacity, and location will each shape its ability to be included within a microgrid. A realistic goal should be to utilize approximately 75% of the total available on-base emergency generation capacity. The end result is 2-3 times the existing load capacity and more flexibility to commanders to complete the mission.

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For those who supported me throughout my Air Force career,
and especially my parents and soon-to-be bride.

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Finally, I would like to thank ESA, Inc. (creators of EasyPower), and Cummings Power Generation. I worked directly with ESA, Inc., about getting a licensed copy of their software to the University and made use of their technical expertise. The generator models created within the software were made possible by the support I received from Cummings Power Generation. They shipped data sheets with information required to accurately model all of the emergency generators used in this research.

Thank you all very much!

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LIST OF ABBREVIATIONS

1PH – Single-Phase, One-Phase

3PH – Three-Phase

AFB – Air Force Base

ANSI – American National Standards Institute

ATS – Automatic Transfer Switch

CI – Current Injection

DG – Distributed Generator

DR – Distributed Resource

IEEE – Institute of Electrical and Electronics Engineers

SLG – Single Line-to-Ground

SYNC – Synchronize, Synchronizing, Synchronization

THD – Total Harmonic Distortion

USAF – United States Air Force

1. INTRODUCTION

1.1 Motivation

United States military installations throughout the world are often subjected to threats and attacks, whether direct or indirect. Attacks are typically focused on a specific objective, and a likely target is the electrical power distribution system. A direct attack may target one or more distribution substations or power transformers. An indirect attack may target the transmission line that supplies the base, or possibly one or more of the generation facilities. One method to combat such threats or attacks is to provide a redundant source of electrical power. The military accomplishes this by installing backup emergency generators at its critical facilities. Emergency generators range in size from 7.5 kW to 2.5 MW, and are typically diesel-driven synchronous machines. The United States Air Force (USAF) current policy to size generators is 75% rated capacity of mission-essential loads only [1]. This is a recent change (10 Jun 05) from 25% rated capacity of total building load. Under the old regime, if a small portion of a facility was authorized backup power, then the entire building took advantage, having continuous power supply. The change in [1] is primarily aimed towards new requirements, but also applies to existing facilities. However, it is not uncommon to still find oversized generators in practice.

The focus of this research will take advantage of the excess emergency generation capacity seen at a typical Air Force base (AFB) and use it to backfeed the local distribution system to maximize the load supplied for sustained outages. The proceeding analysis does not constitute system redesign, but evaluates existing infrastructure to develop a strategy to maximize load supplied.

1.2 Definitions

Distributed generation (DG) is a term that was developed within the last half century to describe generators embedded within an electrical distribution system. It is interchangeable with the term *distributed resource* (DR), except DR is much broader in that it covers both generation and storage. According to [2], DG is an electrical power source of limited size, typically 10 MW or less, and interconnected at the substation, distribution feeder, or customer load. As such, an emergency backup generator is considered a form of DG and will be classified as such throughout the remainder of this paper.

The *utility* will be defined as the main electrical power source for normal system operations, and having the capability to supply the entire load. In most cases the utility is a separate entity not directly associated with an AFB. In some cases, an AFB may have its own self-sustaining generating plant, but for purposes of this paper, the utility will be referred to as an outside entity.

Loads shall be classified throughout this paper as either critical or noncritical. A *critical load* is one deemed mission-essential by the installation commander. In other words, a critical load is that which is required to successfully complete a mission. Some examples of a critical load may include a command and control center, communication hub, first responder facility, anything associated with the flightline, etc. Critical facilities will be synonymous with having an emergency generator hardwired to the structure through an automatic transfer switch (ATS). *Noncritical loads* shall incorporate all other loads and may include general purpose facilities, family housing, morale welfare and recreation, etc. The portions of a critical load or noncritical load that are absolutely required to be operational and receive power will be referred to as its *essential loading*. This will vary from load to load, but in most case will include portions of the total lighting load, communication equipment, aircraft hangar door motors, heating, ventilation and air conditioning (extreme climate areas), etc. A *microgrid* shall be defined as an intentional electrical island comprised of generation and load [3]. Each microgrid shall have the capability to supply its specified loads (generation > load), as well as the ability to maintain rated voltage and frequency.

1.3 Typical Base Distribution Systems

In general, an AFB power distribution system is similar to any other utility, industry, or campus distribution system. Figure 1.1 shows the one-line diagram of the base modeled in this research. The model was created using characteristics and features common to all bases but does not represent any specific base. As such, the name given to this model was *Typical AFB*.

Power at AFBs originates in the substation(s), located within the base footprint, generally supplied by one or two transmission lines (69 kV or 138 kV) from the utility. Here, voltage is stepped down to distribution level voltages, generally 12.47 kV, but may range from 4.16 kV to 23 kV. Power leaves the substation through a network of distribution feeders and supplies the entire base load. Feeders are typically radial by nature, but often interconnect through normally open switches strategically located to enhance system reliability. Facilities on base receive their power from distribution transformers, which step down the voltage once more to 277/480 V or 120/208 V for three-phase (3PH) loads, or 120/240 V for single-phase (1PH) loads.

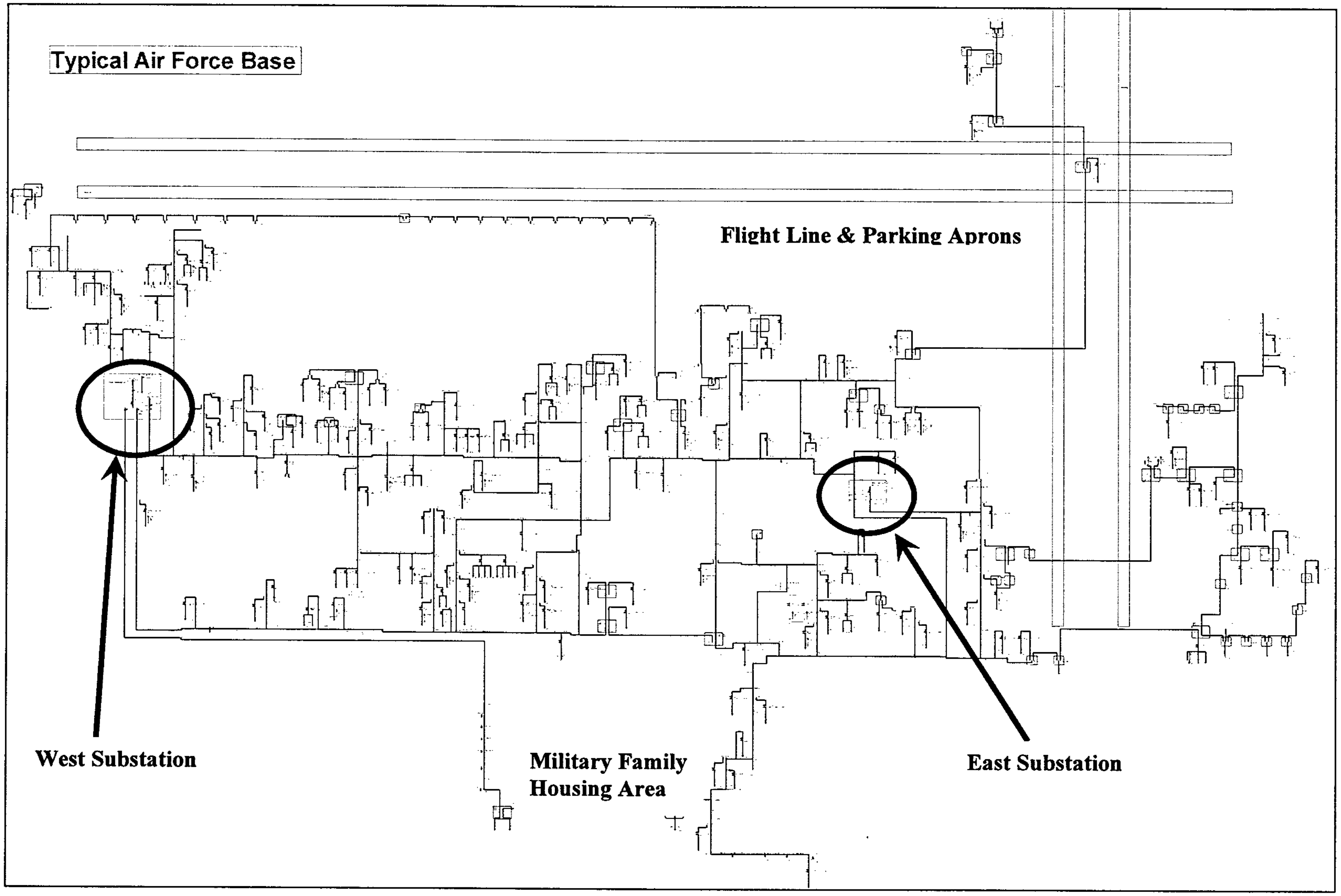

Figure 1.1 One-Line Diagram of Typical AFB in EasyPower

1.4 Analysis Software

The simulations conducted for this research were made possible using EasyPower 7.0 by ESA, Inc. EasyPower is a computer-aided engineering tool used for the analysis of industrial, utility, and commercial electrical power systems. This power system analysis software allows users to perform short-circuit analysis, power-flow calculations, and protective-device coordination directly from the one-line diagram [4]. Many United States military installations around the world today use EasyPower as a tool to model their distribution systems.

1.5 Literature Review

This research is application-specific to military installations. As a result, this author was unable to find any published papers specific to this topic. However, there are numerous papers available regarding similarly related topics, including distributed generation, distribution systems, generators, and short-circuit analysis. The Institute of Electrical and Electronics Engineers (IEEE) recently published a standard (1547) dealing with interconnection of distributed resources with electric utility systems [2]. This standard defines distributed resources and develops guidelines and requirements for performance, operation, testing, safety, and interconnection. Several papers have followed, including [5] and [6], offering additional background and insight regarding IEEE 1547s development.

The objective of this research is to maximize load by connecting emergency generators, utilizing their excess capacity to supply less critical loads during a sustained utility outage. A base model was developed to examine effects on the system behaviors and performance. EasyPower was selected because it is commonly used at military installations and can accurately test and model distribution systems. The authors in [4] created a comprehensive guide that teaches users how to apply and understand results from the software. Generator models were created based on operating data specifications provided by Cummings Power Generation. A procedure for calculating reactance values was clearly outlined in [7].

The authors in [8] – [11] examined scenarios that illustrate impacts of introducing DGs into a distribution network. The most common advantages cited are improved local reliability via peak shaving, voltage and VAR support, and restoration capabilities. However, the papers focused on many of the misconceptions and problems inherent with incorporating DGs into an existing system. Chapter 4 of this thesis takes a closer look at these problems but differs from [8] – [11] in the sense that this research only integrates DGs during a sustained utility outage, so there is never an interface with the utility during a fault analysis or when coordinating protective equipment.

For additional background on power system analysis, [12] was used. The authors do an excellent job combining basic power system theory with a tool used for modeling performance. Chapters on power flow and fault analysis were studied for this research. A more in-depth review of short-circuit analysis is outlined in [13]. Here, two algorithms are applied for sizing circuit breakers.

An approach to optimize load after a system failure was discussed in [14]. Here, shipboard power supplies were analyzed. The optimization considered DGs and islanding to develop its solution. Dc constraints must be removed from the algorithm in [14] to coincide with this research, but the ac constraints remain. One of the major assumptions made in this research deals with the physical connection between DGs and the grid. Specifications provided in [15] validate adding synchronization capability and protection to an existing generator so the focus can remain on maximizing the load.

2. DEVELOPING TYPICAL AFB IN EASYPOWER

Figure 1.1 on page 4 is a snapshot of the entire one-line diagram for Typical AFB. The utility supplies this base through a single 69 kV transmission line, connected at the East (Figure 2.1) and West (Figure 2.2) Substations. The load at Typical AFB is seasonal; its peak of 19.5 MVA occurs during the summer and then drops to approximately 11 MVA during the winter. Typical AFB is modeled with seven distribution feeders. Feeders 1, 5, 6, and 7 are supplied from the West Substation, and 2, 3, and 4 from the East Substation. The total connected switched shunt capacitors installed in the system are 6.5 MVAR. Typical AFB is embedded with 39 DG units, providing a total of 13.9 MVA of generating capacity. A feeder summary is provided in Table 2.1.

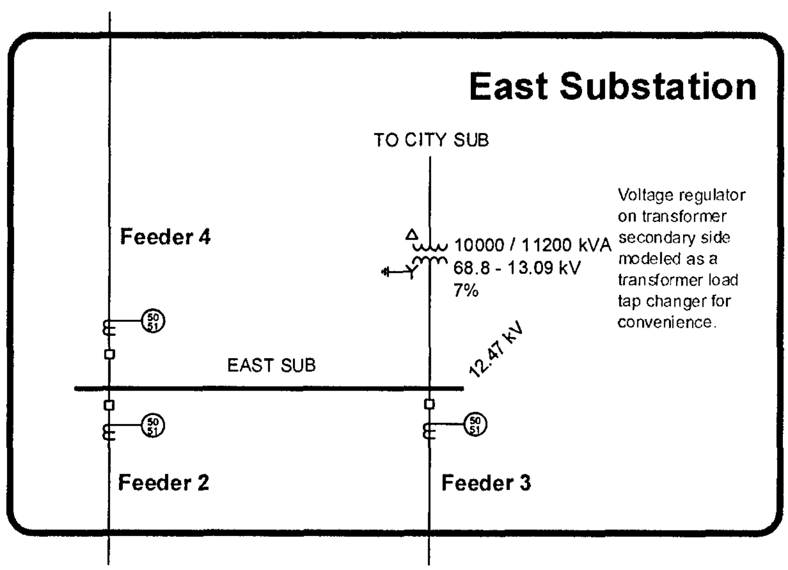

Figure 2.1 One-Line Representation of the East Substation

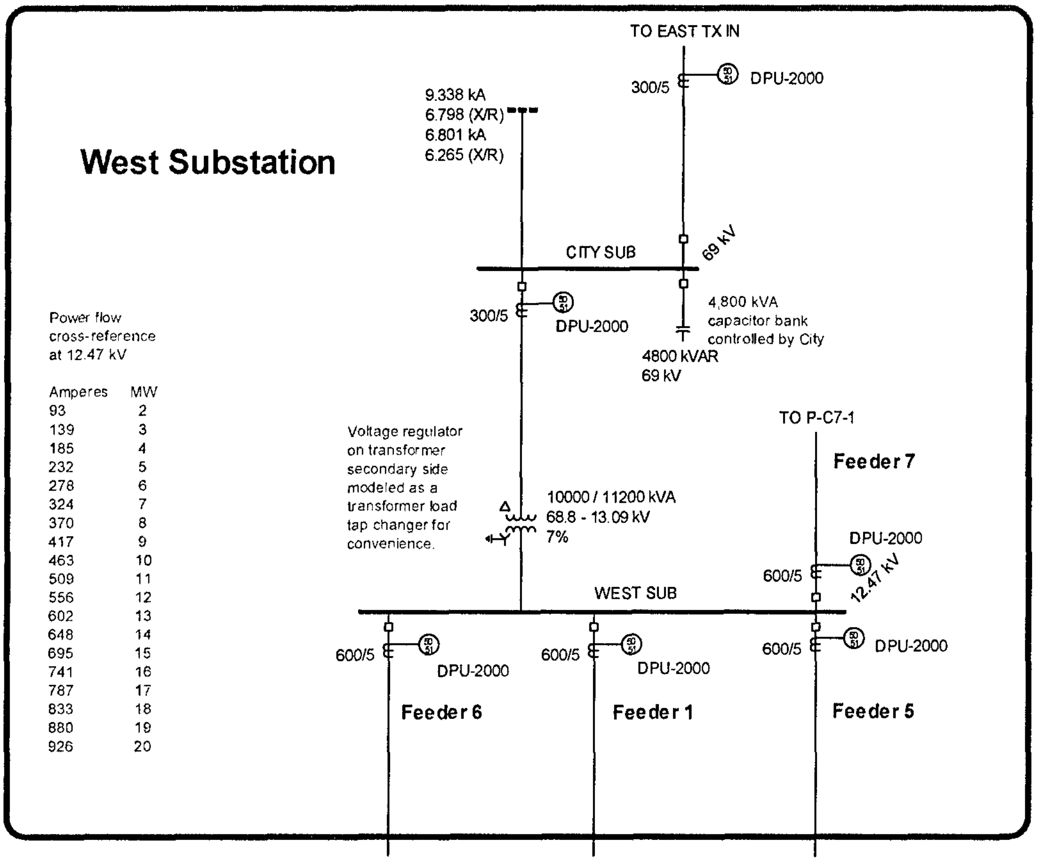

Figure 2.2 One-Line Representation of the West Substation

Table 2.1 Detailed System Summary

Feeder Number	Distribution Voltage (kV_{L-L})	Load Current (A)	Apparent Power (kVA)	Emergency Generation Capacity (kVA)	Number of Generators
1	12.47	103.8	2242	2751	6
2	12.47	89.1	1924	0	0
3	12.47	127.4	2752	2707	6
4	12.47	229.1	4948	5063	14
5	12.47	185.6	4009	2170	8
6	12.47	72.8	1572	0	0
7	12.47	59.1	1276	1207	5

2.1 Generator Model

The vast majority of DGs found on a military installation are diesel-driven synchronous machines. For simplicity, each generator was modeled using nominal Cummings Power Generator specifications. Figure 2.3 displays a typical generator data entry box. This example shows a 500 kW generator rated at 480 V. The generator rating and impedance values need to be calculated for each specified generator kW rating and its corresponding alternator data. In order to perform any desired studies, the program requires subtransient, transient, and zero-sequence reactance values in percent of the generator base.

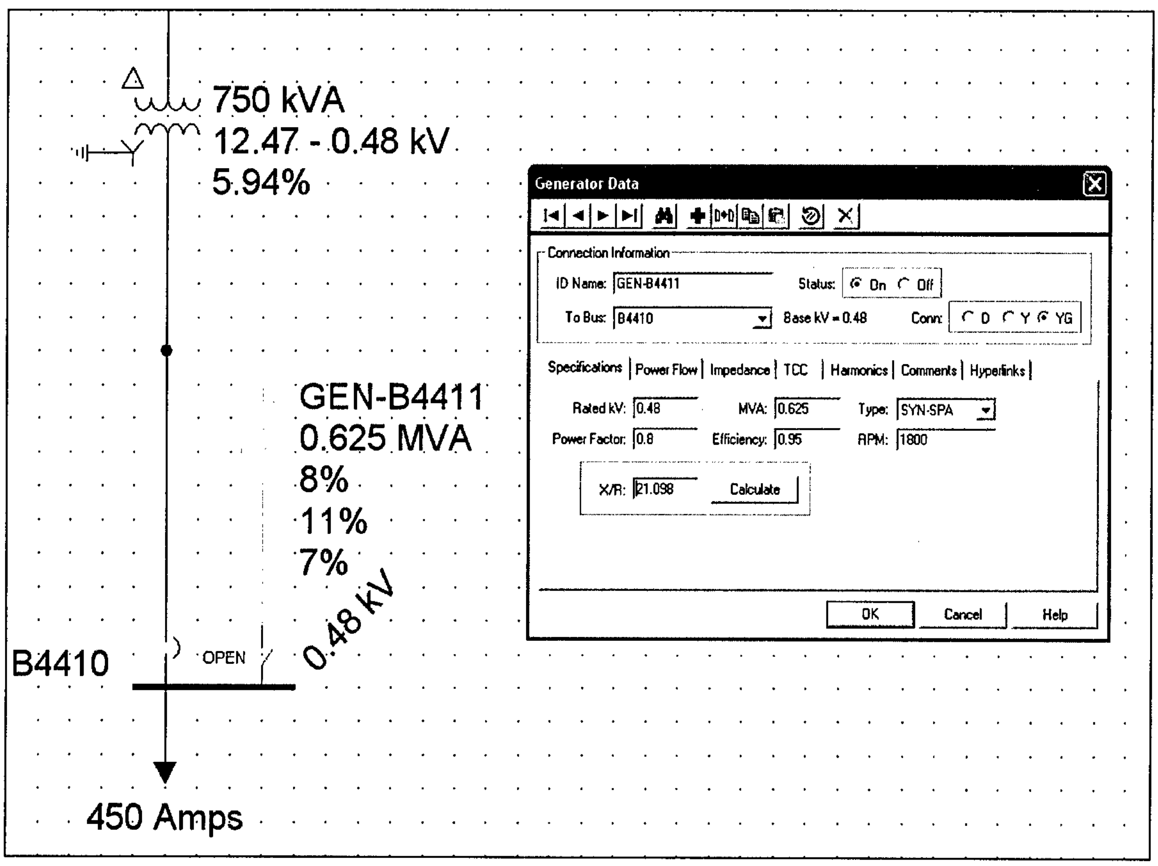

Figure 2.3 Example One-Line of Emergency Backup Generator

Generator apparent power rating can be calculated using Equation (2.1). The power

$$S = \frac{P}{pf} \tag{2.1}$$

factor, if unknown, is generally rated for 0.8 lagging. Generator efficiency is typically given on the alternator data sheet; otherwise, it may be safe to assume each generator to be 95% efficient. Note, however, the efficiency rating on these generators does not affect any power flow or short-circuit calculations. The X/R ratio can either be manually entered, if known, or calculated automatically based on American National Standards Institute (ANSI) C37.010.

Common per-unit reactance values for generators ranging from 40 to 2000 kW [7] are included in Table 2.2. Note these values use the generator MVA base and not the system base. The software automatically converts these values to the system base (10 MVA). Equation (2.2) will bring all generator reactances to a common base. The information required is kV and MVA values for both the generator and the system. A detailed list of generator sizes and reactance values used in this research is provided in Table A.1, Appendix A.

$$_{p.u.}Z_{sys} = {}_{p.u.}Z_{gen}\left(\frac{_{base}kV_{gen}}{_{base}kV_{sys}}\right)^2\left(\frac{_{base}MVA_{sys}}{_{base}MVA_{gen}}\right) \tag{2.2}$$

Table 2.2 Common Generator Per Unit Reactance Values Ranging 40 – 2000 kW Using Own MVA Base [7]

Name	Symbol	Range
Subtransient Reactance	X"d	.09 - .17
Transient Reactance	X'd	.13 - .20
Synchronous Reactance	Xd	1.7 - 3.3
Zero Sequence Reactance	X_0	.06 - .09
Negative Sequence Reactance	X_2	.10 - .22

2.2 Line and Load Model

The one-line diagram for Typical AFB was developed to mimic how a generic AFB would be designed and constructed. The model includes components that would be installed in any operating system, i.e., buses, conductors, transformers, breakers, etc. Buses are necessary to show where two electrical devices are connected and provide a modeling connection point for analytical purposes.

There are multiple distribution feeders that supply the load at Typical AFB. The feeders contain several interconnection points, as well as in-line switches, to isolate faults and maximize reliability. The specified loads were modeled as constant VA and pf. Selected loads were modeled with motors but nothing substantial enough to impact system analysis since military installations in general only have minimal contributions from motor loads. Most of the lines were modeled as overhead, but underground lines were also included in specified areas such as the flight line and family housing. Two different transformer connection styles were modeled: grounded wye-wye grounded (Y-Y) and delta-wye grounded (Δ-Y). These styles are most common to military distribution systems.

An example one-line load model, shown in Figure 2.4, uses a fused S&C switchbox, also common in many distribution systems to isolate the main line and provide additional load connection points. Also in this example is one of the 39 DG units embedded within Typical AFB, shown here connected at bus B5190.

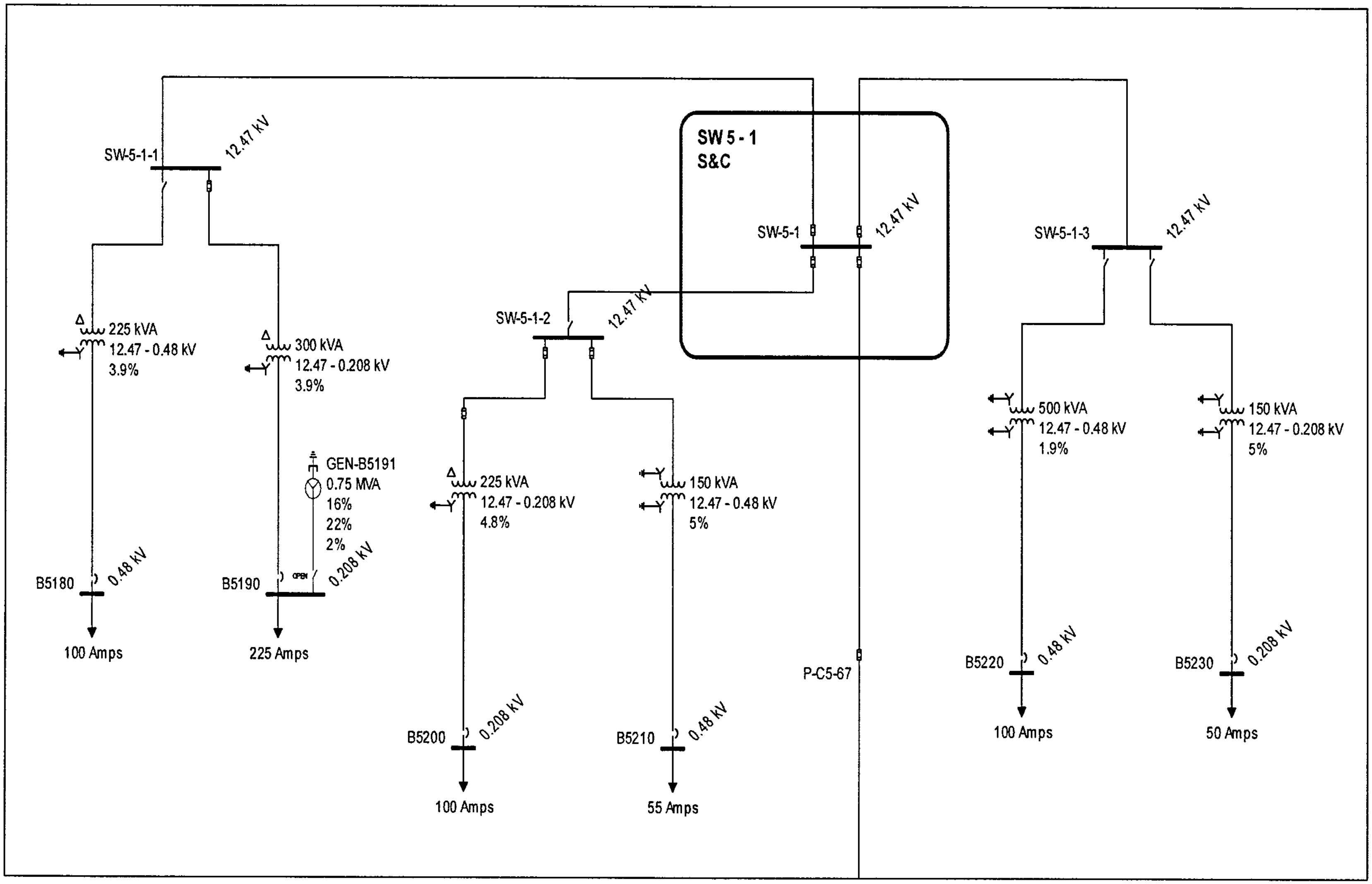

Figure 2.4 Example One-Line Load Model

3. CONTINGENCY ANALYSIS

Four system states were simulated in this research: the base case plus three scenarios. The base case describes normal operating conditions with the utility supplying the entire load. The first scenario removed the utility through blackout, terrorist attack, etc., so only critical loads were powered by their respective DGs. The second scenario was derived from the first. Here some noncritical loads received power from DGs. The third scenario employed essential loading tactics to maximize the quantity of loads supplied.

The hospital at Typical AFB (shown in Figure 3.1), comprised of two relatively large loads, was the only entity not modified in any scenario. The justification here was to avoid negative impacts to life safety. For redundancy purposes, the DG assigned to each hospital load was sufficient to supply both. Figure 3.1 shows the hospital as it was modeled with the two loads connected through a normally open tie-breaker and corresponding DGs. When the

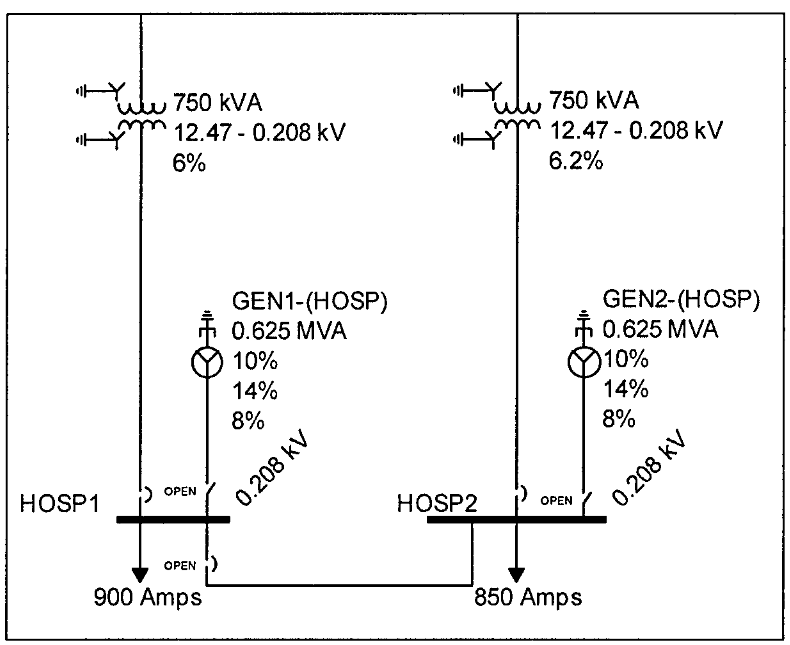

Figure 3.1 Hospital One-Line Diagram

feeder supplying the hospital becomes de-energized, the DGs engage each load and the tie-breaker will close only if there is a reason for one unit to shut down. For example, GEN2 requires maintenance so GEN1 now picks up the load at HOSP1 and HOSP2.

3.1 Feasibility Tests

Power flow and short-circuit tests were performed for each system state to verify and check solution feasibility. These tests ensured that each circuit configuration modeled did not violate any system parameters, including generator limits, thermal line-limits, essential loading limits, voltage limits, transformer limits, and protective device ratings. The calculations performed by EasyPower used a nodal admittance network and sparse vector solutions [4]. The software allows all analyses and database entries to be performed directly from the one-line diagram.

The system model is represented by Equation (3.1), where $[V]$ is the voltage matrix, $[I]$ is the current matrix and $[Y]$ is the nodal admittance matrix.

$$[I] = [V][Y] \tag{3.1}$$

The nodal admittance matrix is in the form [G + jB] where [G] is the bus conductance matrix and [B] is the bus susceptance matrix. The diagonal entries of [Y] are the algebraic sum of all the complex admittances of each branch. The off-diagonal entries are the negative of the admittances connecting any two nodes (buses). Sparse vector solutions are incorporated to quickly solve large distribution networks.

3.1.1 Power flow analysis

Power flow analysis is used to determine voltage magnitude, angle, and power flow for the electrical distribution system, and to identify violations. Buses are categorized into three types: slack-bus, PV-bus, and PQ-bus. The slack bus is required mathematically to account for real and reactive power losses inherent within the distribution network. Typically the largest generator is used as the slack bus, but some special cases may require more than one slack bus. The remaining generator buses, defined as PV-buses, specify the net real power injection and voltage. The PQ-buses, commonly load buses, represent all others. Here, the net real and reactive power injections are specified.

Power flow equations, shown below in Equations (3.2) and (3.3), express the relationship at each bus between the net real power injection (P_{net}), net reactive power injection (Q_{net}), voltage magnitude (V), and voltage angle (θ):

$$f_k^P = G_{kk}V_k^2 + V_k \sum_{m \in H_k} V_m \left[G_{km} \cos\left(\theta_k - \theta_m\right) - B_{km} \sin\left(\theta_k - \theta_m\right) \right] - P_{net_k} = 0 \qquad (3.2)$$

$$f_k^Q = B_{kk}V_k^2 + V_k \sum_{m \in H_k} V_m \left[G_{km} \sin\left(\theta_k - \theta_m\right) - B_{km} \cos\left(\theta_k - \theta_m\right) \right] - Q_{net_k} = 0 \qquad (3.3)$$

where

$$H_k = \left\{ m \mid \text{bus } k \text{ is directly connected to bus } m,\ k \neq m \right\} \qquad (3.4)$$

Two of these four real variables will always be given, regardless of which bus is specified. Equation (3.5) shows the relationship of known variables at each bus. Power flow equations are used to solve for the remaining unknowns at every bus within the system. The system unknowns are expressed in Equation (3.6). The basic power flow can be reduced to that shown in Equation (3.7), where $\underline{u}$ denotes the vector of known or independent variables and $\underline{x}$ denotes the vector of unknown or dependent variables.

$$\underline{u} = \begin{cases} V_0, \theta_0 \text{ at the slack-bus} \\ P_{net_k}, V_k \text{ at every PV-bus} \\ P_{net_k}, Q_{net_k} \text{ at every PQ-bus} \end{cases} \qquad (3.5)$$

$$\underline{x} = \begin{cases} \theta_k & \text{at every PV-bus} \\ V_k, \theta_k & \text{at every PQ-bus} \end{cases} \tag{3.6}$$

$$\underline{f}(\underline{x}, \underline{u}) = \underline{0} \tag{3.7}$$

EasyPower calculates power flows assuming balanced 3PH loads [4].

3.1.2 Short-circuit analysis

Short-circuit analysis is required to determine the available fault current throughout the system. This study is necessary to ensure system distribution equipment is capable of withstanding the available fault current without damage. It also tests the ability of the system's protective devices to successfully interrupt a fault without failing.

The objective of performing a short-circuit analysis is to show that the distribution equipment is capable of withstanding the worst-case fault currents. Four common faults occur in a distribution system. In a 3PH fault three phases are shorted together. Specifically, a 3PH bolted fault is a 3PH fault with negligible fault impedance, which generally produces the highest available fault currents and always the most fault energy. A single line-to-ground (SLG) fault occurs when 1PH of a 3PH system shorts to ground. In some instances this type will produce higher fault currents than a 3PH fault. The last two faults are phase-to-phase and double line-to-ground. These two produce less fault current then 3PH and SLG, so only the latter were evaluated.

Fault current magnitude decays exponentially over the first few cycles after a fault occurs in a system. The rate of decay is inversely proportional to the X/R ratio at the point of the fault so higher X/R ratios will result in slower decays, and vice versa. This decay is due to the diminishing contributions from motors and generators, as well as the effects of dc offset. Dc offset causes the symmetrical current waveform to shift above the zero axis and produces an asymmetrical waveform. A graphical representation of this phenomenon is shown in Figures 3.2 and 3.3. Since the distribution equipment must be capable of withstanding peak fault current, all short-circuit ratings must be checked against the momentary (1/2 cycle) asymmetrical fault current.

Current contributions depend on prefault voltage, subtransient and transient reactances, and exciter characteristics of the generators [8]. The available short-circuit current from the utility at Typical AFB is listed in Table 3.1, page 20. However, for purposes of this research the utility was removed from all calculations except for normal operating

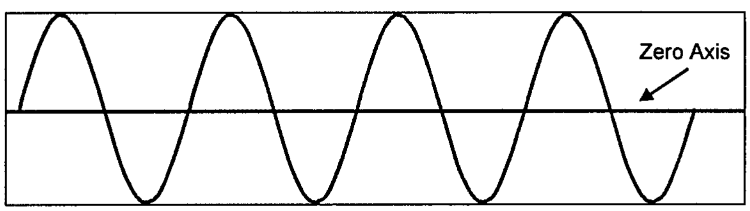

Figure 3.2 Symmetrical Current Waveform

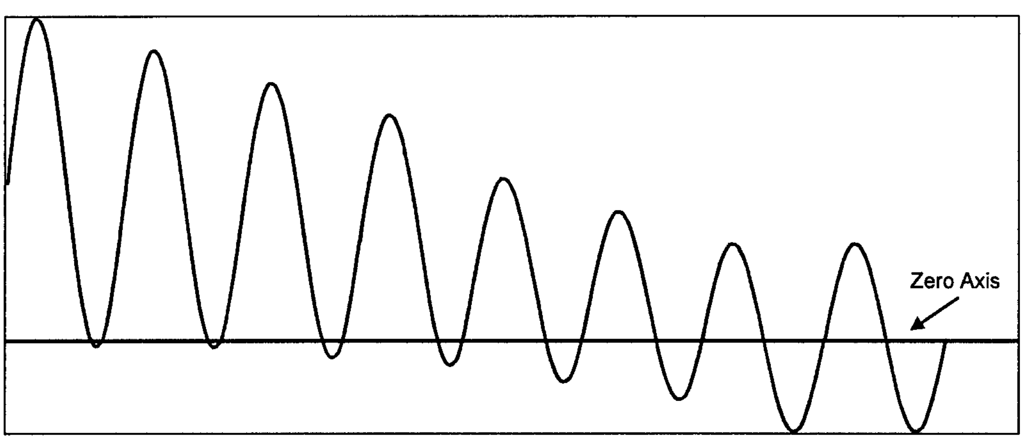

Figure 3.3 Asymmetrical Current Waveform

conditions. Thus, to establish the available short-circuit currents for the three scenarios, each DG's available short-circuit current had to be calculated. These values are based on ANSI C37.010-1999 and are included in Table B.1, Appendix B, for reference.

The majority of military installations have relatively small motor loads. As a result, the fault current contributions from motors will be negligible and most will originate from the generators, or the utility during normal operating conditions. The distribution transformers do not produce any short circuit currents, but they do affect them based on their kVA and impedance ratings. Distribution transformers with either large kVA ratings or small impedances will cause the short circuit contributions to appear much larger than those with small kVA ratings or large impedances. Common 3PH transformer ratings at military installations will range 15–1500 kVA and have impedance values that range 2-7%.

Electrical equipment found in distribution systems is typically given two short-circuit ratings. *Withstand rating* is the level at which equipment exposed to short-circuit current must be capable of withstanding mechanical and thermal stresses until the short is isolated. *Interrupting rating* is the level of current that a breaker can safely interrupt, and depends on voltage.

Military standards for calculating short-circuit currents follow ANSI. Refer to [13] for specific information using the E/X Simplified Method or E/X Method with an adjustment for ac and dc decrements. Most short-circuit softwares use ANSI. EasyPower incorporates a function called SmartDuty that automatically checks equipment duties during this analysis and identifies short-circuit rating violations.

Power flow and short-circuit studies are required for each system state to verify a solution's feasibility. These tests will shape the islanding strategy and determine if a microgrid may be expanded or requires reduction. The number of electrical islands should decrease as DGs are connected, and the number of loads supplied should increase. This will be shown in the four case studies that follow.

3.2 Base Case

The *base case* establishes a baseline how Typical AFB behaves under normal operating conditions with the utility as the sole source of power. It supplies two main distribution substations from a single 69 kV transmission line. Power is then delivered to the rest of the base via seven distribution feeders. The entire load is supplied in the base case with zero violations to system parameters or equipment ratings.

The utility was modeled as an unlimited power supply, or swing bus, with a specified amount of available short-circuit current. Typical AFB short-circuit current is limited to those values shown in Table 3.1. Note that these values are generally specified by the local utility company and are required when performing short-circuit or coordination studies.

Table 3.1 Utility Short-Circuit Current (Referred to the Primary)

Source	Voltage (kV)	Momentary Fault Type (1/2 Cycle)	Symmetrical Fault Current (kA)	X/R Ratio
Utility	69	3-PH	9.338	6.798
		SLG	6.801	6.265

Table 3.2 summarizes the base-case power-flow analysis. It describes the total required system generation and load, as well as system losses. These quantities are provided to establish a baseline of system load and loss requirements for the three scenarios that follow. The system load was modeled under peak conditions, i.e., summer load. Table 3.3 provides a

summary of the base-case short-circuit analysis. Here, the utility is essentially the only source contributing to short-circuit currents since the motors modeled are relatively small. The values shown in Table 3.3 are the maximum symmetrical and asymmetrical fault currents that could appear at Typical AFB from 3PH and SLG faults.

Table 3.2 Base Case Power Flow Summary

System Summary	P (kW)	Q (kVAR)
Total Utility Generation	18 096.5	2878.2
Total Load	17 835	7921
Total Shunt Capacitance Load	0	-6528
Total Losses	-261	1484

Table 3.3 Base Case Short-Circuit Summary - Maximum Values

Voltage (kV)	Momentary Fault Type (1/2 Cycle)	Symmetrical Fault Current (kA)	Asymmetrical Fault Current (kA)
69	3-PH	9.4	12.6
	SLG	6.8	9.1
12.47	3-PH	5.4	8.2
	SLG	6.0	9.2
0.48	3-PH	36.3	48.6
	SLG	36.9	49.1
0.208	3-PH	46.8	58.3
	SLG	46.7	58.3

3.3 Scenario I - Critical Loads Only

Achieving the objective of this research requires improving this particular system state. *Scenario I* describes how every base currently functions in the event of a system failure or blackout. Only critical loads are supplied with power under this scenario. Recall from

Chapter 1 that critical loads are those deemed mission-essential by the installation commander and require a continuous power supply. Scenario I quantifies the amount of excess generation available at Typical AFB by comparing the summation of critical loads supplied to the total on-base generating capacity. This quantity will shape Scenarios II and III.

There are a number of reasons why utility systems may fail. Some examples include a load increase at such a rate that the power grid suffers a systemwide voltage collapse, a terrorist act that damages a critical part of the system (transmission line, substation, etc.), a critical component that fails with cascading effects, or simply an act of nature (storm, tornado, etc.). The duration of each interruption will vary anywhere from seconds to hours to days, depending on the extent of the damage and availability of repair or replacement parts. Regardless of the circumstances, the military's mission remains and must continue.

The ATS at each critical facility detects if the utility fails and automatically starts the generator. When the generator reaches rated speed (frequency) and voltage, the ATS automatically transfers the building load (or critical load only if isolated) onto the generator, as shown in Figure 3.4. Here, the load is supplied either from the utility or the generator, but never from both.

There are 39 critical facilities at Typical AFB, based on the number of generators listed in Table 2.1. Each critical facility varies in size and location. It should also be noted from Table 2.1 that there are no generators on Feeders 2 and 6. These feeders supply the residential areas on base and thus do not directly affect the mission. When the utility is removed in Scenario I, 39 electrical islands are created. A summary of this new system state is provided in Table 3.4. There are no system losses shown here because the DGs are connected directly to their loads. Thus any losses are considered negligible. Recall that the

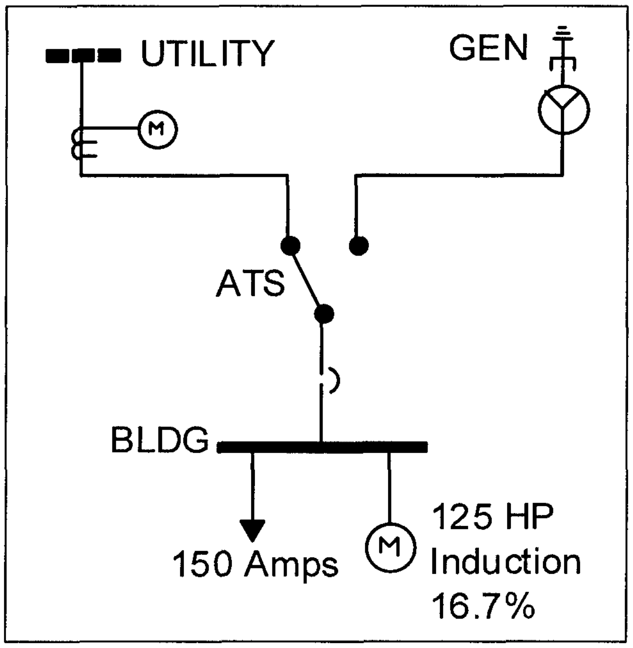

Figure 3.4 Utility and Generator Interface with Building Load

total available onsite generation capacity at Typical AFB is 13.9 MVA. This yields an excess generating capacity of 8.23 MVA. It seems practical with this much excess generation that more loads should be supplied. Military installations have the potential to improve their current design and operating practices to maximize their full potential. Table 3.5 summarizes the short-circuit analysis performed on Scenario I. Here all DGs are connected on the load side of the distribution transformers directly to their loads, so no values are shown at the distribution voltage level. Comparing these values to Table 3.3 shows only one case where the short-circuit currents generated by the DGs are greater than those from the utility. However, the system is still operating within its equipment ratings.

Table 3.4 Scenario I Power Flow Summary – Critical Loads Only

System Summary	P (kW)	Q (kVAR)
Total Dispersed Generation	5187	2284
Total Load	5187	2284
Total Shunt Load	0	0
Total Losses	0	0

Table 3.5 Scenario I Short-Circuit Summary - Maximum Values

Voltage (kV)	Momentary Fault Type (1/2 Cycle)	Symmetrical Fault Current (kA)	Asymmetrical Fault Current (kA)
12.47	3-PH	N/A	N/A
	SLG	N/A	N/A
0.48	3-PH	27.3	43.9
	SLG	37.6	60.4
0.208	3-PH	17.3	27.4
	SLG	18.6	29.3

3.4 Scenario II – Noncritical Loads

Scenario II is derived from Scenario I in that it not only supplies the critical facilities but also begins to power some less critical loads. As stated in Scenario I, the DGs can potentially supply 8.23 MVA to additional loads. Two assumptions must be made before supplying less critical loads. First, it is assumed that there is an existing interface that allows each generator to supply its critical load while simultaneously using its excess capacity to backfeed the distribution system through the distribution transformer. Second, when more than one generator is connected in a microgrid, they are automatically synchronized in terms of phase, frequency, and voltage.

Figure 3.5 shows a one-line representation that illustrates both assumptions. The existing ATS is left in place, but the overall configuration has been modified with the insertion of a synchronizing (SYNC) switch. This switch will close the generator to the remainder of the grid when the relays have matching phase, frequency, and voltage. A device similar to that illustrated in Figure 3.5 is offered from Woodward [15], combining synchronization for isochronous load sharing and generator protection.

Scenario II's performance is summarized in Table 3.6. By allowing the DGs to interface with each other and portions of the grid, 22 islands were created (versus 39 from Scenario I) through trial and error by systematically adding load, connecting generators, and verifying system parameters. Also, an additional 4.2 MVA of load was supplied. Note that

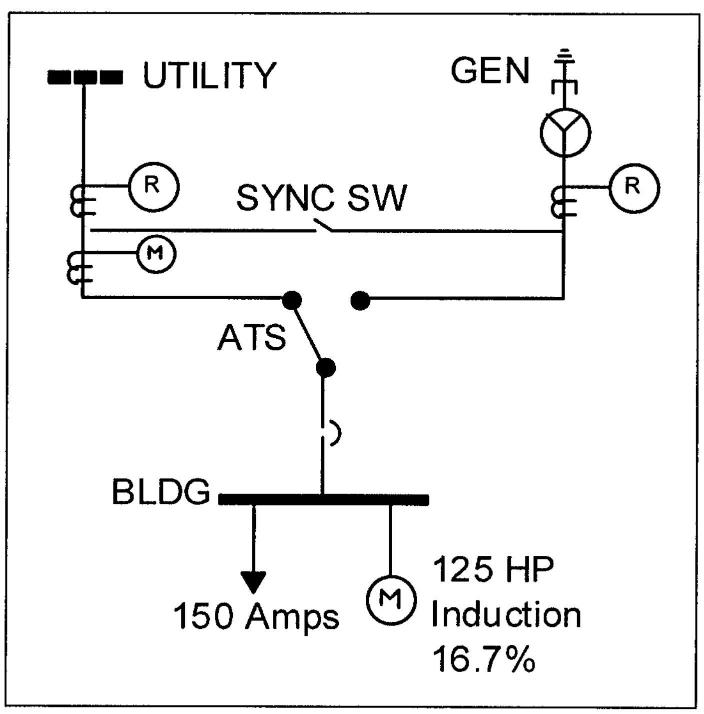

Figure 3.5 Modified ATS with Sync Switch

this quantity is still well below the maximum potential capacity of the DGs.

The short-circuit analysis for this scenario is summarized in Table 3.7. Fault current now appears at the distribution voltage level since DGs are now interconnected at some locations. However, these currents are significantly less than those produced by the utility. The fault current at the 480 V level does not change from Scenario I, but dramatically increases at the 208 V level. However, the base case values remain higher here as well, which implies all the equipment is still operating within its ratings.

It is imperative not to overload any DGs to avoid tripping a single unit off-line, and potentially taking the entire microgrid off-line. Therefore, each generator was loaded to 90% of its rated capacity, providing a cushion for inrush currents or other such transients. In some instances, the DGs were limited by their respective distribution transformers. For example, in Figure 2.4 (page 13) a 750 kVA generator was connected to the same bus, B5190, as a 300 kVA transformer, thus limiting the generator contributions to the microgrid. Also, only rated loads were added; i.e., if a microgrid had capacity for an additional 200 kVA but the next smallest load within that microgrid was greater than 200 kVA, then no additional loads were added. A more detailed explanation of limiting factors affecting power quality as well as load selection procedures can be found in Chapters 4 and 5.

Table 3.6 Scenario II Power Flow Summary – Noncritical Loads

System Summary	P (kW)	Q (kVAR)
Total Dispersed Generation	9100	3716
Total Load	-9038	-3954
Total Shunt Load	0	298
Total Losses	-62	-61

Table 3.7 Scenario II Short-Circuit Summary - Maximum Values

Voltage (kV)	Momentary Fault Type (1/2 Cycle)	Symmetrical Fault Current (kA)	Asymmetrical Fault Current (kA)
12.47	3-PH	0.7	1.0
	SLG	0.8	1.1
0.48	3-PH	27.3	43.9
	SLG	37.6	60.4
0.208	3-PH	30.8	41.7
	SLG	34.1	44.8

3.5 Scenario III - Reduced Demand Factor

The objective of this final scenario was to develop a practical way to maximize the quantity of loads supplied. In previous scenarios, the loads were modeled during peak loading with constant VA and pf. This represents the worst case, which may not yield a true representation of the load, and it certainly does not represent the essential loading at each facility. Typical AFB was already operating under a contingency scenario when it lost its main source of nonemergency power, so ideally not every light needs to be on. If the utility is out of service for an extended period of time, i.e., longer than the mission dictates (on the order of days), then it is in the best interest of the installation commander to provide power not only to the mission-critical facilities but also to some of the less-critical facilities and residential areas.

The majority of facilities on a base can still function successfully on a limited loading capacity. Each can develop a contingency or load-shed plan such that only its essential loads receive power, i.e., lock-out/tag-out nonessential loads. However, some facilities may still require full-load capacity, depending on the loads impact to the installation, and will be driven by mission and climate conditions.

In *Scenario III*, all loads, with the exception of the hospital, reduced their demand factors from 100% to 75% of the total load supplied. This percentage was arbitrarily chosen to observe how the islanding strategy was affected at Typical AFB. The actual reduced demand factors may not be uniform across all facilities for a particular base and in most cases will be much lower than 75% of their peak loading conditions.

With the demand factor reduced, the number of islands at Typical AFB dropped to 18 from 22 in Scenario II, again by trial and error. By expanding the size of most microgrids, the overall quantity of supplied loads increased. A summary is provided in Table 3.8. However, the total on-base generation slightly decreased. Scenario III was intended to demonstrate how the flexibility given to engineers greatly improves when the demand factors are reduced and more facilities receive power. Further reductions correspond to more loads and fewer islands. The challenge is to maximize quantity of loads while preserving all system constraints and loading requirements.

The short-circuit contributions slightly increased from the last scenario with respect to the distribution voltage level. Since the size of most microgrids increased, also increasing the quantity of DGs per microgrid, it makes sense that the maximum fault current contributions would also increase. The results are summarized in Table 3.9. While there are variations between Scenario II and Scenario III, their levels all fall below the fault currents produced by the utility, with the only exception being SLG faults at 480 V. However, the system still satisfies all specified equipment ratings.

Table 3.8 Scenario III Power Flow Summary – Reduced Demand Factor

System Summary	P (kW)	Q (kVAR)
Total Dispersed Generation	8725	2893
Total Load	-8656	-3782
Total Shunt Load	0	890
Total Losses	-69	-2

Table 3.9 Scenario III Short-Circuit Summary - Maximum Values

Voltage (kV)	Momentary Fault Type (1/2 Cycle)	Symmetrical Fault Current (kA)	Asymmetrical Fault Current (kA)
12.47	3-PH	0.9	1.2
	SLG	0.9	1.2
0.48	3-PH	27.4	43.9
	SLG	37.6	60.3
0.208	3-PH	32.7	43.8
	SLG	35.7	46.4

4. SYSTEM-WIDE CONSIDERATIONS

There are numerous issues outside the scope of Scenarios I-III that impact overall power quality and performance when an existing system is modified. Each issue described in the sections that follow will show how the system may be impacted and also help provide insight if or when complications arise after implementing Scenario III.

4.1 Transformers

The most common generator step-up transformer configuration is grounded wye-delta (Y_g-Δ), where the wye is on the high side and connected to the line, and the delta is on the low side and connected to the generator terminals. The advantages of this configuration include reduced insulation requirements on the high side (taper down at neutral), neutral provided for grounding on the high side, and isolation of the generators third harmonic currents in the delta winding on the low side.

For any given critical load, the emergency generators are connected directly to that load through the ATS. In order for these generators to backfeed the distribution system, it is assumed that a modified ATS with synchronization capability is connected between the generator terminals and the incoming line, as shown in Figure 3.5 (page 25). However, the most common transformer configurations found in most base distribution systems are Y_g-Y_g and Δ-Y_g. When the generators are used to supply the grid, these Y_g-Y_g and Δ-Y_g distribution transformers will act as generator step-up transformers.

This new step-up transformer configuration may create a problem within the overall system because third harmonic current will be introduced into the distribution system from each connected generator. Care must be taken to avoid overloads on the neutral conductor or damage to sensitive equipment. Thus the number of DGs allowed to interconnect within a microgrid may be limited. Not all generators produce the same amount of third harmonic current. Synchronous generators with 2/3 pitch for the windings will have less third harmonic than those with other pitches [8]. Typically, utility system voltage distortions are limited to 5% for total harmonic distortion (THD) and 3% for any individual harmonic [2].

4.2 Grounding

Grounding is an important topic in distribution systems, especially in terms of short circuits. Generators not effectively grounded may subject the system to high (up to 173%) overvoltages during SLG faults on a distribution system. The Institute of Electrical and Electronics Engineers (IEEE) defines a system as *effectively grounded* when the positive sequence reactance is greater than the zero sequence resistance ($X_1 > R_0$) and the zero sequence reactance is less than three times the positive sequence reactance ($3X_1 < X_0$). Four-wire multigrounded systems are good examples of effectively grounded systems with respect to their source. Here, voltage rise on the unfaulted phases during an SLG fault are limited to approximately 130% of the prefault conditions [8].

Generator step-up transformer configurations will also shape grounding characteristics of a generator. The Y_1-$\triangle$ transformer configuration will provide effective grounding regardless of the generator-grounding requirement. Other transformer configurations will not guarantee grounding requirements. If the DGs are not effectively grounded, then additional protective relaying may be required to detect primary-side SLG faults to instantaneously trip the DGs off-line. However, critical loads may still experience a few cycles of overvoltages that could damage equipment prior to the breaker opening. It is best to ensure that each DG is effectively grounded to avoid any damage and possibly impact mission requirements. Refer to [8] for more information.

4.3 Islanding

Islanding occurs when a generator continues to supply a portion of the grid that has been electrically isolated from the main utility source. Islands are created either intentionally or unintentionally. Intentional islanding is sometimes used to increase the local reliability within a system. The generators within these islands must be capable of handling the load and any load variations to include inrush currents. They must be synchronized to each other when more than one is still connected. Unintentional islanding can occur when a breaker, fuse, or recloser opens and the DG continues to supply part of the line. An unintentional island should be avoided at all costs. It threatens the safety of linemen who may be out repairing the fault and unaware that portions of the line may still be energized. It could also damage equipment by supplying substandard power quality because generation may not be sufficient to supply the connected load. An unintentional island creates the risk of the utility reconnecting the system when it may not be completely synchronized to the island. This would also cause damage to equipment.

According to [2], "... the DR interconnection system shall detect the (unintentional) island and cease to energize the area electric power system within two seconds of the formation of an island." There are several methods for detecting islands. These are categorized as passive or active and can be performed remotely, which may be expensive, or locally. Active island detection techniques cause the generators to become unstable and shut down. Passive techniques will monitor the generators and send a trip signal to open the circuit breaker after they detect something that appears abnormal.

THD monitoring is an example of a passive technique. Equation (4.1) defines THD where I_h is the rms value of the hth harmonic component and I_1 is the fundamental component of the current from the generator. Under balanced conditions, the THD is typically less than or equal to 5%.

$$THD = \frac{\sqrt{\sum_{h=2}^{H} I_h^2}}{I_1} \tag{4.1}$$

Another passive technique monitors voltage unbalance (VU) between the positive and negative sequence voltage components of the generator, as shown in Equation (4.2). Here, V_1 and V_2 are the positive and negative sequence voltage components, respectively. VU is also typically less than or equal to 5% under balanced conditions.

$$VU = \frac{V_2}{V_1} \tag{4.2}$$

THD and VU measurements will spike when there is a change in loading conditions on the generators. However, this may send false trip signals to the circuit breakers, so the authors in [9] propose a hybrid method combining the advantages of active and passive techniques for island detection.

Installing emergency generation within a distribution system intentionally creates an island after a failure to preserve reliability to critical loads. By interconnecting DGs, there is risk of creating an unintentional island within the distribution system. Avoiding these situations may be as simple as adding an additional frequency or voltage relay to the SYNC switch that would immediately detect a problem within the microgrid and instantaneously isolate the DG to its critical load only.

4.4 System Protection and Coordination

Distribution systems are radial by nature, where the power typically flows in just one direction — from the substations to the loads. As such, the protective devices — i.e., fuses, circuit breakers, relays, etc., commonly found on all distribution systems — are typically designed and coordinated for unidirectional power flow. Coordination becomes more difficult when the feeders are networked through one or multiple interties in the grid some distance from the substations. Adding DGs to the distribution system further complicates design. Here, power has the potential for bidirectional flow. In addition, DGs provide another source of short-circuit current. Several papers have been published, including [9] - [11], which discuss scenarios where coordination between protective devices fails after the addition of DGs into the local distribution system. These authors all assume the utility is operating under normal conditions and contributes in each scenario. However, without the utility this remains a potential problem in the three scenarios evaluated. The grid architecture has changed from its original design (base case) prior to any considerations from DG contributions. As a result, the system protection scheme will most likely become uncoordinated.

Each microgrid essentially operates with minimal efficiency or reliability. This means that a fault anywhere on the line should trip all noncritical loads off-line. Basically, the SYNC switch is sensitive to system perturbations. For example, a fault on the main line should cause each SYNC switch to open, so that only critical loads are supplied from the

DGs. However, their sensitivity should not be set such that an internal building fault trips it. In the case where a fault occurs inside a structure (critical or noncritical), the building's main circuit breaker should still detect and isolate the fault before it propagates further upstream.

While the term *minimally efficient* has a bad connotation, its purpose is required to justify supplying less critical loads for continued mission success. As shown in Scenario I, the entire system is operating in an emergency condition and only providing power to critical loads. The majority of loads (noncritical) on base remain without power. By changing the topology and utilizing the excess generator capacity to supply less critical loads, a percentage of the noncritical loads become operational. For sustained utility outages, even less critical loads appear critical. To treat them as such should not jeopardize the mission success. Degrading the critical load reliability should be avoided. A minimally efficient system protects the critical loads from even the worst cases. Generators and critical loads shall intentionally island themselves if a fault is detected on the line side of the modified ATS. This may be achieved as simply as adjusting the sensitivity of the SYNC switches.

Reliability to critical loads in Scenario II or III must be equal to or greater than that experienced in Scenario I. The SYNC switch should safeguard its critical load. It should also provide an avenue for redundancy in the event of a single DG failure. If one DG fails or requires maintenance, then the other units in the microgrid should pick up that critical load, even at the expense of shedding noncritical loads.

4.5 Maintenance Plan

The emergency generators simulated at Typical AFB, and common to all bases, are diesel-driven synchronous machines. They are common due to their versatility, and are typically used for their black-start capabilities or emergency backup power situations. Diesel generators are not designed to run continuously. The USAF only employs them for continuous operation in an expeditionary atmosphere. But even in these environments, the generators are routinely taken off line. There are typically extra generators available to pick up the load when a unit is taken down, due to failure or for maintenance.

For this research, it is assumed that there are no surplus generators, and every unit is operating close to 90% rated capacity. Mission requirements will not allow any of the critical loads to be taken off line, but the generators will still require some downtime for maintenance. As such, a routine maintenance schedule will need to be developed that incorporates a load-shed plan. Since the generators are operating near rated capacity, there is no guarantee the remaining DGs of that microgrid will be able to pick up the load after one unit is lost. The maintenance plan should remain flexible and coordinated so as not to impede mission objectives.

4.6 Additional Generators

Even for the best-case scenario where 100% of the on-base generation is utilized, not all of the load can be supplied. The peak summer load at Typical AFB is 19.5 MVA but the total on-base generation capacity is 13.9 MVA. This means at least 5.6 MVA of load will not be supplied when the utility is disconnected. Theoretically, it makes sense to have more DGs available for a prolonged utility outage.

DGs strategically placed within a distribution system could maximize other less critical loads supplied. An example would be placing DGs in residential areas or the main substation giving it access to multiple feeders. Additional generators can also be used for redundancy of critical loads or incorporated in a maintenance plan to help alleviate load shedding. Since generators are expensive and contingencies of this magnitude are rare, the solution for additional generators should rather be utilizing prestaged assets within the military's existing network at the outbreak of said event.

5. MEETING THE OBJECTIVE

The overarching objective of this paper is for any military installation, specifically the USAF, whether home or abroad, sustained or expeditionary, to develop and apply a strategy for maximizing load supplied from existing on-base generators during a sustained utility outage. The sequence of operations for such a strategy is discussed in Section 5.1. From Chapter 3, the basic strategy applied to maximize load supplied was to derate each facility to its essential loading and limit the generators by approximately 85-90% of their rated capacity to avoid nuisance-tripping from transient currents. From Chapter 4, several system-wide considerations were discussed. This background should help engineers develop their installations islanding strategy and determine which loads receive power.

5.1 Sequence of Operations

Table 5.1 describes how this strategy is implemented. The first three steps illustrate the sequence of events that would occur during any type of utility outage. Steps 4-6 identify how to meet this new system objective. It is imperative to coordinate this decision-making process with the linesmen and power production personnel who maintain the lines and generators. This will help identify equipment limitations that may not be obvious to engineers and thus minimize future roadblocks. The final stage, steps 7-10, describes the implementation and shows what happens when the base begins to supply power to its noncritical loads.

The planning stage should be performed well in advance of any major utility outage. Engineers will be limited to existing base infrastructure since no part of the main objective

Table 5.1 Sequence of Operations

Sequence Number	Description
1	Loss of utility power
2	Emergency generators start
3	ATS transfers the critical load to their respective generator units at rated frequency and voltage
4	Identify generator capacity and location within the system
5	Identify load requirements (critical, noncritical) and derate where possible
6	Develop an islanding strategy and protection scheme - Generation > Load - Determine controlling generator, typically the biggest
7	Manually isolate islands and loads within islands
8	Energize island distribution system under no load
9	Synchronize generators and incrementally add load to the system - Generation > Load
10	Monitor generators, i.e. speed (frequency), voltage, power flow - Load shed as required - Perform routine maintance - Fuel - Emissions

Notes
1. Steps 1-3 describe the existing sequence of operations where only critical loads are supplied.
2. Steps 4-6 describe the planning stage performed by base engineers.
3. Steps 7-10 describe implementation, which must be performed manually by a collaborate effort of linesmen and power production personnel.

deals with major renovation or construction. It is imperative to first identify any system shortfalls, such as missing equipment (modified ATS with SYNC switch) and then develop a purchasing strategy. This will help avoid lengthy lead-time orders inherent with specialized equipment items. Another critical component to the planning stage is to evaluate the location and quantity of fuses, circuit breakers and air switches within the distribution system. The quantity and placement of isolation devices will either make or break any options involving the islanding strategy and protection scheme. Some reconfiguration may be necessary.

5.2 Problem Formulation

How can a base take the excess capacity from the existing emergency generators and apply those resources to supply less critical loads? One DG may not provide enough excess capacity to supply a second facility, but by connecting multiple generators the possibilities greatly increase. The authors in [14] have formulated an optimization problem for a similar scenario but applied to shipboard power supplies. Much of their theory holds true, though the systems are different.

In both cases the objective remains: maximize the load. The objective function can be set up for each island scenario, using weighting factors for each load based on mission priority and defined as

$$\text{Maximize} \sum_{i} \sum_{j \in L_i} w_{ij} l_{ij} \tag{5.1}$$

From Equation (5.1), the subscripts i and j distinguish the microgrids (up to n microgrids) and loads (up to m loads). The set L_i represents all loads contained within the ith microgrid.

$$i = \{1, 2, 3, ..., n\} \tag{5.2}$$

$$j = \{1, 2, 3, ..., m\} \tag{5.3}$$

Each load is represented by l_{ij} and assigned a weighting factor, w_{ij}, that corresponds to its mission priority. A low-priority noncritical load should be given a weighting factor of one;

and should increase with each priority load. The critical loads shall receive the highest weighting factor.

5.3 Recommendations

A feasible solution must satisfy the system constraints for power flow, generator real and reactive power limits, voltage limits, line limits, and minimal load limits (essential load only). No program currently exists that will automatically create an islanding strategy, given a particular distribution system architecture and priority loading schedule. The best approach to solve Equation (5.1) is through trial and error. The solution will not be unique. For example, areas such as residential housing contain multiple loads but they will be given an equal weighting factor, or priority, so it is arbitrary which of these loads receive power and which remain in blackout.

Special considerations should be made when identifying microgrids and determining which isolating devices remain open or closed. The generator size, excess capacity, and location will each shape its ability to be included within a microgrid. If the DG is particularly small

($P < 50$ kW), or its critical load is greater than 75% of the rated capacity, or it is geographically separated from other DGs, then it should not be considered for inclusion to a microgrid. In most cases, no single DG will be able to supply power to more than one full load. It is better to reduce load demand factors to essential loading and connect multiple DGs. This will maximize the quantity of load supplied as well as provide some level of redundancy. For several reasons the size of each microgrid should be limited. Large microgrids imply multiple DGs, which inject third harmonic currents and may overheat neutral conductors.

Microgrids are minimally efficient; the larger the microgrid, the less reliable the system becomes for noncritical loads.

A realistic goal should be to utilize approximately 75% of the total available on-base emergency generation capacity. At Typically AFB, this equates to approximately 10.5 MVA. However, this is just a ballpark figure, since the total generation produced at Typical AFB for Scenario III was 9.2 MVA. Each base is designed independently and some may contain more congested loads which would be more conducive to achieving this goal, whereas other bases may be filled with long radial feeders. Several of the considerations highlighted in Chapter 4 will also hinder achieving this goal. In actuality, any load supplied outside the original DG applications will be a tremendous asset for the installation commander and may save a few lives.

6. CONCLUSION

This research expanded the traditional thinking of utilizing emergency backup generators. Military installations are often saturated with DGs of various sizes due to the very nature of the mission taking them around the world, often to desolate or unfriendly locations. Several functions within a base are deemed critical and require constant power supply. Often the utility is not sufficient due to existing threats. As a result, many facilities on base require backup generation. The old USAF generator-sizing policy underutilized capacity by 75%. The updated policy improved this situation three-fold, but the majority of inventory remains. By definition, each base has the capability to almost triple its emergency-loading capacity. While this may not be entirely possible, there is certainly room for improvement.

This research considered taking pieces of excess generating capacity from each generator and utilizing it to supply additional loads with power. It is intended for contingencies of great length, on the order of days, rather than hours. A base can function on limited power for short periods of time, but sustained utility outages may negatively impact mission success. The objective of this thesis was to allow any base to maximize the amount of load supplied by utilizing the existing on-base generation and distribution system. The most effective method to achieve this objective was to reduce each load demand factor to its essential loading, and form several microgrids by connecting multiple generators. Each microgrid must ensure its generation capacity is always greater than its load potential.

This paper also identified several obstacles installations must overcome. Each microgrid must satisfy the system parameters and not overload any generators. Other considerations explained how distribution transformers affect third harmonic currents, the importance of an effectively grounded system, and the ramifications for system protective equipment. A generator maintenance schedule and load-shed plan was also recommended.

The overarching sequence of operations is listed in Table 5.1, including steps from normal operating conditions to implementing an islanding strategy to maintaining microgrids. It is reasonably safe to say the objective of implementing this methodology should effectively utilize approximately 75% of the total available on-base generation. The end result is 2-3 times existing load capacity and more flexibility to commanders to complete the mission.

6.1 Future Work

It would be advantageous to construct a fictitious base and perform real-time modeling experimenting with different islanding strategies. Further analysis should be performed to evaluate the effects of third harmonic current injections from DGs since distribution transformers do not provide an ideal generator step-up configuration. This work should evaluate how much third harmonic current is actually injected into the distribution system, establish the thresholds for different distribution configurations (3-wire, 4-wire, overhead, underground, etc.), and discuss different methods of mitigating these injections (additional grounding banks, etc.).

Another subject that requires analysis is the effect of single-phase loading on generator performance. All calculations performed in this research assumed balanced 3PH loads. Power flow in EasyPower does not differentiate any effects of 1PH loading. The DGs will most likely need to be derated for unbalanced loads. But by how much? And what are the ramifications (power quality, maintenance, etc.)?

Another area for further research is to develop an interface that would automatically solve the optimization problem in Equation (5.1) directly from the one-line diagram. The interface would evaluate the system topology, DG size and location, load priority, and essential loading demand factors. The output would give engineers information pertaining to switch configurations, anticipated reliability, maintenance schedule, and a load shed plan.

This thesis provides a starting point for military installations, specifically the USAF, to redefine their emergency-generator applications. The scheme applies to any installation. Only existing infrastructure was discussed, with the exception of acquiring SYNC switches, so any associated costs are minimal. It is justifiable for any military installation to consider connecting DGs during a sustained utility outage because of the mission-flexibility gained by each commander and the increased load supplied.

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APPENDIX A. GENERATOR REACTANCES

Table A.1 provides a detailed list of generator sizes and reactance values. Those less than 35 kW have assumed reactance values because their impacts on the system are considered negligible. All others were taken from Cummings Power Suite v4.1 software package. Each kVA rating was calculated using Equation (A.1) and a power factor rating of 0.8.

$$S = \frac{P}{pf} \tag{A.1}$$

The new alternator reactance values were calculated using Equation (A.2).

$$_{p.u.}Z_{new} = {}_{p.u.}Z_{given}\left(\frac{_{base}kV_{given}}{_{base}kV_{new}}\right)^2\left(\frac{_{base}kVA_{new}}{_{base}kVA_{given}}\right) \tag{A.2}$$

This equation converts per unit alternator reactance values from their own kVA base to per unit reactances using the generator kVA base. EasyPower automatically converts these values to the system base (10 MVA).

Table A.1 Generator Reactance Values in Per Unit Using Own kVA Base

Generator			Alternator			Alternator Given Reactances			Alternator New Reactances (105°C Rise Rating)		
kW Rating	kVA Rating	Voltage Rating	Base kVA	Voltage Rating	Percent Efficency	Subtransient Reactance	Transient Reactance	Zero-Sequence Reactance	Subtransient Reactance	Transient Reactance	Zero-Sequence Reactance
7.5	9.375	208	N/A	N/A	N/A	N/A	N/A	N/A	0.14	0.18	0.09
		480	N/A	N/A		N/A	N/A	N/A	0.10	0.15	0.06
15	18.75	208	N/A	N/A	N/A	N/A	N/A	N/A	0.14	0.18	0.09
		480	N/A	N/A		N/A	N/A	N/A	0.10	0.15	0.06
20	25	208	N/A	N/A	N/A	N/A	N/A	N/A	0.14	0.18	0.09
		480	N/A	N/A		N/A	N/A	N/A	0.10	0.15	0.06
35	43.75	208	45	208	88	0.14	0.19	0.09	0.14	0.18	0.09
		480	48	480		0.11	0.16	0.07	0.10	0.15	0.06
60	75	208	75	208	90	0.13	0.17	0.09	0.13	0.17	0.09
		480	83	480		0.11	0.14	0.07	0.10	0.13	0.06
100	125	208	140	208	92	0.14	0.21	0.1	0.13	0.19	0.09
		480	160	480		0.12	0.18	0.08	0.09	0.14	0.06
150	187.5	208	188	208	93	0.13	0.2	0.09	0.13	0.20	0.09
		480	206	480		0.11	0.17	0.08	0.10	0.15	0.07
200	250	208	267	208	93	0.09	0.14	0.02	0.08	0.13	0.02
		480	286	480		0.07	0.11	0.02	0.06	0.10	0.02
250	312.5	208	365	208	94	0.15	0.21	0.1	0.13	0.18	0.09
		480	400	480		0.12	0.17	0.08	0.09	0.13	0.06
300	375	208	481	208	94	0.13	0.18	0.11	0.10	0.14	0.09
		480	538	480		0.11	0.15	0.09	0.08	0.10	0.06
400	500	208	625	208	95	0.12	0.17	0.1	0.10	0.14	0.08
		480	675	480		0.1	0.14	0.08	0.07	0.10	0.06
500	625	208	688	208	95	0.11	0.15	0.09	0.10	0.14	0.08
		480	750	480		0.09	0.13	0.08	0.08	0.11	0.07
600	750	208	913	208	95	0.19	0.27	0.03	0.16	0.22	0.02
		480	1025	480		0.16	0.22	0.02	0.12	0.16	0.01
750	937.5	208	1063	208	95	0.19	0.26	0.03	0.17	0.23	0.03
		480	1188	480		0.16	0.22	0.02	0.13	0.17	0.02
2000	2500	480	3360	480	96	0.144	0.197	0.027	0.11	0.15	0.02

Notes:
1. Assumed reactance values for generators smaller than 35kW.
2. Each generator kVA rating is based off 0.8 power factor.
3. Alternator data taken from Cummings Power Suite v4.1 Power Suite software package.
4. New reactances in per-unit to the generator set base.

APPENDIX B. GENERATOR SHORT-CIRCUIT CURRENTS

Table B.1 shows the available short-circuit currents produced by each emergency generator at Typical AFB. These values are required to perform short-circuit analysis on Scenarios I-III, described in Chapter 3, and are based on ANSI C37.010-1999.

Table B.1 Individual Emergency Generator Short-Circuit Characteristics

	Generator Number	Size (kVA)	X/R Ratio	Voltage	Momentary Fault Type (1/2 Cycle)	Symmetrical Fault Current (kA)	Asymmetrical Fault Type (kA)
1	1001	125	9.79946	208	3-PH	2.66	3.82
					SLG	2.96	4.26
2	1061	125	9.79946	408	3-PH	1.66	2.39
					SLG	1.87	2.69
3	1071	500	19.3315	208	3-PH	13.86	21.71
					SLG	14.85	23.27
4	1111	938	24.4293	480	3-PH	8.67	13.86
					SLG	12.08	19.30
5	1171	750	22.5768	208	3-PH	12.23	19.43
					SLG	16.86	26.78
6	1181	313	15.8053	208	3-PH	6.67	10.24
					SLG	7.43	11.41
7	3001	44	4.8847	208	3-PH	0.85	1.08
					SLG	0.97	1.23
8	3041	2500	26.2547	480	3-PH	27.32	43.89
					SLG	37.56	60.35
9	3081	9.4	2.3148	208	3-PH	0.17	0.19
					SLG	0.19	0.21
10	3201	44	4.8847	208	3-PH	0.85	1.08
					SLG	0.97	1.23
11	3211	75	7.104	12470	3-PH	0.03	0.04
					SLG	0.03	0.04
12	3221	44	4.8847	12470	3-PH	0.01	0.02
					SLG	0.02	0.02
13	4051	625	21.098	480	3-PH	9.39	14.82
					SLG	9.79	15.47

Table B.1 Continued

	Generator Number	Size (kVA)	X/R Ratio	Voltage	Momentary Fault Type (1/2 Cycle)	Symmetrical Fault Current (kA)	Asymmetrical Fault Type (kA)
14	4101	125	9.79946	208	3-PH	2.66	3.82
					SLG	2.96	4.26
15	4111	375	17.1342	208	3-PH	10.39	16.09
					SLG	10.75	16.64
16	4121	500	19.3315	208	3-PH	13.86	21.71
					SLG	14.85	23.27
17	4141	44	4.8847	208	3-PH	0.85	1.08
					SLG	0.97	1.23
18	4151	44	4.8847	208	3-PH	0.85	1.08
					SLG	0.97	1.23
19	4171	250	14.2141	208	3-PH	8.65	13.12
					SLG	11.54	17.49
20	4181	75	7.104	208	3-PH	1.59	2.16
					SLG	1.77	2.41
21	4261	625	21.098	480	3-PH	9.39	14.82
					SLG	9.79	15.47
22	4281	25	3.2883	208	3-PH	0.47	0.55
					SLG	0.54	0.63
23	4291 (Hosp)	625	21.098	208	3-PH	17.33	27.37
					SLG	18.57	29.32
24	4301 (Hosp)	625	21.098	208	3-PH	17.33	27.37
					SLG	18.57	29.32
25	4371	500	19.3315	480	3-PH	8.58	13.44
					SLG	9.01	14.11
26	4411	625	21.098	480	3-PH	9.39	14.82
					SLG	9.79	15.47
27	5001	125	9.79946	480	3-PH	1.66	2.39
					SLG	1.87	2.69
28	5011	313	15.8053	480	3-PH	4.17	6.41
					SLG	4.70	7.21
29	5191	750	22.5768	208	3-PH	13.00	20.65
					SLG	18.35	29.15
30	5291	250	14.2141	480	3-PH	3.33	5.05
					SLG	3.75	5.68
31	5471	44	4.8847	208	3-PH	0.85	1.08
					SLG	0.97	1.23

Table B.1 Continued

	Generator Number	Size (kVA)	X/R Ratio	Voltage	Momentary Fault Type (1/2 Cycle)	Symmetrical Fault Current (kA)	Asymmetrical Fault Type (kA)
32	5491	313	15.8053	480	3-PH	4.17	6.41
					SLG	4.70	7.21
33	5551	125	9.79946	208	3-PH	2.66	3.82
					SLG	2.96	4.26
34	5561	250	14.2141	208	3-PH	8.65	13.12
					SLG	11.54	17.49
35	7041	125	9.79946	208	3-PH	2.66	3.82
					SLG	2.96	4.26
36	7051	188	12.3032	208	3-PH	4.00	5.95
					SLG	4.46	6.63
37	7071	18.8	2.8096	208	3-PH	0.35	0.40
					SLG	0.40	0.45
38	7241	125	9.79946	480	3-PH	1.66	2.39
					SLG	1.87	2.69
39	7261	750	22.5768	480	3-PH	7.51	11.93
					SLG	11.42	18.15

Comments:

1. X/R values based on ANSI C37.010