A SunCam online continuing education course

Reliability in
Mission Critical Applications
Part I – Electrical Systems

by

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A. Introduction

This course is developed to provide an introduction to reliability associated with mission critical applications. This may also be considered a good refresher course for those who work in the electrical engineering field and have a familiarity with mission critical systems. Mission critical reliability is a useful topic for any Engineer to be familiar with associated with their interest in design of mission critical systems. Any discussion on reliability should generally include mechanical systems reliability, however for the purposes of this course, and simplicity's sake, mechanical systems reliability (including power to the mechanical systems) will NOT be addressed but may be presented in a future course.

This course will review some electricity basics, it will provide an explanation of several electrical components important to providing redundancy, and it will establish definitions so as to help to reader understand how different levels of reliability can be and are frequently quantified.

The reader of this course should be able to use the tools gained to understand reliability in mission critical applications.

B. Basics

Background:

Mission critical systems are systems that are needed in order to keep the business purpose of an organization functional. If a mission critical system does not fulfil its mandate then the operation of the company will likely be impacted in a significant way, including financially. Often times they serve the purpose of keeping data processing, or keeping a life safety functions on line. As a result, mission critical system design must be performed with an understanding of the risks and be carried out it a way that meets the needs of the end user organization.

All component will fail eventually. This is an extremely important fact to recognize in approaching the incorporation of reliability into a system so that it fulfills its mission critical system mandate. Keep this in mind as the information unfolds. It is worth noting that "equipment reliability" is a different topic and for information on analysis of mean time to failure and topics related to “non-mission critical” equipment reliability refer to other courses available from SunCam associated with reliability in building systems.

Given the fact that all components will eventually fail, “reliability” as discussed in this course is related the reliability of the overall system and its ability to achieve the mission of the business.

It should be recognized that reliability is validated as a function of the availability of the critical system.

It is worth noting that in the industry there are differences of opinion associated with the percentages of “uptime” without “downtime” that various availability configurations of the equipment can provide for a system. *Uptime* is a term that expresses the condition of mission critical systems when they are functioning as required / desired and the services are and continue to be available. *Downtime* is the term assigned to the period of time after a failure occurs; while services are not available, and until the critical support systems are restored.

Reliability in general is ensured by providing “redundancy” and fault tolerance (i.e. avoiding single points of failure).

There are several organizations that established definitions and levels or tier ratings associated with mission critical systems. This course will not discuss or comment on those types of rating systems only to say that they do have value in establishing a baseline for those in the industry to work from within their understanding. There are some ways of expressing reliability that have different interpretations, as a result there is some subjectivity associated with a discussion on the topic of reliability and uptime.

As noted above, this course will in general focus on and mainly discuss the reliability of electrical systems for mission critical systems. The engineer should keep in mind that mechanical cooling is also typically a critical aspect of any mission critical system. If the mechanical systems fail, some aspect of the critical equipment (for example critical computing equipment) may overheat thus shutting down the equipment on a thermal overload, and causing the mission to fail regardless of the robustness of the electrical systems. As a result, even though the electrical systems delivered the power required for the business purpose in a reliable fashion, the mission will have been considered to have failed. To expand your understanding of this and for information on reliability in mechanical systems, refer to a course that specializes in that topic.

Electricity Basics and Power:

This course is intended to be useful to individuals at all levels of experience as well as the full variety of engineering and architecture background (Civil, Mechanical, Electrical, etc.). As a result, some basics will be touched upon that may seem rudimentary to some, but for others will be useful to hear for the first time or as a refresher. Regardless, it will be believed to be valuable to establish this information and have it in one place for the reader's reference.

For everything to function requires power. The main source / type of power needed for most equipment in the modern world is electricity. Electricity is frequently and most typically provided to a location via a purveyor of electricity commonly referred to as the electric utility provider. As most engineers learn during the fundamental courses on electrical engineering, electrical power is conveyed on wires also referred to as transmission lines or cables. This being the case, the utility company is referred to as the "source", and everything being powered by the user is referred to as the "load".

Electrical engineers use simple diagrams in engineering; some of which are referred to as electrical *single-line diagrams* or *one-line diagrams (single-line or one-line for short)*. These terms are frequently used interchangeably and these diagrams are extremely useful. The name is thus given because the path of power from the source to the load is shown with single lines, regardless of the number of wires used for any given feed. These single-line diagrams are also distinct from circuitry diagrams and are meant to reflect the distribution of power, not necessarily the functionality of the circuitry. So that reliability can be understood, this course will define and reflect some symbols commonly used on single line diagrams and explain the component they represent. Additionally it will present some simple one-line diagrams so that reliability can be understood graphically.

A wise person said, "electricity follows laws… and I don't know why it (electricity) does what it does, but I know it does it". That said, electricity can be dangerous if not treated with respect, but it does follow rules. While electricity basics are not the purpose of this course, a few definitions and illustrations of descriptions will be provided to help explain some of the terms and processes used in this course.

At a high level, a coulomb is a measure of electric charge providing a unit value of said electric charge. Current is a measure of electric charge in motion or the rate at which the charge of electricity (coulombs) flows. While it is somewhat suspect to do so (and not fully accurate), if compared to water in a full hose, current could be compared to the flow rate. It is worth noting that the electron theoretically might not travel very far, but if the "pressure" is applied (termed as "voltage") at one end of the system, the other end of the system (of equivalent size) will "immediately" also move or flow at the same rate it flows at the end of the system the voltage is applied. Current is expressed in the International System (IS) of Units in Amps or Amperes.

Amps is defined in terms of the charge over time as coulombs per second. The equation to describe Amps is expressed in Equation E-1.

$$Amps = \frac{Coulombs}{Second}$$

EQUATION E-1

In the "power law" equations (developed by Faraday), Current is typically expressed as the term "I". In these same equations, *Voltage* is expressed as "V".

Voltage can also be defined. Again, although the comparison technically breaks down, if electricity in a wire was understood in terms of a fully filled hose passing a liquid under pressure, voltage might be considered similar to the "pressure". Voltage is also the current times the resistance of the medium. A mathematical definition of Voltage is expressed in Equation E-2 where "R" is the resistance:

$$V = I\ x\ R$$

EQUATION E-2

A practical reality of Equation E-2 is that in a circuit, voltage increases with resistance, and current decreases with resistance. Different materials provide different resistances and likewise, different cross sections of the conductive material provides a different amount of resistance. A larger cross section of wire will produce less resistance and therefore the voltage of the system will produce less current in the larger system.

Power is expressed in the International System (IS) of Units in Watts (W). 1,000 W is referred to as 1 Kilowatt (kW), and 1,000 kW is referred to as 1 Megawatt (MW). Power is a function of Current (in Amps or Amperage) times Voltage (in Volts or Voltage) where Current is expressed as “I” and Voltage is expressed as “V”.

Electricity is basically available as direct current (DC) or alternating current (AC). It was found as the electrical industry evolved that AC power is capable of conveying power longer distances with less losses.

The mathematical definition of Power in DC systems is expressed in Equation E-3:

$$P = I\ x\ V$$

<u>EQUATION E-3</u>

The mathematical definition of Power in 3 phase AC systems is expressed in Equation E-4 (Noting that this is line to line voltage, not line to neutral assuming a power factor of 1):

$$P = I\ x\ Vx\ 1.73$$

<u>EQUATION E-4</u>

The mathematical definition of Power in single phase AC systems is expressed in Equation E-5:

$$P = I\ x\ V$$

<u>EQUATION E-5</u>

The practical reality of Equations E-3 through E-5 is that to provide the same power, if the voltage is decreased, the current must be increased / will increase and vice-versa.

Therefore in terms of practical usage, at the utility purveyor level, AC power is typically transmitted long distances at very high voltages. This is because at high voltages, a smaller cross section of wire (which has more resistance than a larger cross section of the same material wire) can still be used to convey the electricity at the power generated.

At the point of need, a variety of voltages may be required since different pieces of equipment are designed to function at lower specific, yet varying voltages, depending on the type of equipment and the intentions/needs of the manufacturer. As a result, power “transformation” is required at points throughout the system. So while there are transformers located throughout the utility transmission infrastructure for the purposes of requiring less wire to transmit higher power, there is also invariably a transformer at the interface between the utility transmission and the end user so as to not only make the electricity less dangerous to deal with, but also to achieve the voltages required by the equipment. It is worth noting or clarifying once more time that at the lower voltages (after being transformed), providing the same current to the load requires a much higher cross section of wire, therefore higher material costs in construction for the lower voltage distribution.

It is also worth noting that in AC systems, the voltage and current may get “out of phase”, therefore depending on the “power factor” or how much leading or lagging occurs between phases, there may be the *appearance* of additional power. As a result, while “real power” is expressed in W or kW, apparent power is expressed in VA or KVA, which is kilo-volt-amperes. Some equipment such as UPS systems, which will be discussed later, typically identify their capacity using KVA rather than kW.

One other useful piece of information is an understanding to the description of voltages in AC systems. A three phase system will have three legs out of phase by 120 degrees. When voltage is tested “phase to phase” the reading will be different than when read “phase to ground” or “phase to neutral”, As a result, the voltage of AC systems are described in both ways. The common examples are 120/208V or 277/480V. The smaller value is the line to line reading while the larger value is the line to neutral or line to ground reading.

C. Components

This course will not discuss in great detail the methods the utility companies use to generate power except to say that it is generated by moving magnets through coils of wire, and the processes used to move the magnets can get their “energy” from sources such as hydro power, nuclear power, burning coal to generate steam, or other fuel, etc.

The network of distribution is regularly referred to as “the grid” and the grid distributes electricity very effectively, but due to the nature of the transmission systems, the components are often exposed, or the load demands of the grid may fluctuate greatly ultimately causing a loss of electricity in the system from place to place from time to time. In this way, although the utility grid is robust and extremely reliable for everyday non-critical use, it should be not be considered highly reliable for systems that are mission critical and require power at all times.

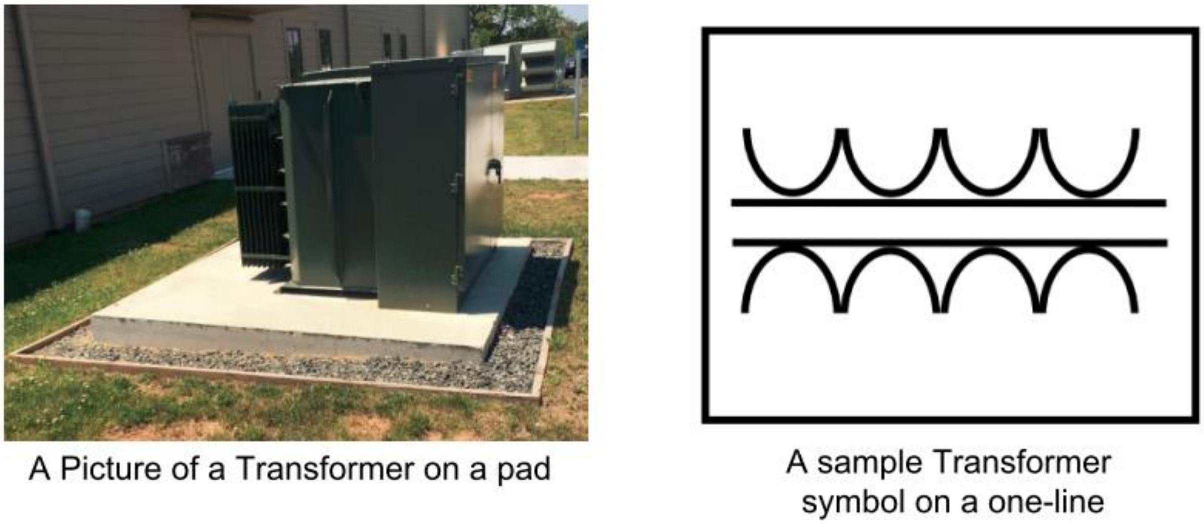
That said, this section of the course will explain components of the electrical system one might expect to observe at the end users facility to convey the power effectively to the critical and non-critical equipment at the site.

Transformers:

Transformers are used to create the various voltages required in a transmission and/or distribution system. Transformers change or transform the voltage in the system to a different value (in the case of a utility transformer at the user location, the input voltage is higher and the output voltage is lower). It “works” by placing wires with different numbers of windings per length adjacent to another set of windings with more or less windings per the same length. While there are losses (efficiency losses) in a transformer, the ratio of windings is known and manufacturered to specifications, and the transformer will provide the transformed output voltage anticipated as required.

It is worth noting that there are different transformer configurations available that, while having design differences, in general employ the same basic principal noted above. These include Wye-wye, delta-wye, wye-delta, delta-delta and zig-zag transformer configurations. Delta-wye transformers for example create a neutral feed on the output side. At a high level, this is accomplished by configuring the input side of the 3 phases in a “delta” (i.e. triangular) configuration, and configuring the output phases in a “wye” or “star” configuration.

The following Figure F-1 shows a picture of a utility transformer as well as an example of a symbol for a transformer as shown on many electrical single line diagrams.


A Picture of a Transformer on a pad

A sample Transformer symbol on a one-line

Figure F-1
(A Transformer and its Symbol)

A simple single line of the utility power to the building load is shown in Figure F-2:

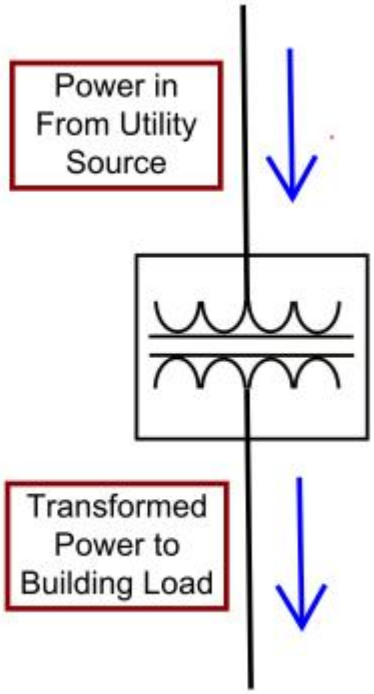


Figure F-2
(Single Line of Utility Power through Transformer)

It is noted that power coming into a building typically enters from the transformer through a utility company switch, often referred to as a Service Entrance Switch (SES). From the SES, power will typically go to a Main Distribution Panel (MDP) where it will be further distributed throughout the facility. For simplicity in this course the SESs will not be reflected in the single lines showing utility sources. It is worth noting, an SES may be located separately, or in the same line up as the MDP.

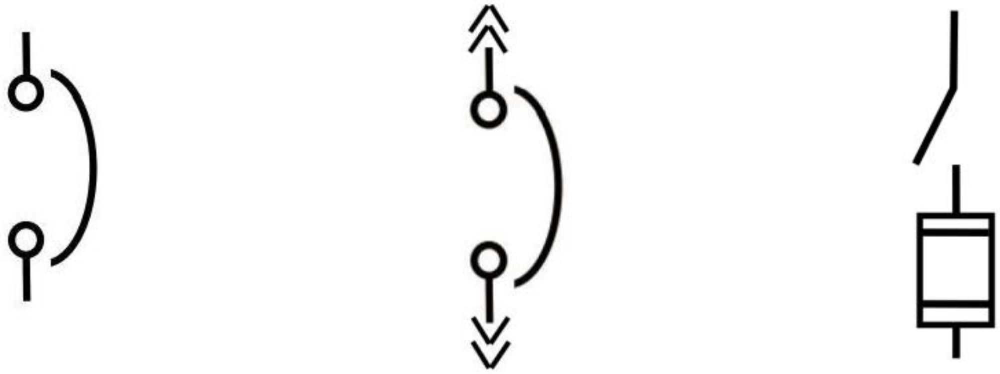
Power Distribution Basics, Overcurrent, Arc Flash and Short Circuit Protection:

Power distribution is the term given to the planned conveyance of the electricity throughout the site and/or building. Power is distributed via the wires (or feeders) to panels. The design of panels, breakers and wires must all be thoroughly sized and calculated based on the load and where it will be needed. In the United States, the National Electric Code (NEC) defines the requirements that must be used in approved "code compliant" design.

There are tables in the NEC for feeder sizes, conduit sizing, and derating feeders based on various parameters. Additionally there are standard sizes for the commercially available panels, breakers and wire sizes that the engineer will take into account in the power distribution design. Detailed information about electrical design or the NEC is not covered in this course, please refer to resources on these topics for support in these areas.

Larger panels are often referred to as switchboards. While some older equipment and/or utility equipment designed for certain purposes may have fuses most modern distribution electrical panels and switchboards will be equipped with circuit breakers. A *circuit breaker* (or "breaker") is a device designed to provide overcurrent protection, sometimes for both input and also for output distribution. Overcurrent protection is the phrase used to describe the fact that if the current in the circuit achieves a certain level (for a certain duration of time), the downstream equipment is protected since the device will "trip" open.

Figure F-3A shows an example of the symbols often used on one-line diagrams for the purposes of reflecting circuit breakers and fused switches.



A Circuit Breaker Symbol used on Single Line drawings

A Symbol for a "Draw Out" Circuit Breaker

A Symbol for a "Fused Switch"

Figure F-3A
(Some Sample Circuit Breaker Fused Switch Symbols)

A circuit breaker that can be "racked out" of switchgear (even larger distribution equipment) for maintenance purposes, without having to open the gear, is referred to as a "draw out breaker". This may have a distinct symbol, but may not always be shown differently on single lines. Regardless of the breaker type, or if it is a panel, switchboard, or switchgear, the breaker will connect to the "buss" (i.e. a series of metal bars inside the panel that the breakers "latch on to" in various ways). The circuit breakers are also connected to the feeders that distribute power from the breakers to other sub-systems or equipment.

Figure F-3B shows some pictures of buss in a piece of equipment and a panelboard with its associated circuit breakers.

Buss Panelboard

Figure F-3B
(Pictures of Buss, Panel, and Circuit Breakers)

Figure F-3C shows a picture of switchgear with the hoist available to assist in removal of the circuit breakers once racked out.

Figure F-3C
(A Picture of Switchgear)

As noted above, circuit breakers are sized to trip open if a certain amperage is exceeded for a certain duration. Overcurrent protection sizing and trip settings are topics beyond the scope of this course but as noted, the size parameter is defined in terms of the amps that will cause the breaker to trip. Additionally, the breakers, panels, and gear are each respectively sized to handle and interrupt a large short circuit and/or arc flash event. It is worth noting as alluded to above, that there are settings within larger breakers that can be adjusted to define the various durations that will allow a coordination within the system to take place. Arc flash and short circuit sizing is also beyond this course, but the terminology used to rate the equipment is referred to as the KAIC rating (K (for kilo or thousand) Ampere Interrupting Capacity) of the equipment. When higher KAIC ratings are needed that circuit breakers can provide, fused switches are available that can provide it.

Figure F-4 shows an example of what a single line depiction of a panel and its breakers may look like for larger switchboards, switchgear, and their respective breakers. In this figure, there is an “input breaker, and four (4) sub-feed breakers shown. The number of breakers in a panel or board can vary widely.

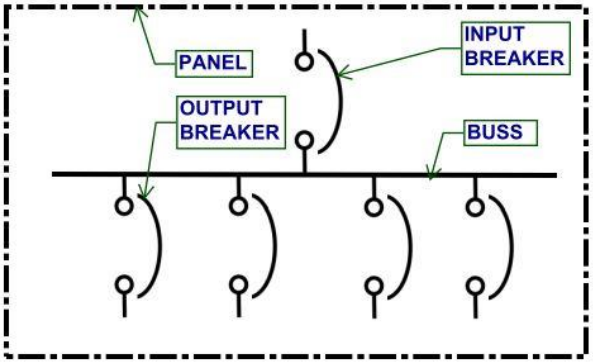


Figure F-4
(A one line symbol of a Panel/Switchboard and its Associated Breakers (including input breaker))

One notable point regarding mission critical panels, especially those feeding IT and other sensitive equipment is that they should be designed with Transient Voltage Surge Suppression (TVSS) devices which protect the downstream equipment from voltage spikes.

Figure F-5 shows a sample symbol of a panel with breakers (in this example, the panel/switchboard has no input breaker (i.e. the “main” feeders are connected to the buss via lugs only, which is often referred to as Main Lugs Only, or M.L.O..)

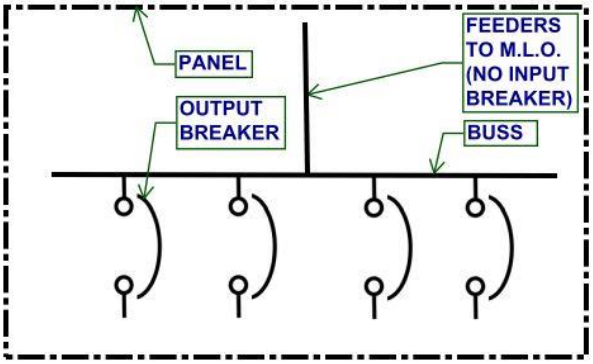


Figure F-5
(One line symbol of a Panel/Switchboard and its Associated Breakers (with no input breaker, i.e. M.L.O.))

Generators:

Generators are a critical component of good reliability design. In mission critical design, the facility typically requires the load to have an alternate source of electricity available. A *generator* is therefore considered a locally available back-up power source that creates its own electricity (from another source of energy). This other source of energy can be delivered and/or stored and is not as readily interrupted (i.e. natural gas via a pipeline, or a fuel tank containing the fuel for the engine as delivered by a vehicle, etc.)) for times when the utility source of electricity has been interrupted (or “lost”)).

As an example, a very common type of generator used in mission critical applications is a diesel generator. A diesel generator has an engine that runs on diesel fuel. The diesel fuel is stored in tanks which can be sized to accommodate the runtime durations the end user feels are necessary to ensure sufficient refueling can be performed before the utility source can be re-established during significant utility outages. For example, significant outages can occur during large weather events whereby utility power to a facility is lost for a week or more. So the tank can be sized based on the fuel burn rate at full load for the duration desired.

In mission critical applications the back-up power available via the generator is most appropriately referred to as “standby power” and as such the equipment will frequently be referred to as the standby generator(s). Sometimes the use of the term “emergency generator” occurs, but there is a caution related to this terminology. The NEC refers to an emergency generator as one used to support building life safety functions, and in most mission critical applications some of the stricter configuration requirements of a life safety emergency generator are not required. As a result, it is typically advisable to follow the NEC requirements for standby generators. It is worth noting that some of the confusion is exacerbated by:

1. The fact that as of the writing of this course, requirements associated with the regulation of exhaust/emissions generally identify the use of all generators as emergency generators regardless of the life safety intent under the NEC.
2. The labeling of the generator source as “emergency” on some transfer equipment.

It is worth indicating for the purposes of expressing options available related to reliability that “dual fuel source” generators are available that can run on both diesel and natural gas (to be clear, one fuel source at a time). This might be a good option for an owner that has concern with the reliability of diesel fuel deliveries.

Figure F-6 shows a picture of a generator as well as an example of the symbol for a generator as commonly reflected on many electrical one lines.

A Picture of an Enclosed Generator on a pad

A sample Generator symbol on a one-line

Figure F-6
(A Generator and its Symbol)

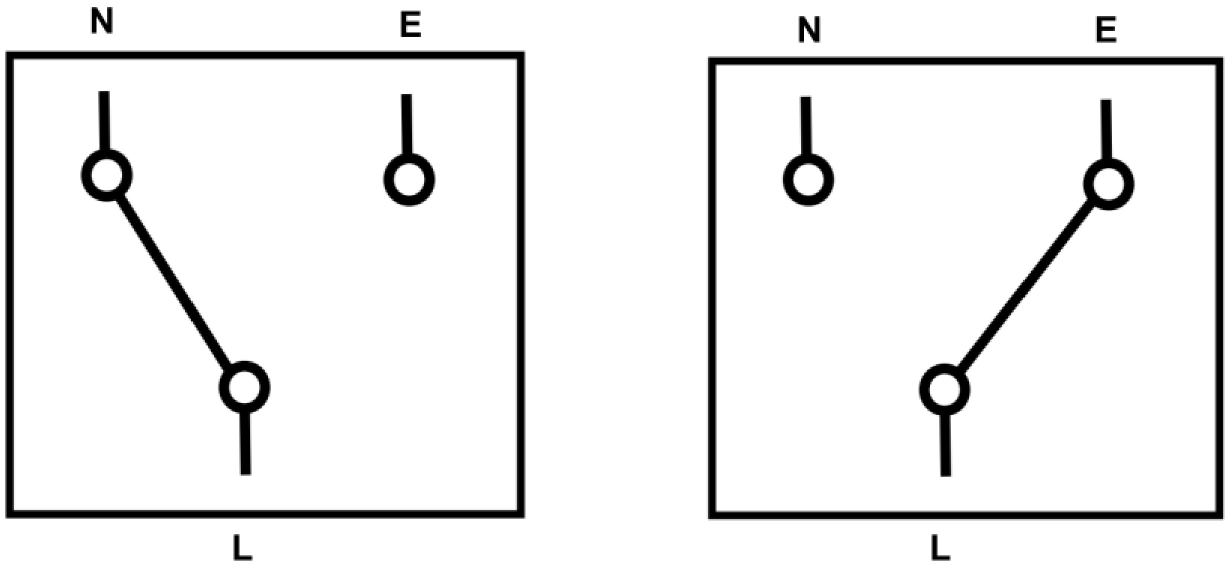
Transfer Switches and the Resulting Reliability:

Transfer Switches are very important in reliability design. Transfer switches come in “manual” or “automatic” configurations. The transfer of electric power from the utility source to the standby/back-up source very frequently occurs through transfer switches. While it is noted that some switchgear has breaker pairs that have the “intelligence” to perform the required transfer function, for the simplicity of this course only transfer switches will be discussed in any sort of depth.

In mission critical design, it is typically appropriate to transfer the power as quickly as possible, and as a result, the design intent will be for the transfer between sources to occur automatically. An *Automatic Transfer Switch (ATS*) is a transfer switch that performs this transfer automatically. An ATS has internal logic, control circuitry, and sensing that recognizes when the power source on one side has been lost and will therefore transfer the load to the alternate source. With a normal ATS the load ***is*** dropped momentarily, but the alternate source will typically be able to assume the load relatively quickly. Since there is a break in the power, this is referred to as an “open transition” transfer.

It is worth noting that some ATSs (for planned transfers) can synchronize the utility source and generator source and transfer between sources without a momentary drop to the load. This would be referred to as a "closed transition" transfer. This can be useful to the end user (for example to avoid the unnecessary use of batteries during the retransfer). Closed Transition configuration is not always allowed by utility companies as there is a perception of risk to the utility. To be clear, closed transition only operates upon restoration of the utility source and during the transfer back to utility from generator, or perhaps during testing, but is not available for unplanned utility outages.

Figure F-7 shows an example of a typical symbol for a basic ATS as is commonly reflected on many electrical single line diagrams.



<u>Figure F-7</u>
<u>(An ATS Symbol in both positions)</u>

The basic ATS will have three (3) points of connection (in terms of the single line). In all cases the "output" point is the load side connection (labeled as "L" in the figure). The other two "input" points can be referred to as the "primary" side and the "secondary" side. The primary side is frequently referred to as the "normal" side (labeled as "N" in the figure) and the secondary side is referred to as the "standby" or "emergency" side (labeled as "E" in the figure). Most ATSs use the "Normal", "Emergency", and "Load" labels on the gear. As noted earlier, this terminology should not cause confusion with respect to the NEC requirements on standby generation; the manufacturer's equipment may use the terms normal, emergency, and load, but the overall configuration (if not intended to be emergency equipment under NEC) could still be considered a standby configuration.

As alluded to above, the primary and secondary sources could both be generator sources, or they could both be utility or other distribution sources. Perhaps the utility company has two different substations available to provide electricity to the site. Or perhaps two different utility companies are close enough to bring an electric service to the site. In either of these cases, an ATS could be configured to provide redundancy of two (2) electrical utility sources to carry the load. Not to express the obvious, but having redundant utility sources of electricity is more reliable than having only a single source.

Figure F-8 shows a diagram of two (2) utility sources feeding an ATS

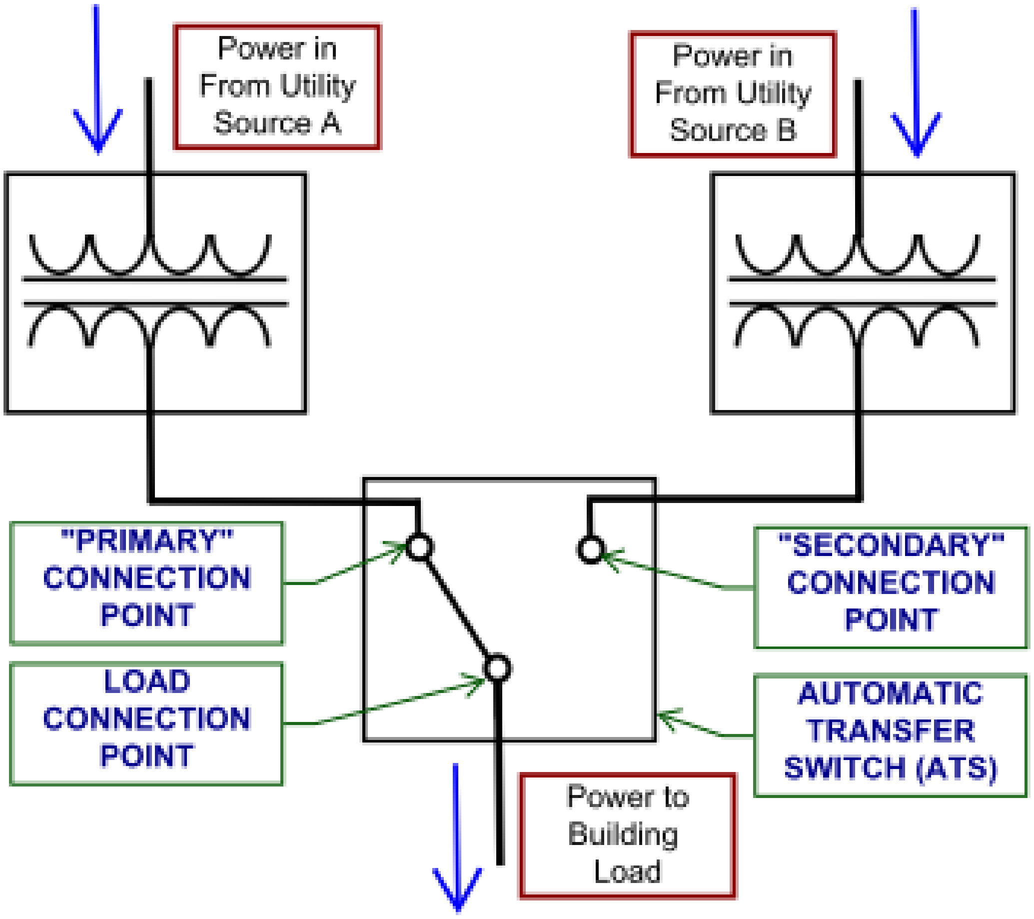


Figure F-8
(An ATS fed by via two (2) Utility Transformers)

While two (2) utility sources is more reliable than one, often regional events such as blizzards and hurricanes can effect *both* utility sources, so even though many losses of utility power to the load can be assuaged, a truly reliable configuration will incorporate an on-site power generation to support the critical mission.

Figure F-9 reflects a single line diagram that incorporates an ATS to transfer power to the load between a single utility source and a generator.

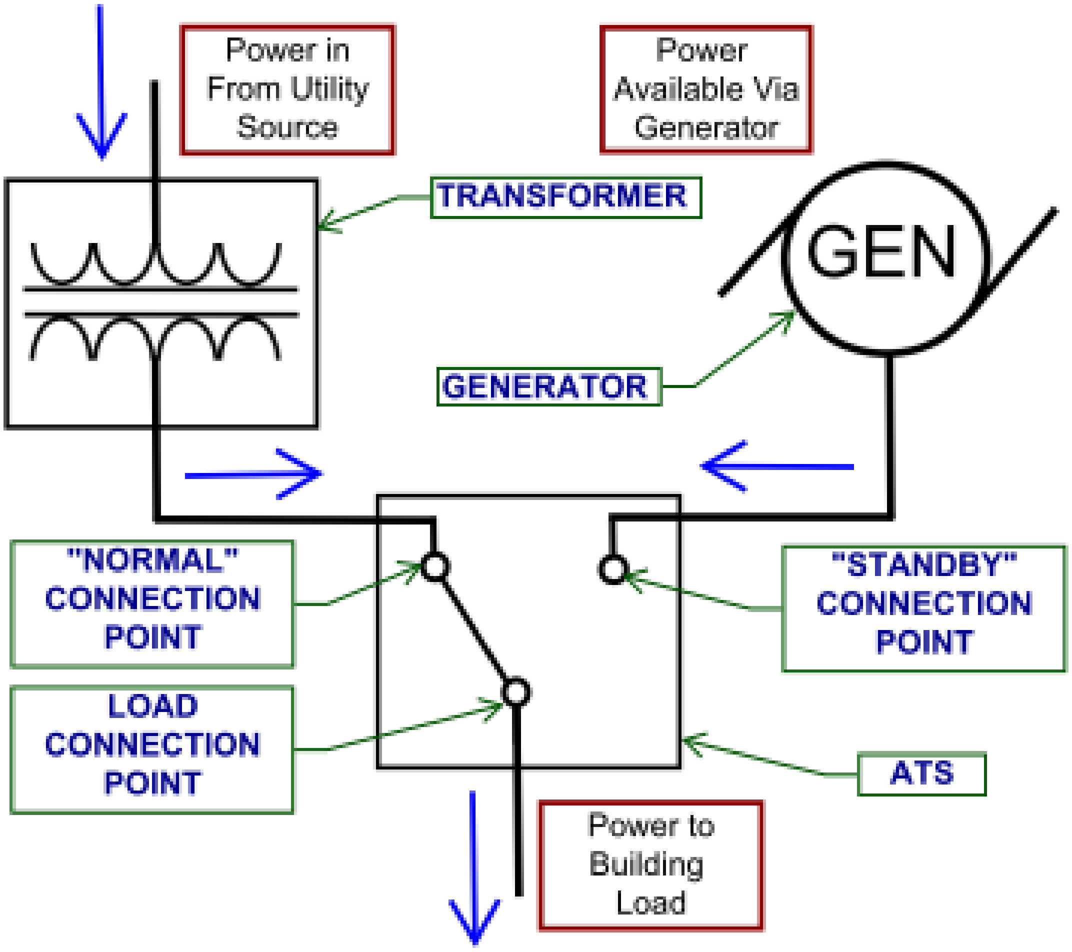


Figure F-9
(An ATS fed by a Utility Transformer and a Generator)

As noted above, an ATS has internal logic, control circuitry, and sensing that recognizes when the utility source has been lost. In the scenario reflected in Figure 9, upon sensing a loss of utility power, the ATS sends a start signal to the standby generator.

Once the ATS senses that the power from the generator source is up to the proper frequency and is stable, the ATS switches to the alternate source and the load is assumed by the generator. The ATS is able to and will switch back to the utility source once it senses the stable restoration of the *preferred* utility power. There may typically be logic programmed into the switch to account for such things as a planned delay prior to transfer (to confirm the utility outage is more than momentary), as well as a post-transfer delay keeping the ATS from immediately retransferring back to utility once the ATS senses that the utility source has been restored. This post-transfer delay is typically programmed into the logic in order to confirm the utility source is relatively stable which avoids unnecessary wear and tear on the ATS. To expound, it is preferable (from an "extend the life of the equipment" strategy perspective) to continue to run the generator a little longer, rather than "banging" the switch back and forth between sources due to an unstable momentary restoration of utility power.

Figure F-10 shows a variation of the graphical depiction of the power being on utility vs. being on generator, highlighted to make it easy to understand.

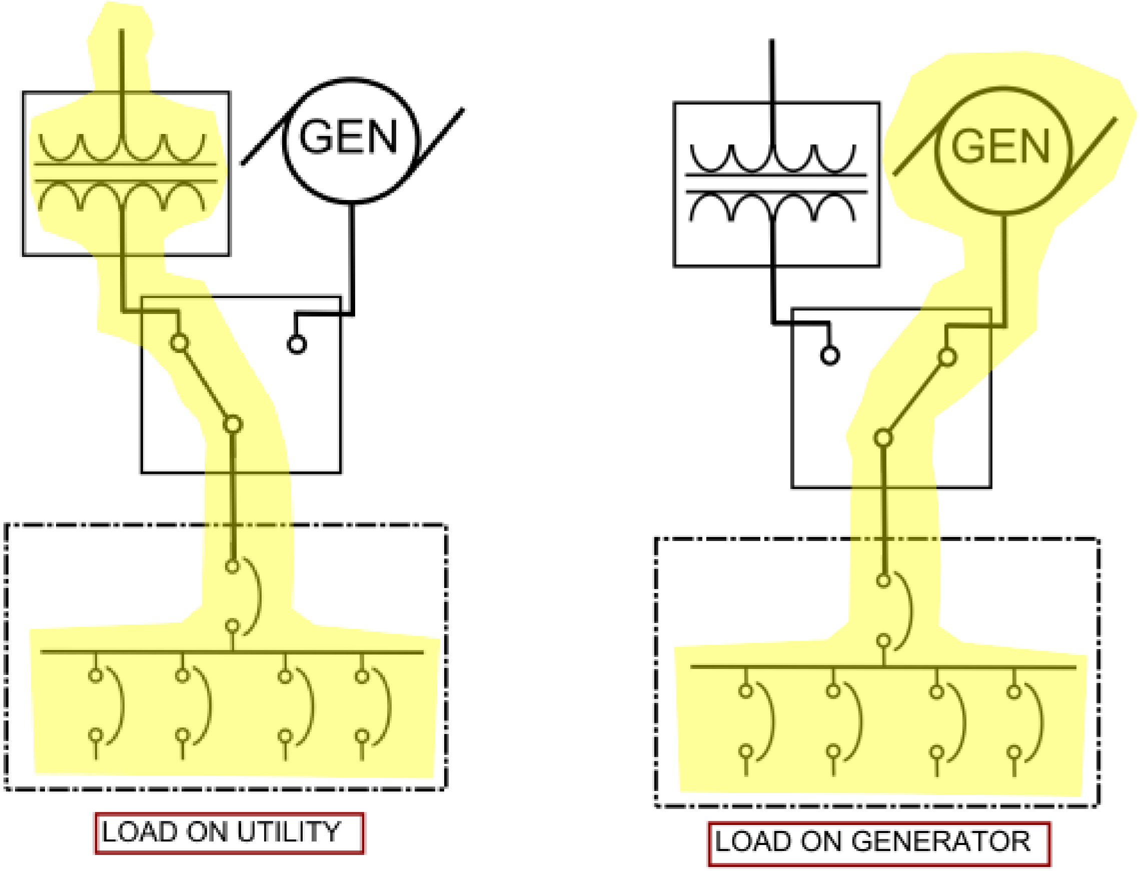


Figure F-10
(System on Utility vs. System on Generator)

Although single points of failure, fault tolerance, and maintainability in mission critical design will be touched on later, one final point worth noting with respect to ATS's is that it is considered unsafe for an electrician to work on a standard ATS without requiring both sources to be locked out (i.e. a standard ATS must drop the load for an extended duration in order to be repaired or replaced).

An ATS that *can* be maintained/repaired without dropping the load is referred to as a bypass isolation ATS. A bypass isolation ATS is more expensive than basic standard ATS due to the additional components required to make it functional. Although an extended duration outage may also be required for the full replacement of a bypass isolation ATS, all of the critical components can be serviced and/or replaced *without* an outage, keeping them functional for many years. It is worth mentioning that the bypass isolation ATS may have a different symbol on a single line diagram. An example of a bypass isolation ATS symbol is shown in Figure F-11.

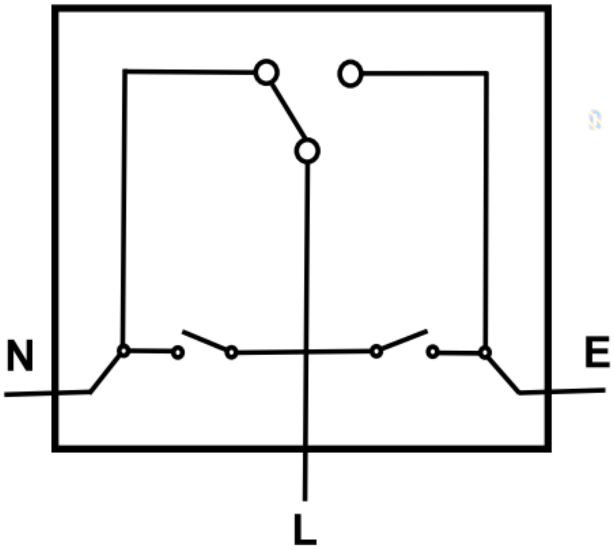


Figure F-11
(Bypass Isolation ATS symbol)

While a bypass isolation ATS is more robust and expensive than a standard ATS, and it may bring value and flexibility in terms of maintainability in many scenarios, they do not remove the single points of failure if the systems consists of a single power train. This will become clearer later in the course.

Uninterruptable Power Supplies (UPS)

An *Uninterruptable Power Supply (UPS)* is a system/component intended to keep electrical equipment from seeing an interruption in electricity at all. In mission critical facilities, power often needs to be provided to information technology, data, and network equipment load in a constant and controlled manner. This can be done through the implementation of a UPS system.

While there are several types of UPS systems available (that may use mechanical energy to provide backup), a common type that will be discussed in this course is the battery powered “double conversion” UPS system. Since this course is about reliability configurations, a detailed explanation associated with how UPS systems function is beyond this course. However, on a basic level, a double conversion UPS system takes Alternating Current (AC) input power and through a “rectifier”, converts it to Direct Current (DC) power and then converts it back to AC through an “inverter”.

The DC power maintains a charge on the batteries while providing power from the batteries to the UPS system’s inverter (which as noted above is the component that converts the power back to AC). If/when there is a loss of the input AC power, the UPS system (through the charge available on the batteries) continues to send output power to the downstream load without an interruption (until the batteries are fully discharged, in which case the load is dropped if input power is not restored).

Depending on the number and type of batteries will determine the run time duration under full load that the UPS system can maintain/carry the load in an uninterrupted fashion.

Double conversion UPS systems can utilize wet cell or dry cell batteries and typically come configured with internal bypass functionality (often called maintenance bypass) so that the unit can be maintained. In order for a UPS system to be replaceable without interruption to the connected load, an additional ancillary bypass circuit is required beyond what comes with the unit. This is often referred to as a “wrap-around bypass” circuit.
Figure F-12A shows the symbol for a “single module” double conversion UPS as is often depicted on single line diagrams.

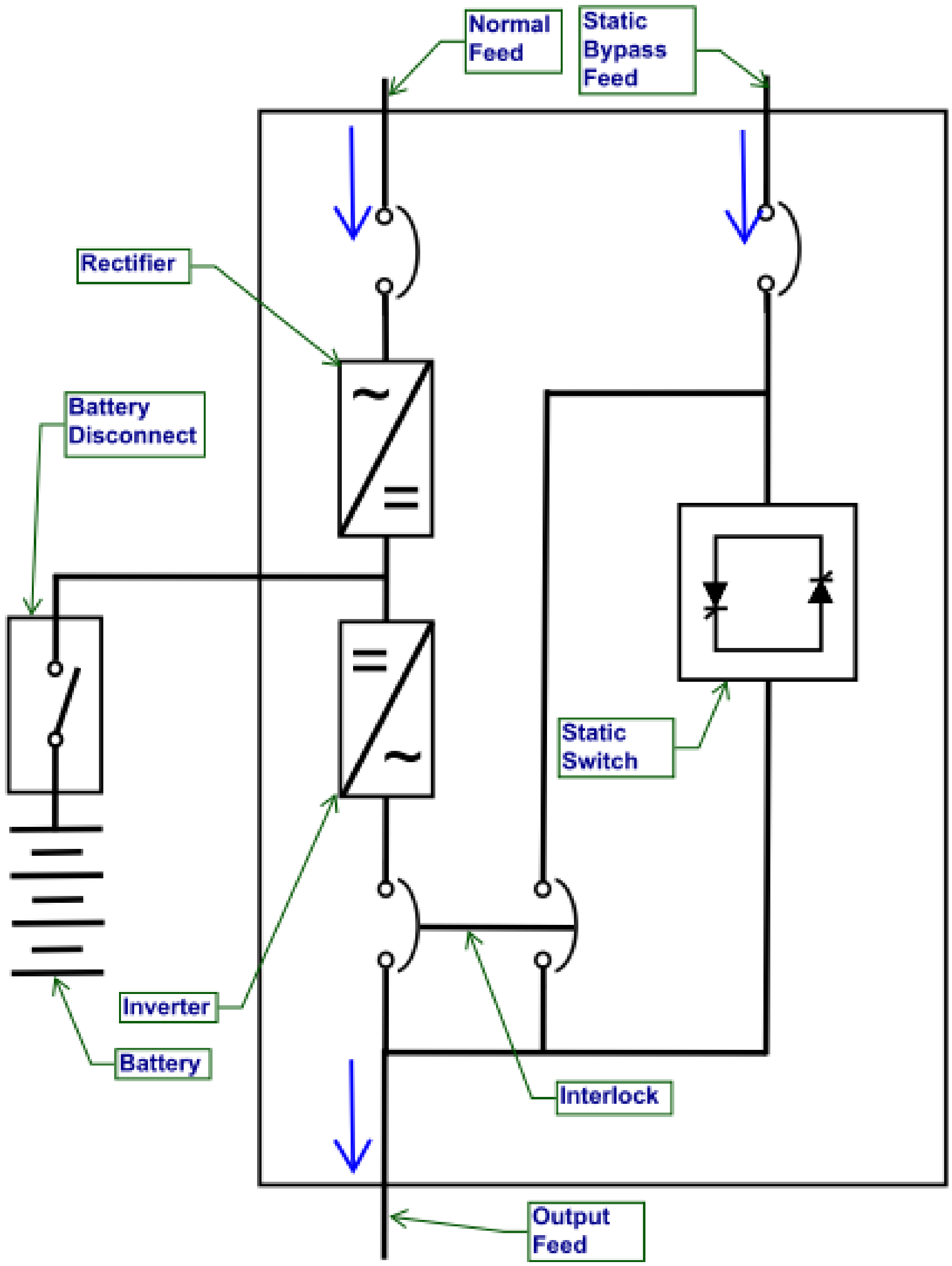


Figure F-12A
(A UPS one line symbol)

Figure F-12B shows a picture of a UPS system and a battery room.

UPS System

Battery Room

Figure F-12B
(A UPS and associated battery room)

Within the UPS topic is the availability of what is termed a Multi-module UPS, which may share a control cabinet, but has multiple modules within it to provide the power in a redundant fashion. For example, if there was 500 KVA of demand load, one could purchase a 750 KVA UPS system with three 250 KVA Modules. As will be explained later, this would provide N+1 module redundancy to the load via a single UPS system.

Within the topic of batteries, the main types of batteries used in these system are wet cell batteries (typically for larger systems) and dry cell or Valve Regulated Lead Acid (VRLA). Wet cell batteries off-gas significant quantities of hydrogen gas, which requires an exhaust system. For any mission critical UPS system with batteries, Battery Monitoring is recommended.

D. Redundancy Quantified

In the industry there is some confusion and a lack of a common acceptance among all users and stake-holders associated with the proper nomenclature for redundancy. That said, this course will define and depict redundancy in terms of system redundancy and component redundancy. The reason for the confusion should become self-evident, so it is valuable to recognize that although this course will present redundancy in the way described, there are other interpretations and paradigms through which industry experts present these terms.

Need vs. Capacity:

In order to fully appreciate redundancy and the terminology used, a discussion on *Need* versus *Capacity* must ensue. *Need* is the term for the “demand load” of the systems (i.e. how much electrical power does the system NEED to provide).

The *capacity* is the amount of power the system CAN provide. If the capacity of a power train is designed to provide the demand without any additional components, then it is considered to be an “N” system. If the system has components that can be lost and the need still met, the phrase “redundant capacity” may be used. This will be explained in further detail below. Most regular electrical distribution systems would be considered need based, and may or may not have any sort of reliability features (Generators, UPSs, etc.) built in.

N

As noted above, *N* is the term used to describe a single system or a single component within that system providing the demand need.

> *NOTE: By adding a generator to a system, some would consider that N+1 or 2N in terms of the electrical service. For the purpose of this course it will be considered that the utility service is not a highly reliable source of electrical power, therefore always requiring a generator in order for a mission critical electrical system to be considered to have a minimally acceptable level of reliability. As a result, we will graphically depict an N system to be one that has both a utility and a generator source. Just be aware that there are reasonable arguments to be made either way, and there are applications where it may be acceptable from a business decision perspective to not have both, but these are infrequent in systems that require high levels of uptime.*

Figure F-13 depicts a reliable N system with N components. It is considered reliable due to the fact that there is a generator backing up the utility service, and any critical components that require electricity at all times are fed by a UPS system that can ride through any “blips” in the power train due to the transfer of power from the utility to the generator.

The power train goes from the utility/generator to the load which is fed below the UPS.

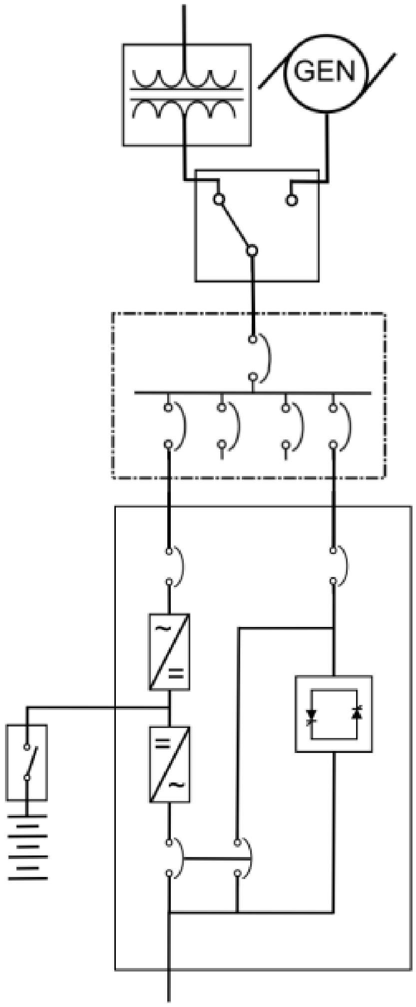


Figure F-13
(A single line of an "N" system with "N" components)

If the UPS and Generator are both sized to handle the demand need, the system is considered an N system with N components.

Figure F-14 shows an N generator system with N components. In this example, the need (N) is 750 KW and the capacity of the system is also 750 KW.

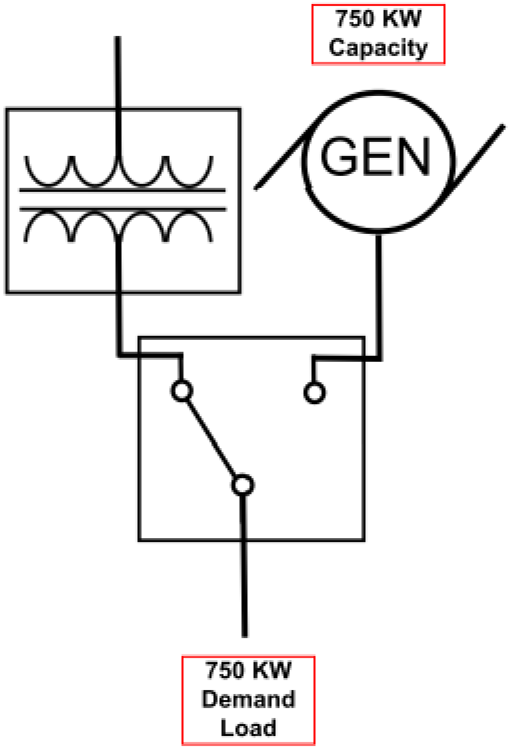


Figure F-14
(A single line of an “N” generator system with “N” components)

Figure F-15 also shows an N generator system with N components. In this example, the need (N) is 1500 KW and the capacity of the system is also 1500 KW because two (2) generators, each providing 750 KW are paralleled to provide the demand need.

It is worth noting that the system is not considered to have good “fault tolerance” due to several single points of failure (SPOFs), including the paralleling switchgear, the ATS, and the distribution components. (This of course is, as noted above, stated with the understanding that the generator system is the critical power train, and loss of the utility / utility outage is expected and therefore NOT considered “a failure”).

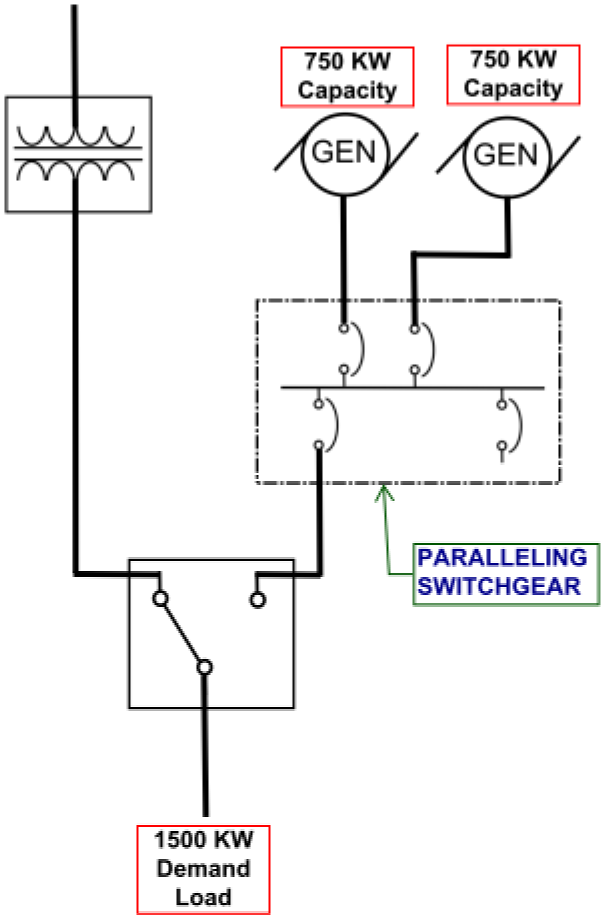


Figure F-15
(A single line of an "N" generator system with "N" components including two (2) generators designed to function in parallel)

N+1 components:

N+1 is the term used for the addition of components to the system for redundancy and to accomplish the mission of additional reliability and/or maintainability of the components. The business drivers behind why one would choose this strategy are many and are not be discussed in this course.

Figure F-16 shows an example of an N+1 configuration since the demand load is equal to the capacity / size of a single generator, and an additional generator is provided in the design. In this example, the demand load is 750 KW and the system is capable of providing 1,500 KW.

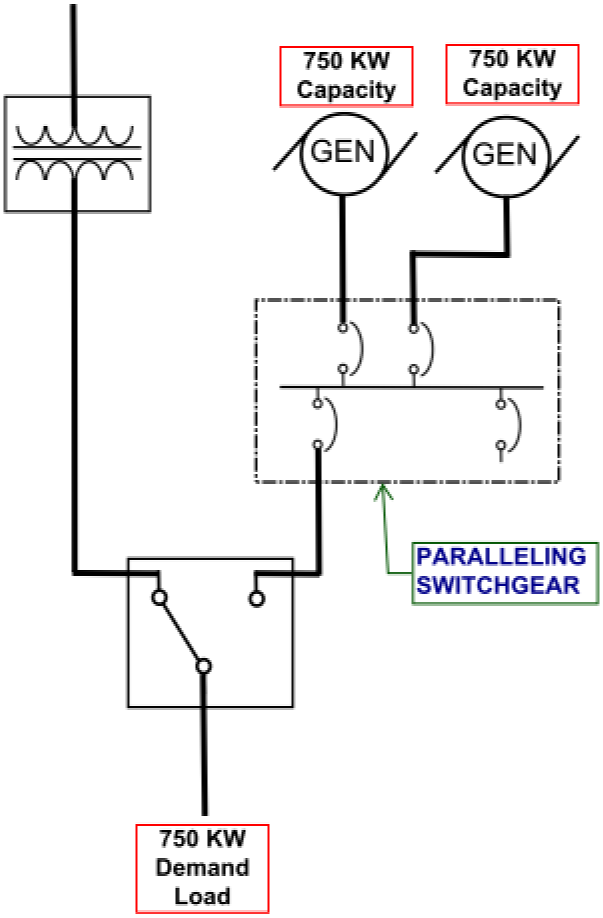


Figure F-16
(A single line of an "N" power system with "N+1" generator components)

In Figure F-16, the theoretical capacity of the system is 1,500 kW, however the "redundant capacity" of the system is 750 kW.

Some in the industry might refer to Figure 16 as a 2N configuration, and while that is arguably correct from a component perspective, that is not how 2N will be termed or depicted in this course. Rather it is preferred and generally more accepted to describe operating component redundancy in terms of "N + x"

Figure F-17 should provide further clarity as it also provides a graphical example of an N+1 configuration consisting of three (3) generators.

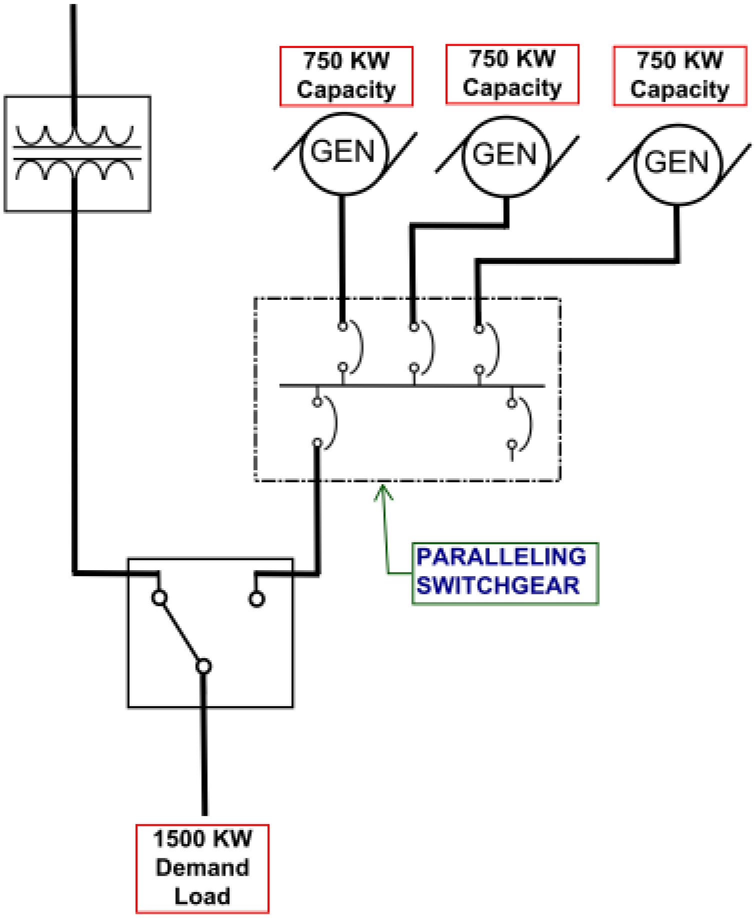


Figure F-17
(Another single line of an “N” system with “N+1” components based on demand load being 2 x capacity of the components)

Since the demand load in Figure F-17 is equal to the capacity of two (2) of the generators, an additional generator is provided in the design to create component redundancy. In this example, the demand load is 1,500 KW and the system is sized to handle 2,250 KW. The theoretical capacity of the system is therefore 2,250 kW, while the “redundant capacity” of the system is 1,500 kW.

The main benefits of an N+1 system are two-fold:

1. If the major components need to be serviced / maintained, they can be temporarily taken out of service one at a time in a planned fashion and the load will theoretically still be handled by the other components if the need arises.
2. Since all components can and will fail at some point in time, if there is a major equipment component failure, the system will statistically be anticipated to continue to ride through the event on the remaining components without dropping the load.

One can imagine that components could easily be configured as N+2, N+3, etc. These configurations are appropriate to imagine, but are not graphically depicted here. An N+2 configuration might be beneficial to ensure component reliability during maintenance, but it would probably be considered a better use of resources to install components in a 2N configuration with temporary connection points for additional components if desired to accomplish approximately the same goals, in a more fault tolerant fashion, avoiding single points of failure.

Fault Tolerance:

In this section "fault tolerance" is defined and is a term used to identify the degree to which a system does not contain any "single points of failure" (SPOFs) that will cause a loss of the load if they occur. For example, if a system has redundancy on the components that create the power, but only a single power train then most of the distribution components of the system are still SPOFs leaving the system exposed, and often difficult to maintain without downtime. So while redundant components to provide the power IS beneficial, if the system itself is not duplicated, there will still be many SPOFs leaving the system considered to be intolerant to faults.

Figure F-18 shows an example of some SPOFs in a system with redundant components.

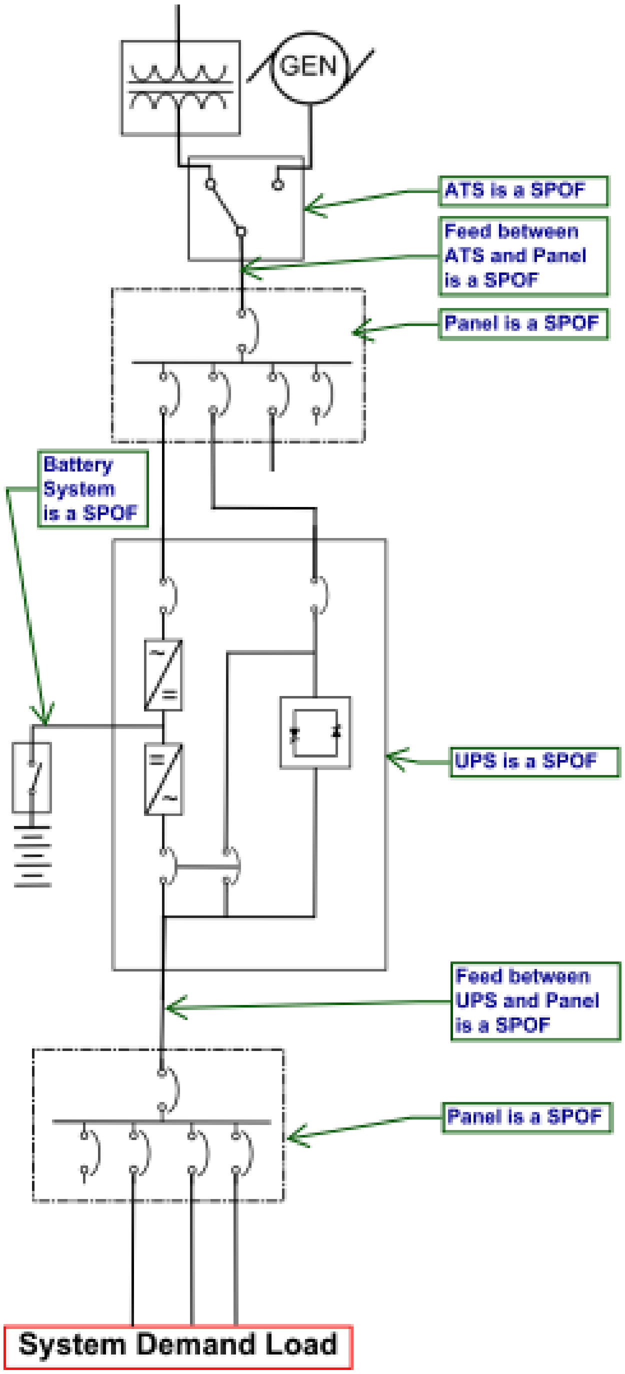


Figure F-18
(A single line of a system with some SPOF's identified)

2N systems:

2N is the term in this course used to describe **system** redundancy. This system configuration provides additional fault tolerance and will accomplish the mission of redundancy, reliability and maintainability to an entire system if desired. The business drivers behind why one would choose this strategy are also many and will not be discussed.

Figure F-19 shows an example of a complete 2N system configuration.

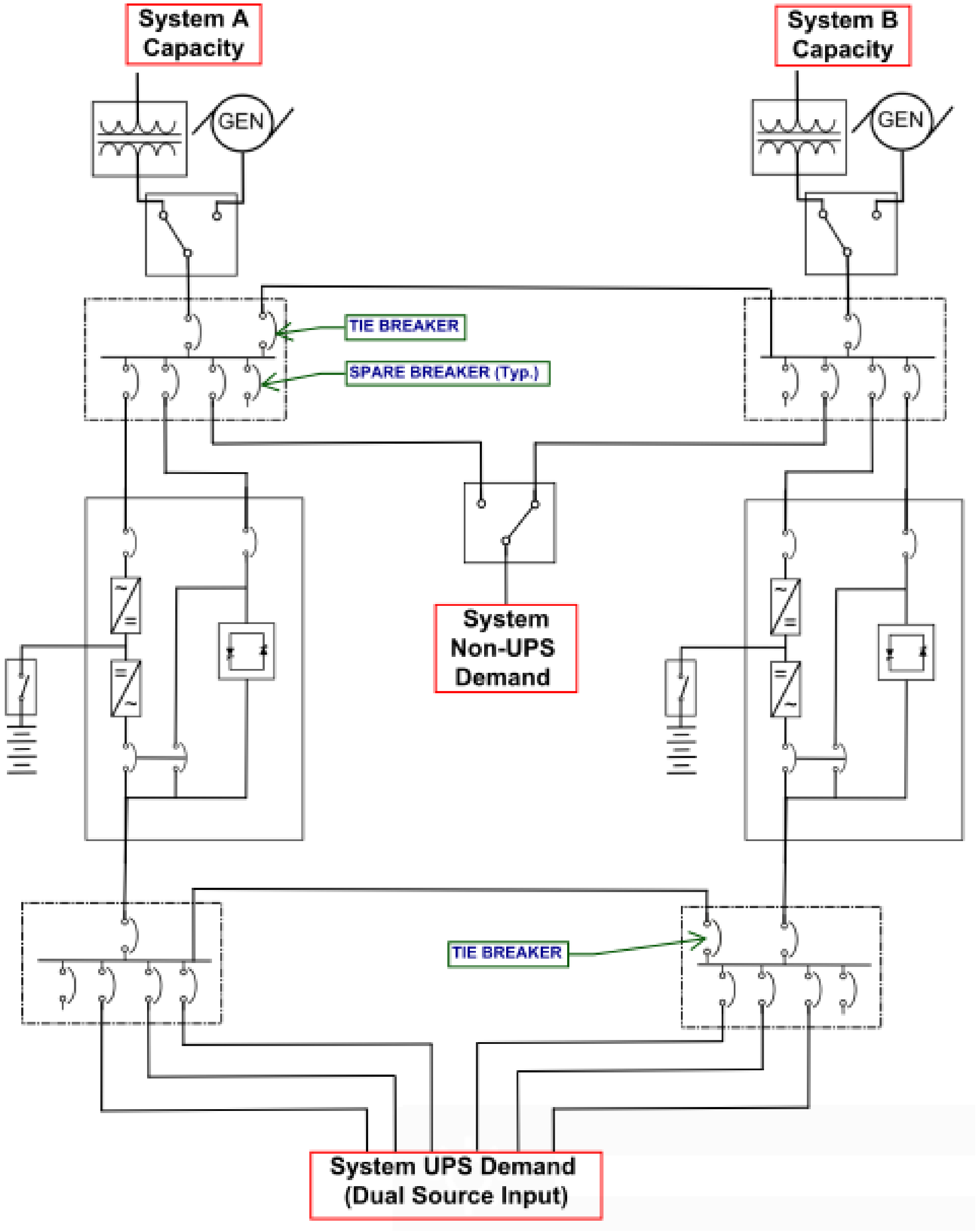


Figure F-19
(A single line of a "2N" system based on demand load being the capacity of either system)

In this example, the demand load is not defined, but is of course a combination of both the UPS and Non-UPS load. Since the 2N system itself achieves "N+1" component redundancy, it is as reliable from a component standpoint as an N+1 system, but since any component of either power train can be lost, there is more fault tolerance in a 2N system. This reflects how there is better reliability in a 2N system than an N+1 system.

Some points of interest that are beyond the scope of this course but worth noting are the "ties" (via normally open tie-breakers) that are reflected. These features are components to a 2N system that allow flexibility for maintenance purposes. Note that a "wraparound bypass" of the UPS system is NOT depicted.

2N+1

2N+1 is generally a phrase that describes an extremely redundant, fault tolerant, and maintainable system. A major reason to consider a 2N+1 system is in order to provide redundancy during maintenance scenario. One can imagine a 2N+1 generator scenario by sort of combining Figures 15 and 17, if each A & B Power train had multiple and redundant generators on each power train. In this way, either the A or the B power train can be taken fully out of service, and the remaining power train would still have redundancy while it carries the load.

This sort of scenario, while feasible, begins to get extremely costly from a constructability and budgeting standpoint and there are options that can minimize the need for this even if this degree of maintainability is desired. For example, if it truly is required that a system have redundancy while being maintained, "a swing" component can be designed that can function on either buss requiring only three (3) generators or three (3) UPS systems instead of four (4). This would bring down the cost somewhat. Or, instead of purchasing the swing equipment, the switchgear on each power train can be configured with a spare breaker sized to accommodate a temporary "roll-up" generator. In this way, the facilities team can plan maintenance windows around planned equipment rentals, and serious capital expenditures can be saved in the design.

Of course the best way to decide what is best for a facility is to know the business needs of the enterprise and engage a qualified engineer with experience in mission critical reliability design.

Hybrid Options

There are many configurations available that an experienced design engineer can use to value engineer, cut back, and/or save the owner money; depending on the budget availability. There are many of these kinds of opportunities available within a project, and the experienced engineering team understands all of the nuances and knows many ways how to get the client the best "bang for their buck", based on their program goals and budget. Ultimately these things are a business decision for the owner, but understanding the options helps provide guidance to the best decision for the enterprise.

As an example, a "maintainable UPS" scenario might be a "scaled back" hybrid of a 2N system. In this sort of example, there are basically two (2) power trains, but only one of them delivers power on UPS. While some owners may require having two (2) UPS systems, some may recognize that being on generator is typically very reliable once the generator is up and running, so maintenance and/or replacement of the UPS in the maintainable UPS design scenario feasibly occurs on generator power, *or* a rental UPS can be obtained and connected in a planned fashion during the UPS maintenance window for added protection.

This kind of approach would save capital dollars to complete the project, and a second UPS can always be added later if further funding becomes available. In a similar way, the facility could be designed "day one", with two (2) power trains and only one (1) of them has generator backup. There are plenty of options to provide an owner with a robust, scalable solution that they can grow into with their need.

Figure F-20 shows an example of a "maintainable UPS" scenario referenced above.

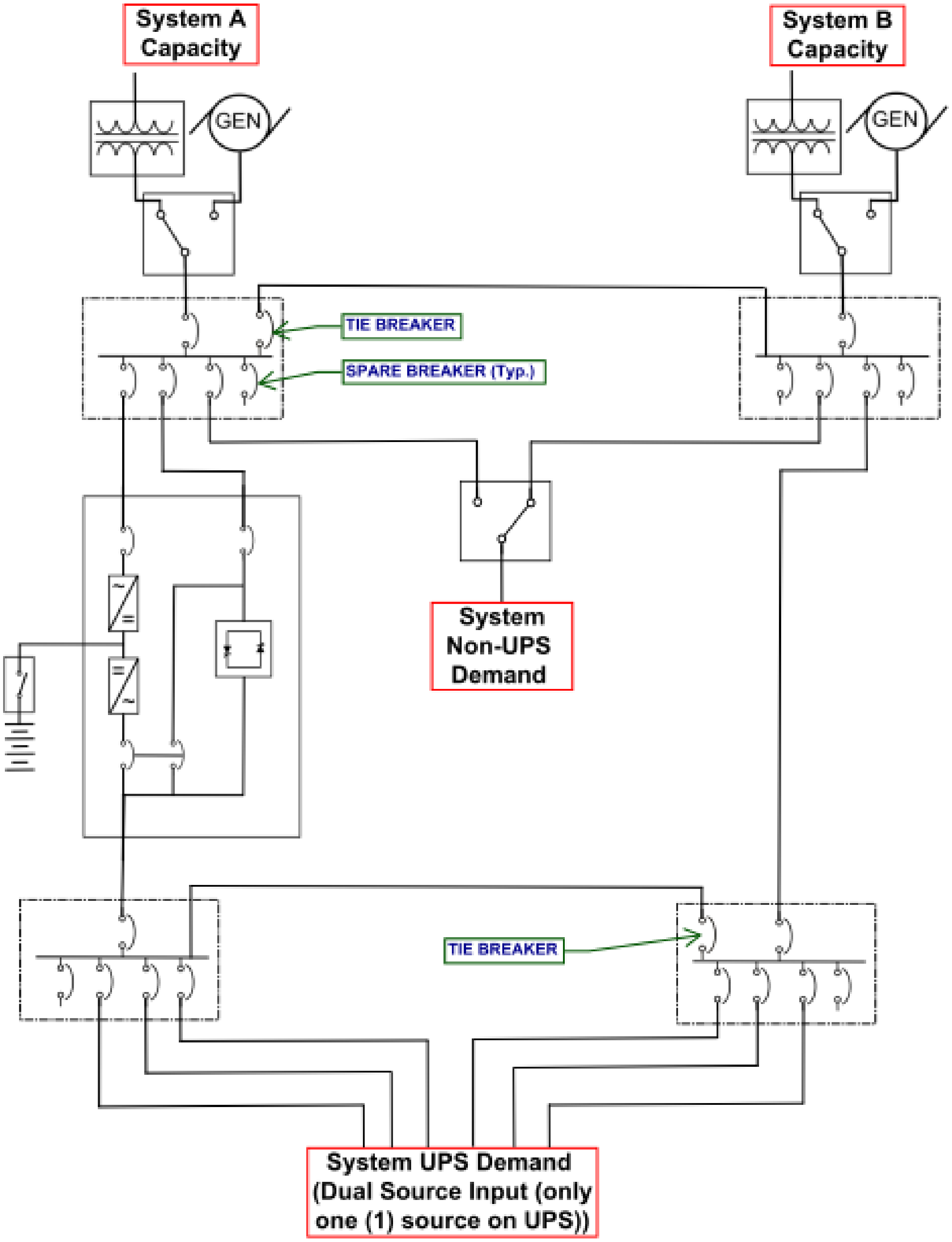


Figure F-20
(A single line of a "Maintainable UPS Design")

E. Summary and Conclusion

This course provided an introduction to reliability associated with the electrical systems supporting mission critical applications. The student of this course should now be able to have knowledgeable high level conversations regarding reliability, redundancy, fault tolerance and maintainability of mission critical systems as well as a working knowledge of some of the most common components that these systems consist of.

Reliability is an important topic for any engineer and facilities manager to be familiar with, especially as relates to the degree they are required to design, manage, or expected to comment on mission critical systems.