

Implementing Nanogrid Into the Critical Facility

Improving Reliability, Efficiency, and Future Adaptability

A Technical Paper prepared for SCTE by

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1. Introduction

As cable broadband networks evolve to meet capacity and performance expectations – pushing legacy functions outward toward the edge – critical facilities are challenged to maintain reliability, forcing operators to revisit their power architectures. The ever-growing reliance on high-speed network connectivity are driving the transition to distributed access architectures, with Remote-PHY Devices (RPDs) in edge nodes taking on much of the work that had been traditionally performed in critical facilities. High-density virtual CMTS (vCMTS) and edge gateway server racks are replacing legacy equipment in the critical facility, increasing network capacity and performance, but at the cost of increased energy consumption and associated thermal loading. Heating Ventilation and Air Conditioning (HVAC) systems, not traditionally backed up by batteries, may need to be reconsidered as a critical load. As described in SCTE 184, “Modern equipment densities can overheat an environment in less than an hour without adequate cooling making any additional installed capacity unusable.”ⁱ

At the same time, external threats to the utility grid – extreme weather events, electric vehicles, heat pumps and air conditioning units – are leading to more frequent and longer utility outages, adding to grid instabilityⁱⁱ, and placing more reliance on the effectiveness of the power backup system. This combination of increasing grid instability, reliability expectations and added thermal load may drive operators to revisit their existing critical facility (CF) power architectures.

In addition to increasing reliability, operators are focused on meeting their corporate sustainability goals toward reducing overall energy consumption and reliance on fossil fuel sources^{iii,iv}. Improving power efficiencies in the critical facilities and introducing distributed energy resources can help these efforts^v. A nanogrid architecture can allow the use of distributed energy resources (DERs) such as wind or solar to supplement utility power, allowing operators to realize additional cost benefits by avoiding peak usage utility rates or selling power back to the grid^{vi}.

In this paper we will:

- 1) Walk through a complete critical facility outage with today’s architectures.
- 2) Identify threats to critical facility reliability.
- 3) Look at how changes to critical facilities will lead to additional reliability challenges.
- 4) Explore nanogrid architectural steps that could be implemented to increase reliability.
- 5) List additional benefits from moving to the proposed nanogrid architecture.
- 6) Anatomy of a Critical Facility Blackout.

Figure 1 shows a diagram of a typical high-level medium sized cable broadband critical facility (CF). Utility power supports the entire facility through the Essential AC bus, with on-site generators (GEN 1 and GEN 2) to maintain operation during utility outages. Figure 1 shows two Automatic Transfer Switches (ATs): the Utility-to-Generator (UTG) and Generator-to-Generator (GTG). The UTG detects the loss of the main power source (the utility) and automatically switches to power from the generators. The GTG selects which generator to connect. In the event of a prolonged outage, operators can bring a portable generator (PORT GEN) and, using the Manual Transfer Switch (MTS), start supplying energy to the CF.

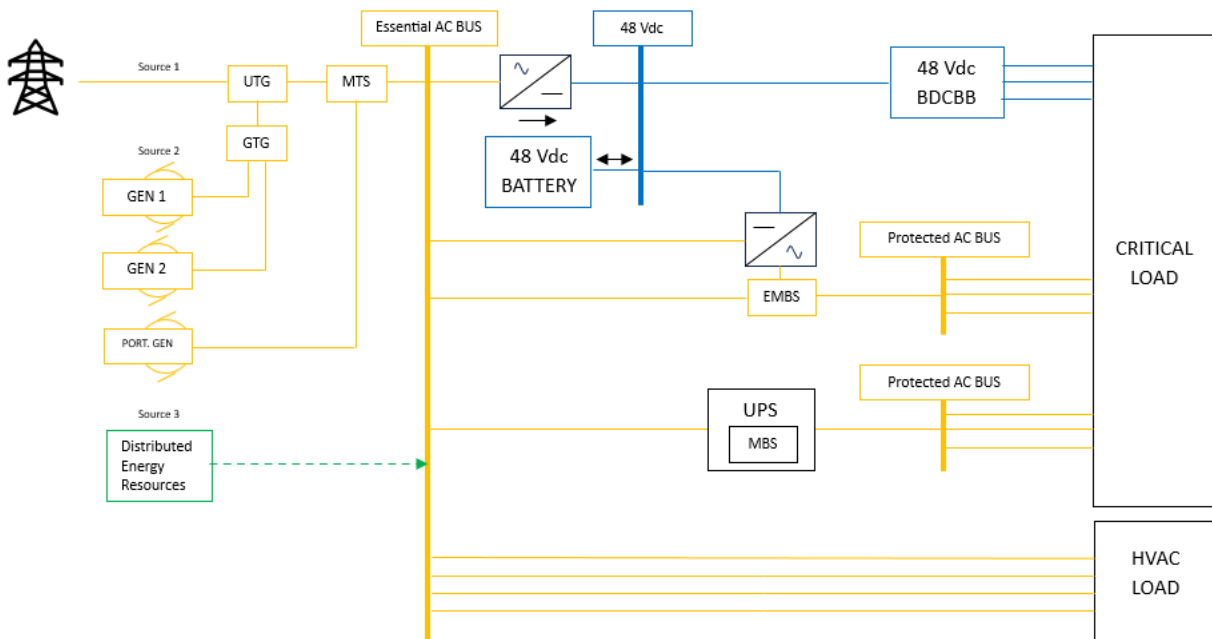


Figure 1 - Example of Present Powering Architecture in a Critical Facility

1.1. Critical Facility Power Elements

The Essential AC bus is the common point from where the different loads throughout the critical facility are fed, with various power conversions and battery backup. The Essential AC bus also supplies the Heating, Ventilation, and Air Conditioning (HVAC) load, which oversees keeping the operating temperature of the CF. In this architecture, the HVAC system is not supported by batteries. If both the utility and the generators are lost, the HVAC system ceases to work.

Critical loads (CL) include all IT equipment such as servers, routers and CMTS racks whose operation is deemed absolutely necessary for maintaining network operations. In the present architecture, the CL must be supported for a typical period of 2 to 4 hours when utility power and the generators fail. To support the CL, there is a 48VDC bus supported by battery energy storage. A unidirectional AC to DC converter (rectifier) charges the batteries and provides power to the CLs.

Most CLs accept 48VDC as input power and can be fed directly from the 48VDC bus through a Battery Distribution Circuit Breaker Bay (BDCBB). This provides very high source reliability and continuity.

A portion of CLs must run from AC. To supply these loads and support them in case of outages, the CF has a Protected AC Bus that is supplied from the 48VDC bus through a unidirectional DC to AC converter (inverter). During an outage, the inverter supplies power to the load until the batteries are exhausted. The connection includes an External Maintenance Bypass Switch (EMBS) which allows the inverter to be disconnected for maintenance.

Finally, the CF designers may want to include Distributed Energy Resources (DERs) such as solar PV or wind to help achieve the company's sustainability goals, lower the energy bills, and in some cases extend the runtime of the batteries. The Essential AC Bus also provides the point of common coupling for the DERs. However, integrating diverse DERs into the AC bus is more complex than integrating them using DC, due to the need to match the AC frequency, phase, and voltage^{vi}.

1.2. Figure 1 Utility Power Outage

Figure 2 shows a time diagram of a utility power outage followed by a loss of the generator backup. At the beginning, the HVAC and CL are running from the Utility AC Grid. At instance (1), the CF loses power from the Utility, the ATS (the UTG) connects to the Generator, and the Generators start supporting the HVAC and the CL. During this period, the HVAC regulates the temperature at a safe level. After some time, at instance (2), the Generator is lost, and the CL must run from the battery storage. This can last for between 2 to 4 hours, until the batteries are exhausted in instance (3). However, in this condition, the HVAC is not working, and the temperature starts to increase since cooling is only due to the natural air flow in the CF. Depending on the power density of the CF, within a short period of time it will reach the Critical Temperature, at which point the CL will be dropped.

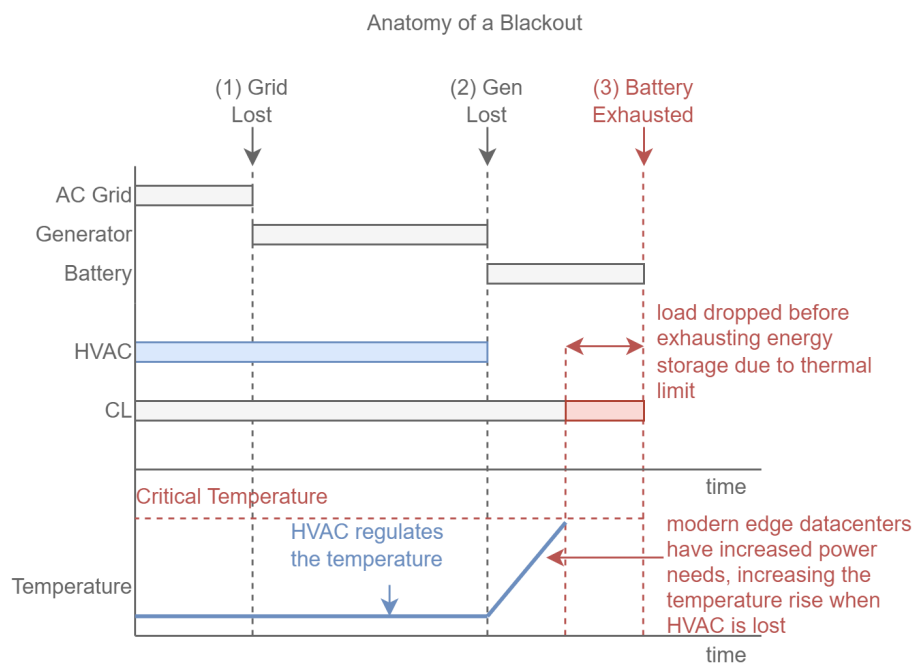


Figure 2 – Critical Facility Outage Time Diagram

2. Reliability Weaknesses with Today’s Critical Facility Architecture

The current CF architecture shown in Figure 1 has been serving well for years, but new emerging technologies are pushing the limits. The current architecture can have several critical risk factors that compromise its reliability: the generator, the ATs (GTG and UTG), the HVAC, and the batteries.

2.1. Generator Failure

The generator is made of thousands of parts and pieces, all required to function properly to provide backup power. As such, the generator reliability can be a risk factor.

2.2. Automatic Transfer Switch Failure

As shown in Figure 1, the Utility-to-Generator (UTG) detects the loss of the Utility Power and automatically connects to the generators (GEN 1 or GEN 2). If the UTG fails and does not perform its function, there is no redundant component that can connect to the generators. At this point, the CL starts drawing power from the 48VDC battery bus. However, the HVAC, not supported by the 48VDC battery bus, will not be running. This greatly increases the chance of either exhausting the batteries or reaching critical temperature before the utility power is restored or the portable generator is connected. The inverse problem can also happen: the UTG can remain in the GEN position, even when the Utility outage is resolved, causing the system to exhaust the fuel and batteries, resulting in dropping the CL.

A similar problem can be observed with the Generator-to-Generator (GTG) ATS. The GTG may make the wrong decision (connecting to GEN 1 when it should connect to GEN 2), or it may fail to perform the action. Transfer Switches are complex devices with mechanical, electrical, and software components. They have a relatively high failure rate.

2.3. Loss of HVAC

Figure 1 indicates how the HVAC is connected to the Essential AC Bus. In this architecture, energy flows into the Essential AC Bus only from the Utility, GEN1, GEN2, or PORT GEN. This is important since it implies that the HVAC system is not supported by the batteries. To support the HVAC system from the batteries, the AC/DC battery charger should be bidirectional and there should be many more batteries.

A loss of the HVAC system does not immediately trigger a failure based on temperature. Forced air circulation can delay temperature increase long enough to connect the PORT GEN. However, as power density increases, loss of the HVAC system will result in the failure of the CL.

2.4. Battery Reliability

Battery reliability is high when batteries are properly maintained and in a controlled temperature environment.

3. Evolving Critical Facility Changes Will Add to Reliability Concerns

3.1. Increasing Energy Demands

As an example, the CL energy requirements per rack for a medium facility may grow by 40% in the upcoming years. Since the HVAC continues to be sized at a one-to-one ratio of cooling to power, the facility will need 40% additional HVAC loads.

3.2. Higher Loads Make HVAC Critical

Modern edge datacenters are increasing in power and power density. In this condition, there is more heat to be removed from the CF. Current load densities will raise the temperature above the critical temperature threshold in less than one hour without support from the HVAC system^{vii}. The CL will be dropped before the Battery Energy Storage System (BESS) and DERs are exhausted. Given this scenario, it becomes clear that the HVAC needs to become part of the CL. The advanced infrastructure will need to support the HVAC load. Supporting the HVAC load requires higher DC voltages to be able to distribute available power from the BESS to the HVAC.

3.3. Utility Grid Strains Leading to Increased Reliance on the ATS

The CFs will have to perform under significantly more stress due to the increase in Utility power outages and at significantly higher reliability levels. Data from the U.S. Energy Information Administration (shown in Figure 3) shows that utility outages are increasing. Moreover, this increase is driven by major events (snowstorms, hurricanes, and wildfires), which are expected to keep increasing in frequency and severity. Each outage event is one chance for the ATS to fail, increasing the probability of a failure.

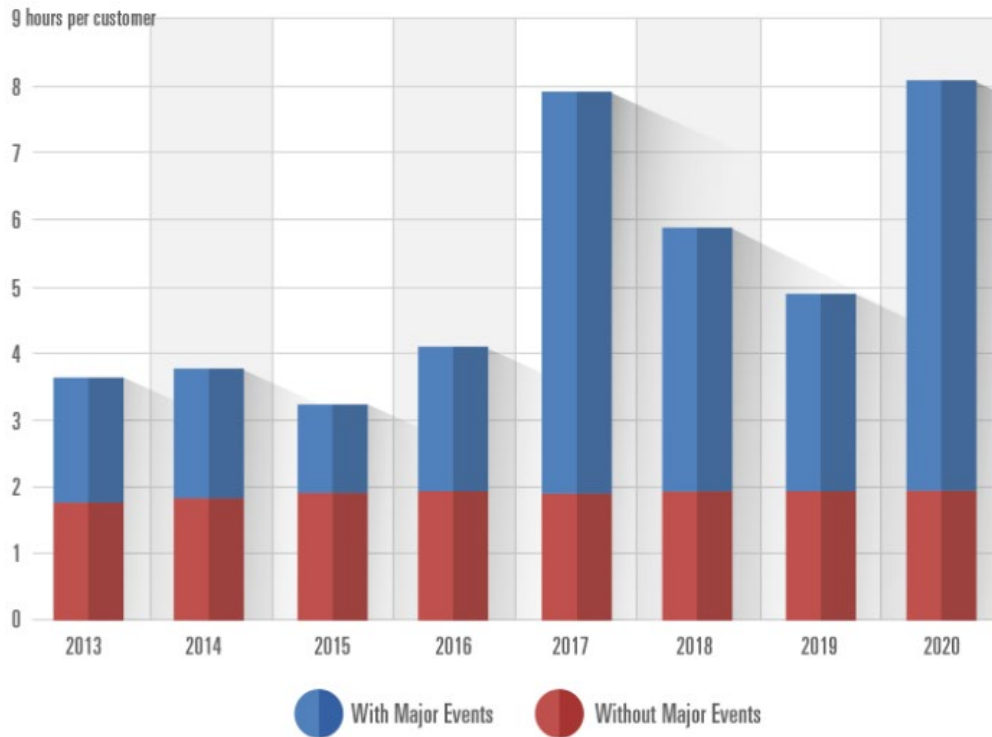


Figure 3 – Average Duration Total Annual Utility Power Interruptions, United States (2013-2020)ⁱⁱ

Other industry trends such as autonomous vehicles, IoT, smart city applications, and industry 4.0 solutions push the reliance on the internet infrastructure. Future applications that rely on an underlying, high bandwidth, low latency data network will impose further restrictions on the reliability of the CF.

4. Implementing Nanogrid to Address Power Reliability

This section outlines a new proposed CF architecture to overcome the reliability challenges, increase efficiency, and simplify integration with DER. The proposed architecture is based on a DC nanogrid concept using a higher DC voltage essential bus. This section also presents three transition architectures to illustrate the possible evolution from the current architecture to the final proposed architecture. A full migration to the final architecture would be required to benefit from the proposed reliability increases.

In the context of this paper, a nanogrid utilizes the common concepts found in a microgrid but for a building-size microgrid.

4.1. Transition #1: Distributed Energy Resource Connectivity

Figure 4 shows a diagram of the Transition Architecture #1. This architecture shows several significant changes with respect to the architecture in Figure 1. Namely:

1. The AC to DC converter linking the Essential AC bus and the 48VDC bus is now bidirectional. This allows the DERs to be connected to the 48VDC bus and then transfer their energy to the essential AC bus.
2. There is now also a high voltage DC bus (380V in this paper) supported by 380V batteries. This bus can support some native 380VDC CLs which are now emerging. The 380VDC bus is linked to the 48Vdc bus through a bidirectional DC to DC converter, which allows it to run from the 48VDC battery backup and even support it. The loads are directly connected using a 380VDC BDCBB.
3. The DERs can now be connected either to the Essential AC bus, the 48VDC bus, or the 380VDC bus. Integrating DER at the 380VDC level is straightforward as it does not require synchronization and uses less power conversion stages (e.g., typical applications of PV use 600VDC or 1000VDC arrays, which are allowed by the NEC^{viii}, integrating at the 380VDC level requires just a simple DC to DC converter).

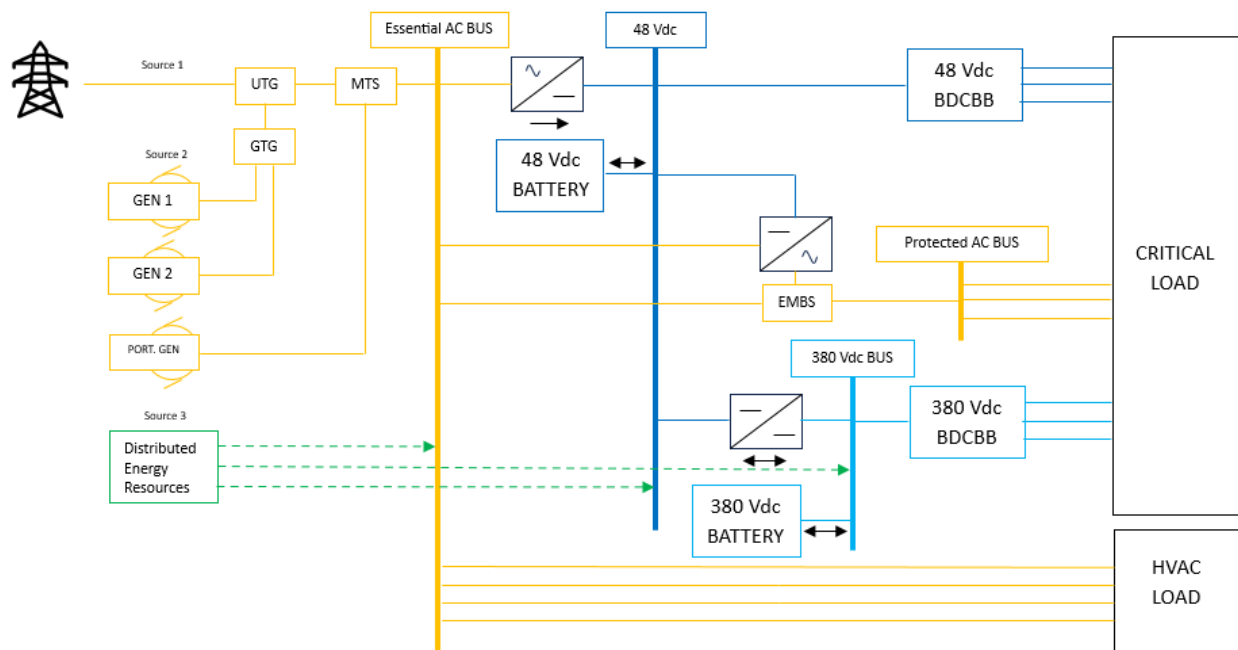


Figure 4 - Transition Architecture #1

Although the Transition architecture #1 provides improvements in efficiency and allows better integration of DERs, it still has the same critical reliability problems: the HVAC is not supported by the batteries and the ATS is a critical risk factor. Furthermore, integrating DERs at the 380VDC level can result in lower efficiency if the energy must be transferred to the Essential AC bus for utilization.

4.2. Transition #2: Protected 380VDC bus

Figure 5 shows a diagram of Transitional architecture #2. This architecture shows a significant change with respect to Transitional Architecture #1 in Figure 4: The high voltage DC bus (380VDC in this case) is fed from the Essential AC bus, instead of the 48VDC bus, using a bidirectional AC to DC converter. This arrangement reduces the number of power conversions needed to feed the 380V load and charge the batteries, increasing the efficiency of the system. Furthermore, it reduces the number of power conversion stages needed to feed the energy from the DERs into the Essential AC bus.

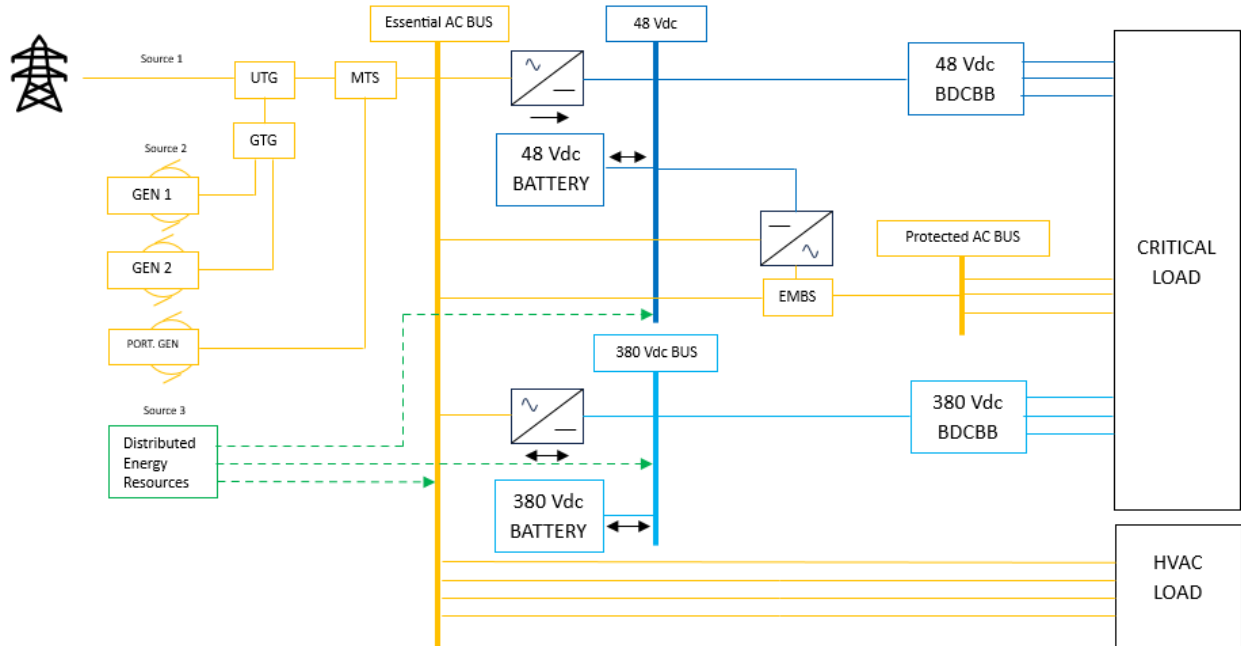


Figure 5 - Transition Architecture #2

Although the Transition Architecture #2 provides improvements in efficiency and integration of DERs compared with Transition Architecture #1, it still has the same critical reliability problems: the HVAC is not supported by the batteries due to capacity concerns and the ATS is a critical risk factor.

4.3. Transition #3 / Final Proposed Architecture: Protected DC Bus

Figure 6 shows a diagram of the proposed advanced nanogrid CF architecture. Compared with the architectures in Figure 1, Figure 4, and Figure 5, the proposed architecture includes the following changes:

1. This advanced nanogrid architecture implements the creation of a protected 380VDC bus, where all the sources and loads are connected. This replaces the essential AC bus.
2. Multiple energy sources:
 - a. Source 1: The utility connection will be transposed using bidirectional rectification. It will be modular and use redundant components like the rectifier stages in Figure 1. A contactor could be provided which could provide islanding of the electrical system if desired.
 - b. Source 2: The Generator(s) (GEN1, GEN2, and PORT GEN, if available) connect to the system using a unidirectional AC to DC converter (a simple rectifier). It will be modular

- and use redundant components like the rectifier stages in Figure 1. The output of the rectifier is DC, eliminating the need for AC synchronization.
- c. Source 3: Utilizing a Battery Energy Storage System (BESS) which supports the protected 380VDC bus, potentially using a DC-to-DC converter. It will be modular and use redundant components like the rectifier stages in Figure 1.
 - d. Source 4: The DERs are connected directly to the protected 380VDC bus.
3. The HVAC load is fed from the protected 380VDC bus using a DC to AC inverter system, and therefore is supported by multiple sources of energy. Alternatively, the HVAC could use 380VDC directly as equipment becomes available. This allows the cooling function to continue.
 4. An ATS is no longer required; the generators are attached to the protected 380VDC bus by using rectification.

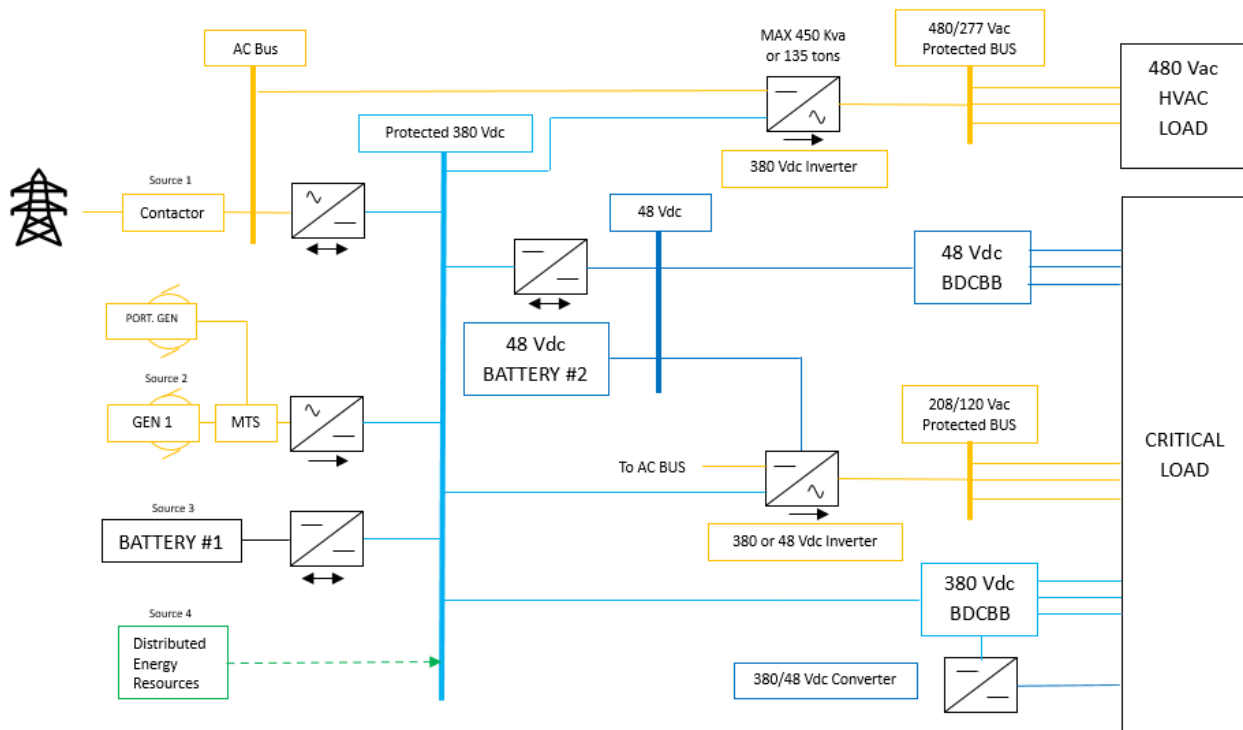


Figure 6 - Transition #3 / Final Proposed Architecture

The proposed nanogrid architecture addresses the major critical reliability factors – supporting the CL while providing the required cooling.

Figure 7 shows an updated time diagram of a utility blackout. Using the proposed architecture, the HVAC system is supported by the BESS and DERs. If the generator is lost in (2), the temperature of the CF is still controlled by HVAC system. This allows the facility to use the entirety of the BESS and DER. If DERs are available, they can help support the load and batteries during the blackout to extend the runtime of the CF.

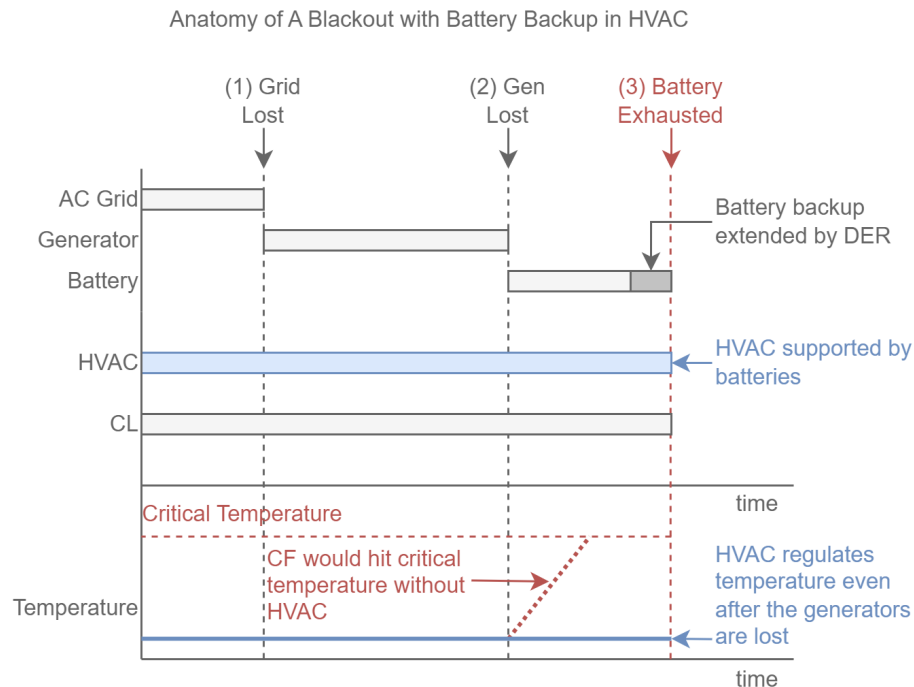


Figure 7 - Critical Facility Outage Time Diagram with the Proposed Architecture

5. Additional Benefits in Efficiency and Adaptability

The proposed nanogrid architecture can directly mitigate the major critical reliability risks associated with CFs; however, this is not the only benefit. Using the 380VDC bus architecture provides reduced losses in power transmission and simplifies integration of DERs.

5.1. Efficiency Gains by Using High Voltage DC Distribution

Using a protected 380VDC bus, allows the power distribution to be done at higher voltage (380VDC compared to 48VDC). Using 380VDC has the significant advantage of reducing losses in the DC distribution.

Using a 380VDC distribution can significantly reduce the number of conductors needed to route power to the loads. For example, an arrangement of cables (72 750mcm cables) in a tray can carry 359kW at 48VDC or 2.5MW at 380VDC, almost 7 times more power. Furthermore, a smaller arrangement of cables (12 750mcm) can carry over 85% more power at 380VDC than the 72-cable arrangement at 48VDC^{ix}. This is an 83% reduction in conductor costs while increasing power delivered by 85%.

5.2. Distributed Energy Resources Adaptability

Integrating DERs at the 380VDC level is significantly easier than integrating using an AC bus and more efficient than integrating at a 48VDC level. This improved integration of DERs can allow operators to achieve their sustainability goals by using more renewable energy sources.

Using the bidirectional AC-to-DC grid interface, the CF can interface the grid and provide power from the renewables to support it. Typical applications may include frequency support and reactive power compensation.

6. Conclusions

This paper presented an analysis of existing critical facilities for cable broadband applications from the point of view of energy consumption and reliability. It describes the current architecture and impacts on the facility performance during an outage. Two critical areas for improved reliability were identified:

- 1) Adding battery backup to support the HVAC load.
- 2) Reducing the reliance on the ATS.

This paper proposes using a high voltage DC nanogrid architecture for the critical facility power system. Replacing the essential AC bus with a high voltage protected DC bus (380VDC in this example) not only allows more efficient power distribution, but also simplifies integration of the battery energy storage system and distributed energy resources.

Incorporating DERs can also help operators meet their sustainability goals by reducing utility consumption and implementing other operating modes, such as peak shaving and demand side management.

Abbreviations

BDCBB	Battery Distribution Circuit Breaker Bay
BDFB	Battery Distribution Fuse Bay
BESS	Battery Energy Storage System
CF	Critical Facility
CI	Critical Infrastructure
CL	Critical Load
CMTS	Cable Modem Termination System
DCDC	DC to DC voltage transformation
DER	Distributed Energy Resources
GTG	Generator-to-Generator
HVAC	Heating Ventilation and Air Conditioning
MTS	Manual Transfer Switch
PORT GEN	Portable Generator
PFC	Power Factor Correction
RPD	Remote-PHY Device
UPS	Uninterruptible Power Supply.
UTG	Utility to Generator

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