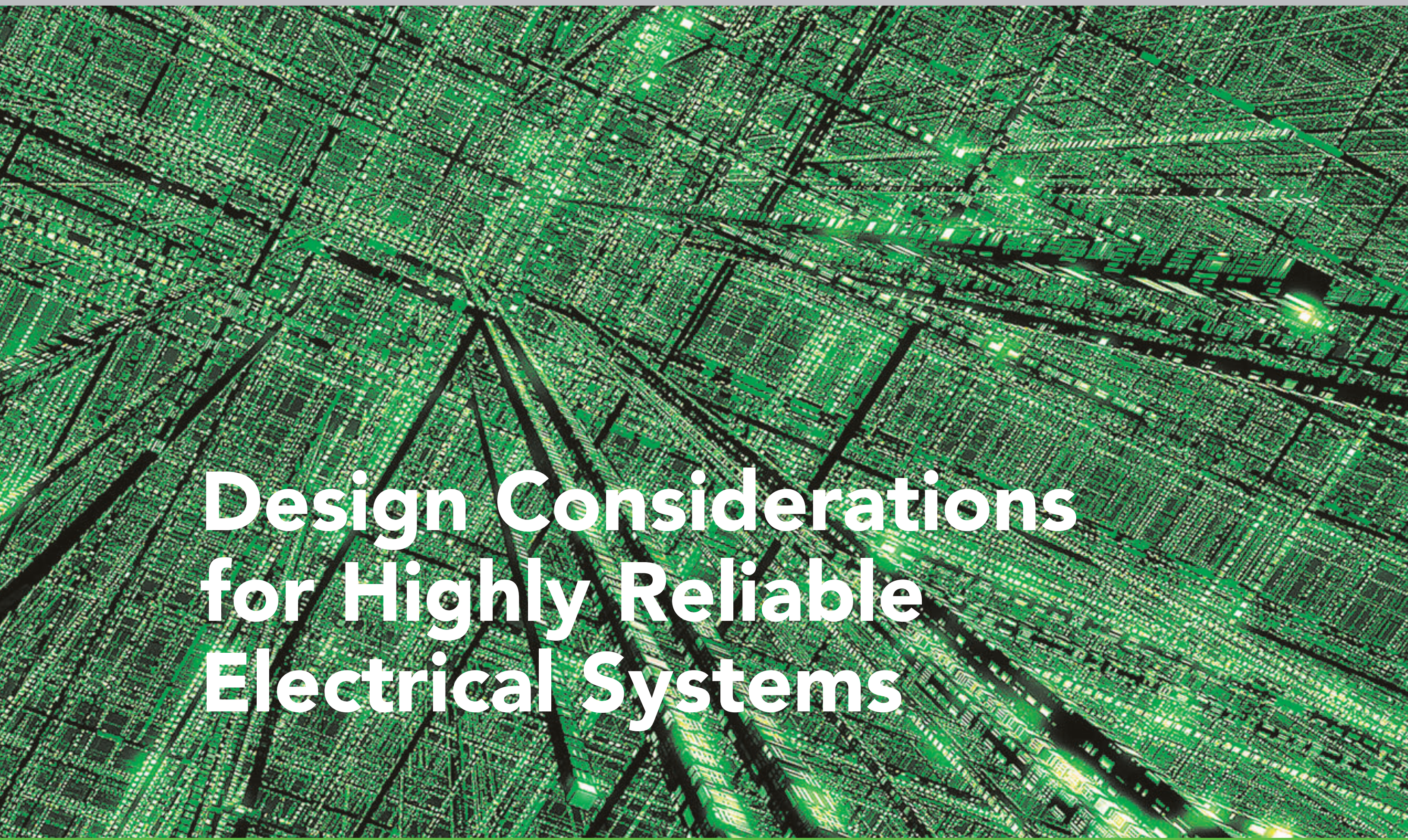

Design Considerations for Highly Reliable Electrical Systems

By Dennis Julian

Designing highly reliable electrical systems requires a holistic view of the complete system. Consideration must be given to installation specific issues and phasing, experience level of the operators, how the system will be operated, how the owner intends to use the system, the required level of availability, future expansion or modification and preventative maintenance.

Let's review some of the features and design considerations that should be explored during design. There is no cookie cutter approach or design. Each project and owner has requirements, goals and cost considerations that must be met. A successful design meets these stipulations.

The electrical system design must be tailored to meet the requirements of the project. This does not mean each project must be a completely custom design. A design should be developed that uses standard designs, components, assemblies, control software, etc that is assembled to meet the goals of the project. This allows tried and true designs to be used that have been continuously improved over many projects resulting in fewer potential problems and unknowns during construction, start up and commissioning.

Distribution Voltage

In general, the higher the distribution voltage the more cost and energy efficient the system is. For large loads medium voltage (greater than 601V in North America and or 1000V elsewhere) can be used to minimize losses and ampacity requirements of equipment and conductors. Medium voltage distribution requires a higher level of training for personnel due to the increased risks inherent in operating equipment that carry higher amounts of power. Multiple large generators in parallel can quickly require high ampacity equipment with high short circuit fault duty. The use of medium voltage generators (maximum of 15 kV) can make the ampacity and short circuit currents more manageable. Since the utility power source and the generator source may be of the same voltage, the system design must be careful not to introduce single points of failure like using a common transformer to get to the utilization voltage.

Higher IT equipment utilization voltage will increase energy efficiency and reduce installation costs. The use of 120/208V systems provides a maximum of 208V at the IT equipment.

To get the 120/208V power from the typical 277/480V requires service voltage transformers. This additional equipment increases installation costs and energy loss while providing an additional level of power isolation from the power source. Using 230/400V distribution systems increases the IT utilization voltage thereby increasing energy efficiency and reducing installation costs. For maximum efficiency and to minimize cost the service voltage should match the UPS systems input and output voltage. Some installations are using 277/480V power for the IT equipment. This has the same advantages as the 230/400V system with the added advantage of being a higher voltage with its inherent efficiency improvements and it is the typical distribution voltage used in North America. The disadvantage is that 277V IT power supplies and receptacles are not standard equipment at this time. Using 230/400V or 277/480V IT distribution voltages require the system design to use 4 pole circuit breakers or ATS switches to maintain isolation of the neutral between the generator and utility power sources.

DC power distribution systems operating at 380 or 550 volts are another efficient distribution system that minimizes the number of power conversions and therefore experiences less efficiency losses. Similar to the 277V distribution systems the equipment availability may limit the opportunities to maximize its use.

Distribution Equipment

Equipment selection is influenced by the level of availability, quality desired and the available budget as determined from the answers to the questions about project goals.

Often, the terms switchgear and switchboard are used interchangeably when in fact there are differences between UL 1558 switchgear and UL891 switchboard construction. Both can be used, but the additional cost of switchgear also provides additional features not typically available in switchboard construction. In simple terms, switchgear is more rugged and heavy duty than switchboard construction. Switchgear construction provides better separation and compartmentalization thereby limiting damage between components. Switchgear is generally larger, heavier and requires rear access. Switchboards can be more compact, lighter and in tight spaces can be front access only. Generally switchboards are less expensive and have shorter manufacturing times.

The automated operation of switchboards/switchgear occurs through programmable logic controllers (PLC). For redundancy, dual PLCs can be provided with one taking over immediately if the other fails. The sequence of operation needs to be detailed and account for each operating and failure scenario. The system should be designed to "seek any source" so it will cycle through the available power sources until an acceptable one is found. Redundant control power sources should be specified so that if any power source is available the controls will have power. Battery backup will allow the controls to continue operating even during power failures. Designing the generator start circuit to be normally closed will allow the generator to receive a start circuit even if all control power is lost thereby providing the controls with an alternate power supply to allow the control system to be reenergized.

Transfer systems can be circuit breaker (CB) type incorporated into the switchgear/switchboard or separate automatic transfer switches (ATS). Four pole CBs or ATSs should be used if the distribution system requires a neutral connection from the utility and the generator. This will provide isolation between the systems allowing either to operate independently and allowing protection relays to operate correctly.

Uninterruptible power supply (UPS) systems come in a variety of designs. They can be solid state type or mechanical (rotary) type. The can be off line (standby), line interactive or double conversion. They can have various modes of energy efficient operation including powering the load from a continuously rated static switch thereby minimizing the system losses to 1 or 2 percent or can automatically put unneeded modules in a multi module system into an idle mode to increase the system efficiency. Both of these modes are automatic and revert back to normal operation if input power or load is outside of predetermined set points.

120/208V IT distribution systems fed from 600V or 480V systems will require transformers (PDUs). The type of PDU selected can affect the system efficiency, potential arc flash hazard and may become a single point of failure. Transformers have no load and load losses. No load loss is the energy required for the transformer to operate and is present whenever the transformer is energized. Load loss varies with the load on the transformer. Most transformers are not fully loaded. Efficiency ratings at full load are therefore not representative of how they will actually operate. Energy standards such as NEMA TP1 (similar to DOE level CSL-1) are based on determining efficiencies at part load (35%). NEMA premium efficiency transformers (DOE CSL-3) specifies a level of efficiency that is 30% higher than TP1 CSL-1). There is often a tradeoff between no load and load losses. Increasing the amount of material in a transformer will decrease the load losses and decrease its operating temperature rise but will increase the no load losses. If transformers are normally lightly loaded, like in 2N distribution systems, attention should be given to minimizing no load losses.

Static switches can be used to provide automatic connection between different UPS or power systems. They add complexity to a system, increase cost and required maintenance and can be a single point of failure. If not carefully designed and managed unplanned static switch operation can lead to overloads and shutdown of the systems to which they are connected.

Generator systems are available in a wide variety of voltage and fuel systems. Natural gas units have slower response to block loads and may need to be oversized but have the benefit of lower emissions. Unless an onsite storage system is provided they are dependent on a gas supply system that is off site and not under the operator's control. Diesel generators have better response and block loading characteristics. Storing large amounts of diesel fuel on site is generally feasible if required. Dual fuel units provide the benefit of diesel operation and on site storage with the advantage of natural gas engine lower emissions and the ability to increase the operation time for a given amount of onsite diesel fuel by supplementing it with gas.

Generator exhaust emissions are an important factor in the specification and operation of a generator unit. During design it must be determined how the generators will be operated. If the generators will be operated in excess of the allocated non emergency hours allowed by the EPA (or stricter local regulations) then a unit certified by the manufacturer to meet the stricter emissions requirements is required. Third party emissions treatment added to a unit in the field does not meet the EPA regulations.

Arc Flash

Highly reliable systems may require energized modification, operation or preventative maintenance. Accurate and comprehensive MOPs (methods of procedure) should be developed and verified prior to performing any work. Human error is the number one reason for unplanned system outages.

Operating energized electrical equipment is typically required to allow transfers between power sources or to allow the system to be put into a condition to protect the critical load while performing work on the system. Unless the equipment is UL listed arc resistance switchgear, performance tested and classified as arc resistant in accordance with ANSI/IEEE C37.20.7, operation of the equipment will require personnel to be suited up with the proper protective clothing and equipment (PPE) as defined by NFPA 70E. ANSI/IEEE Type 2 Arc Resistant switchgear protects personnel at the front, back and sides of the equipment. Type 1 switchgear protects personnel at the front only.

Arc flash hazard levels are categorized into 6 levels (from minimal to dangerous exposure): cat 0; cat 1; cat 2; cat 3; cat 4; and dangerous. Above cat 2 the required protective clothing starts to become restrictive and hinders efficient, accident free operations. Cat 4 protective clothing is hot, bulky and very restrictive to performing operations. The dangerous level indicates that there is no prescribed protective clothing recognized by NFPA or OSHA.

Maintenance or modifications may be desired when equipment is energized. OSHA and NFPA 70B recommend that all work be done while equipment is de-energized. An energized work permit is required that indicates reasons and procedures to perform energized work. Some maintenance operations require the equipment to be operating to determine if there are any abnormalities. Infrared scanning of electrical equipment, conductors, busses and connections must be done under load. During these scans it can be determined if there are hot spots that require immediate correction or if there has been a change in normal operation based on comparison with previous scannings.

The ability to safely do infrared inspections requires access to the components to be scanned. Personnel performing infrared scans must comply with OSHA and NFPA 70E safety requirements for arc flash exposure.

Well thought out system engineering and properly planned and performed preventative maintenance actions can directly avert unplanned failures and outages. Systems should be engineered to allow maintenance to occur while minimizing the direct impact of maintenance work on the system operation.

Having a reliable system requires regular preventative maintenance. It is necessary to design electrical distribution systems to allow maintenance to be performed de-energized or without endangering the critical load or have arc flash ratings of cat 4 or below.

If the system cannot be designed to lower the arc flash hazard then alternate methods of performing preventative inspections must be engineered into the system.

Some of these alternate systems include heat sensing material that is mounted to the terminations that will change color upon reaching certain temperatures; or infrared sensors that monitor the areas of concern and send the information back to a central monitoring station for trending and alarming.

The safe operation of electrical switchboards and switchgear that are not listed as arc resistant requires not being in front of the device being operated. Typical operations include opening and closing circuit breakers (CBs) or racking them out of the equipment when drawout construction is used. Various methods are available. Remote operating switches (sometimes called "chicken switches") or remote CB racking controls or equipment can be used to keep the operator away from the front of the equipment while the device state is changed.

Equipment can also be provided with remote operating panels that allow operations to be performed from a location remote from the equipment. The remote panel can be hardwired direct control or be through computer control (PLC or SCADA system) with a display panel (HMI). By locating the remote panels within sight of the equipment but not directly in front of the equipment the operator can be kept out of the most hazardous zone if an equipment failure occurs and a lower level of PPE may be acceptable.

A reliable system can be designed to minimize arc flash hazards. Equipment requires regular preventative maintenance and modifications. It is necessary to design electrical distribution systems to allow maintenance to be performed de-energized or without endangering the critical load or have arc flash ratings of cat 4 or below.

If the system cannot be designed to lower the arc flash hazard then alternate methods of performing modifications and preventative infrared inspections must be engineered into the system. Lower arc flash designs can be accomplished in various ways including 2N distribution systems, lower capacity sources (smaller transformers) to limit the available power, protective device settings that minimize arc flash, zone interlocking of circuit breakers, bolted fault devices on medium voltage systems to cause the overcurrent devices to operate quicker, arc flash sensors, or reduced settings activated during maintenance either automatically or manually. Alarms are required to verify that he reduced settings are reset when the work is complete. Reduced settings may endanger the critical loads due to the increased sensitivity and loss of selective coordination of the overcurrent devices.

Some of the alternate systems to manual infrared scanning include heat sensing material that is mounted to the terminations that will change color upon reaching certain temperatures; or infrared sensors that monitor the areas of concern and send the

Project Requirements

The owner's goals for the project will influence and are essential to determining the design of the electrical system. Some questions that should be asked are:

1. What is the required availability of the system?
   a. Redundant components? (e.g. Uptime Institute Tier II)
   b. Concurrently maintainable? (e.g. Uptime Institute Tier III)
   c. Fault tolerant? (e.g. Uptime Institute Tier III)
   d. Design for one event? Two events? Planned and/or unplanned? (e.g. ANSI/BICSI-002 class F4)
2. Are there any regulatory requirements? (e.g. SEC, FDIC, COPS)
3. What are the financial or business penalties (reputation or regulatory) for downtime?
4. What are the economic goals or constraints?
5. Are there competitive considerations (cost, speed to market, repeatability, or service level agreement)?
6. Modularity and scalability requirements for future growth, business plan, cost considerations?
7. Experience level of operators?
   a. 7x24 staffing with experienced and well trained electrical staff?
   b. Need for fully automated response or manual intervention?
   c. How often and comprehensively are operators trained?
   d. On site personnel or off site contractors service and maintain equipment?

UPS Operating Modes Defined by IEC 602040-3

The IEC standard has identified three UPS topologies. They are defined by the relationships and dependencies (or lack thereof) between input and output voltage and frequency characteristics.

1. VFI—Voltage and Frequency of the Output are Independent of Input Voltage and Frequency—this is only possible if they are generated independently, as in a double conversion mode or topology.
2. VFD—Voltage and Frequency of the Output are Dependent on the Input. This is true if there is no voltage regulation or independent generation of the output, which identifies a standby or offline mode. There can be some passive filtering, but no active power correction.
3. VI—Voltage of the Output is Independent of Input (Frequency In = Out). This is descriptive of line interactive mode or topology.

These definitions are based on the ability of the UPS to maintain these relationships within a defined range without requiring battery power. These definitions focus on what the UPS actually does (and therefore, what problems it can address) as opposed to how it actually achieves the result.

information back to a central monitoring station for trending and alarming.

High Resistance Grounded (HRG) Electrical Systems

HRG systems may reduce the overall quantity of phase to ground faults and the subsequent arc flash incidents. Upon the first fault to ground there is a warning and it is important that the facility responds before the second fault occurs. Since the first fault level is lowered, the opportunity for the fault to escalate to a multi-phase fault and the amount of damage occurring is reduced. But upon a second phase to ground fault or a multi-phase fault the damage is not limited. Therefore, the arc flash hazard labeling must be for the worse condition.

Resistance grounded medium voltage generator systems (over 600V) are typically used to provide additional protection to the generator alternator during ground faults.

For systems under 600V, other considerations include the fact that the neutral point of the system is no longer fixed. Upon a phase to ground fault the other phase voltages rise to the phase-to-phase voltage level. In a 277/480V system the typical voltage to ground is 277V. Upon the first phase to ground fault the voltage from the other phases to ground could increase to 480V. This can damage components (wiring, power supplies, controls, metering) not typically rated for this voltage. Common component voltage ratings are 300V and 600V.

UPS systems depend on a fixed neutral point on the electrical distribution system. When there is no fixed neutral reference point such as for a delta connected system or a high resistance grounded system, the UPS system must be modified to create its own neutral reference point.

There are some operational advantages to an HRG system but there are also some additional costs. These include making all components rated for the higher phase-to-phase voltage, installing the resistors and monitoring systems required for an HRG system, and modifying other systems such as UPS systems.

Generator Emissions Regulations

Local emissions regulations may be stricter than the US federal regulations and therefore are in addition to EPA regulations.

EPA Generator Emissions Regulations (document EPA–HQ–OAR–2010–0295 final rule published June 28, 2011) define two types of generators:

Emergency generators – operate only if utility power is lost. The time of operation when there is no utility power is not limited.

Maintenance checks and readiness testing is limited to 100 hours per year. There is no time limit on the use of emergency stationary internal combustion engines (ICE) in emergency situations. The owner or operator may petition the Administrator for approval of additional hours to be used for maintenance checks and readiness testing, but a petition is not required if the owner or operator maintains records indicating that Federal, State, or local standards require maintenance and testing of emergency ICE beyond 100 hours per year.

Emergency stationary ICE may operate up to 50 hours per year in non-emergency situations, but those 50 hours are counted towards the 100 hours per year provided for maintenance and testing. The 50 hours per year for non-emergency situations cannot be used for peak shaving or to generate income for a facility to supply power to an electric grid or otherwise supply non-emergency power as part of a financial arrangement with another entity. For owners and operators of emergency engines, any operation other than emergency operation, maintenance and testing, and operation in non-emergency situations for 50 hours per year, as permitted in this section, is prohibited.

Non-Emergency generators – may operate an unlimited number of hours including when utility power is available. This includes time for electrical system maintenance, UPS system maintenance or storm proofing mode. For this flexibility the system must be designed for a lower level of exhaust emissions. Larger kW (HP) units may require diesel particulate filters (DPF) and Selective Catalytic Reduction (SCR) systems.

Selective Catalytic Reduction (SCR) systems – Already in wide use on stationary diesel engines, SCR systems incorporating aqueous urea injection into the exhaust stream passing over a suitable catalyst reduce NOX up to 90 percent. Systems consist of an SCR catalyst, urea injection system, urea tank, pump and a control system.

Diesel particulate filters (DPF) traps are designed to physically capture particulate matter from the exhaust stream. They can either be simple mechanical filters requiring frequent replacement, or they can be catalytic filters that provide periodic or continuous oxidation (regeneration) of the trapped particulates into CO2. PM traps with continuous regeneration have already reached a high level of commercialization and are being employed on stationary diesel engines in areas with strict particulate matter emissions regulations. Ultra-low sulfur diesel fuel is needed to prevent contamination of the conversion catalysts. However, filtration efficiencies up to 90 percent have been demonstrated.

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