

Applying the National Electrical Code to Substations

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Abstract:

A discussion of the National Electrical Code (NEC) and National Electrical Safety Code (NESC) design considerations as applied to utility substations, including working clearances, cable tray, cables, conduit, conduit fill, and station services in electrical equipment enclosures.

Through the guidance of the National Electrical Code (NEC), we can meet the need for safe low-voltage designs by applying the NEC in substations whenever possible and practical. This paper will primarily focus on low-voltage, single phase designs (600V or less). In order to apply the NEC to substation design, we must first and foremost educate ourselves and understand the intent of the NEC and then decide how it can be utilized in what we are doing.

The NEC and NESC contain many applications for safeguarding personnel and equipment. The topics in these publications are so broad that it would be difficult or even next to impossible to discuss in their entirety. There are many topics such as grounding and bonding, warning signs, illumination, PT and CT secondary grounding requirements, etc. that this paper will not address. This paper will discuss a few specific applications of the NEC while referencing the use of the more prevalent NESC and IEEE documents in utility applications.

The purpose of the NEC is the practical safeguarding of persons and property from hazards arising from the use of electricity (Section 90.1). Refer to Section 90.2 of the NEC for a listing of which installations are covered and those that are not.

The purpose of the NESC is the practical safeguarding of persons, utility facilities, and affected property during the installation, operation, or maintenance of electric supply and communication facilities, under specified conditions. (Section 1, Rule 010). Refer to Section 1, Rule 011 for a listing of which installations are covered and those that are not.

In terms of the electric utility industry, the NEC does not cover installations in utility substation electrical equipment enclosures (sometimes referred to as control buildings) and is not usually subject to electrical inspections. Design considerations of the NEC, specifically low-voltage applications, are defined more completely in the NEC than in the NESC. In other words, the NESC provides criteria for what is to be executed, but not how it is to be accomplished, whereas the NEC defines both a standard for and methods of implementation.

Although design within a utility substation falls under the jurisdiction of the NESC, the NESC does not specifically cover utilization wiring like the NEC does. It is our interpretation as consulting engineers that the NEC should therefore be applied as a best practice in some specific applications within the electrical equipment enclosure. Examples of these applications are: AC station service design, wiring methods and practices, and installation and selection of cables and raceways.

The general contractor and consulting engineer are subject to the provisions of the NEC if the client specifies that the design and installation should adhere as such. Failure to comply with the rules could

result in an installation that does not sufficiently protect personnel and/or equipment. Ask yourself what it means to you when your specification includes verbiage for the design engineer and/or vendor to apply the NEC. We see this in many specifications, including our own. What does this mean if the NEC doesn't apply in utility substation installations?

The NESC covers a myriad of design rules for utility designs of high-voltage applications, whereas the NEC primarily covers low-voltage installations and utilization wiring. This paper will convey that there are specific areas within a utility substation that fall within the categorized code rules of the NEC where the NEC may be more stringent than those of the NESC. This is a presentation of the use of these rules in concert, as well as from the standpoint of an electrical inspector who may know and apply the NEC in the inspection rather than the rules of the NESC.

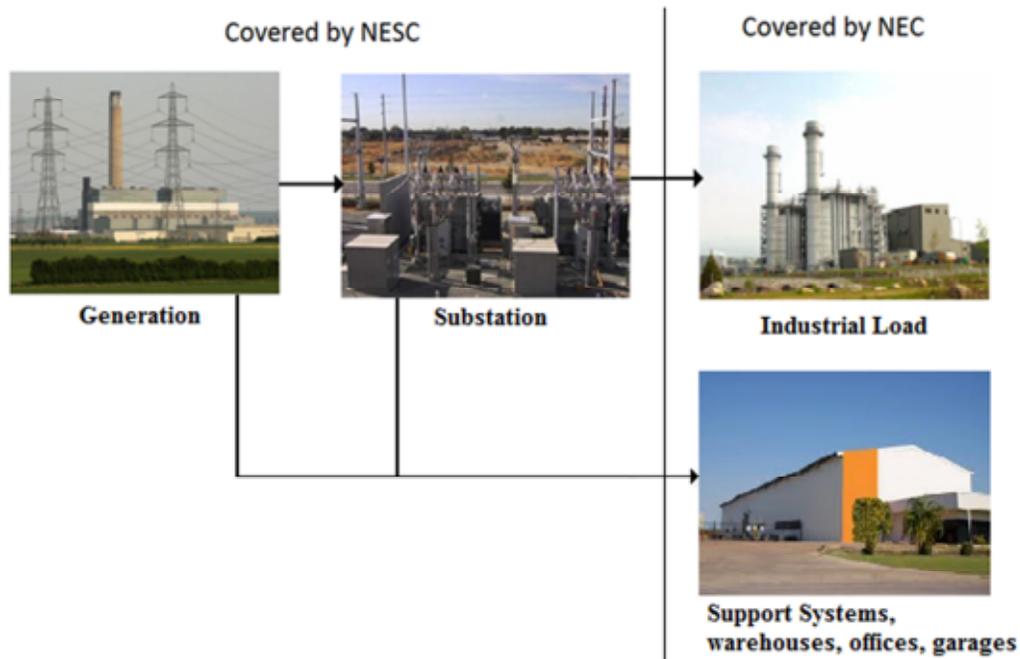


Figure 1: Scope of NEC and NESC

Electrical Equipment Enclosure

Working Space

Working space (600V or less) around electrical equipment is covered in Article 110, Section II of the NEC and Rule 125 of the NESC. Both codes require that sufficient access and working space is to be provided and maintained around all electrical equipment to permit ready and safe operation and maintenance of such equipment. This paper highlights some of the similarities between the two codes but there are additional restrictive rules and requirements of the NEC.

Both codes require the same width and depth to a working space as identified in Tables 110.26(A)(1) and 125-1 of the NEC and NESC, respectively. The height of a working space is where the codes begin to be different. The NEC requires a working space height of 6'-6" from the floor/finished grade or to the height of the equipment, whichever is higher. The NESC simply states that the height is to be no less than 7'0".

The NEC goes on to further detail dedicated space above electrical equipment, recommending no equipment that is not associated with the electrical installation be installed in this space. As simple and straightforward as the dedicated equipment space may be, this is one of those common sense applications where a design engineer should give consideration.

As an example, the design engineer should avoid placing equipment that is not part of the electrical system in the dedicated equipment space, as it causes safety and maintenance issues. If the foreign equipment were to require maintenance, a situation arises in which personnel are working directly over electrical components which could possibly present a safety hazard. Additionally, the intent of the NEC is to prevent any leaks from the foreign equipment to enter the electrical system from above. There are a few exceptions to the rule, such as installation of fire suppression systems. If it is simply unavoidable to install equipment above electrical components, the NEC provides guidance to the design engineer on how to mitigate the hazard.

We feel that this additional component (dedicated equipment space) of the NEC is important too; although the NESC does not require dedicated equipment space, it does make sense to account for it.

Battery Rooms

Almost every substation electrical enclosure contains a battery bank(s). Some battery banks are housed within separate “battery rooms” adjacent to the main enclosure, whereas some are placed in the common area of the electrical equipment enclosure. Depending on the type of battery, it is well known that hydrogen gas can be released when batteries are charging, and it is also well known that hydrogen gas can be highly explosive in concentrated amounts.

NEC Article 480 contains rules on storage batteries that require the area to be ventilated in such a manner to prevent the accumulation of an explosive mixture.

IEEE 484 also requires that the battery areas be ventilated to prevent the accumulation of hydrogen gas. Furthermore, it mentions that the battery area will not be considered a hazardous classified location if one meets the ventilation requirements.

In the event that a battery area is not vented, a classified hazardous location can occur. NESC rule 127 requires that electrical installations in classified areas follow the requirements of NEC Articles 500 through 517, along with the rules outlined in rule 127 of the NESC. Basically, if a battery room is not ventilated, then the NESC dictates that we follow the NEC for additional safety design.

The NEC contains a multitude of rules and protection techniques that prevent the ignition of flammable gasses, liquids and vapors. In addition to ventilation, such techniques include installation of gas detection systems, gas/vapor tight cables, conduit seals, flexible connections listed for Class 1 Division 1 locations, special grounding and bonding provisions, explosion proof boxes and fittings, etc.

Cable Tray

Cable Tray is another area in the electrical equipment enclosure that has applicable NEC provisions. Approximately 90% of the electrical equipment enclosures Ulteig works on or designs utilize a cable tray system. The cable tray may come installed as part of a pre-fabricated electrical equipment enclosure or be installed in the electrical equipment enclosure by the construction crew on site. Some of the areas that should be considered when using a cable tray in either of these applications include electrical bonding, tray structural support, fill, cable selection and cable de-rating.

Manufacturers of cable tray provide several different options for width and rung spacing. The width of the tray will be directly related to the fill, and the fill is directly related to the type of cables used. The NEC allows for multi-conductor, single conductor, and combinations of multi- and single conductor in the tray, but the fill and allowable ampacity of the cable depends on which installation is used. The fill of the cable tray is covered in Table 392.9. NEC Section 392.11 has three subsections that cover the ampacity ratings that are to be used for cable in each of these applications.

Depending on the requirements or design practices of the substation owner, there are situations where the cable tray may contain any combination of multi or single conductor cables, however, single conductor cable is restricted to be 1/0 AWG or larger. Multi-conductor cables that are type TC (tray rated cable) must be smaller than 1/0 AWG.

It is important to note that the requirements for cable trays are also broken up by voltage and cable size. Most applications are for 2000V or less, but Sections 392.12 and 392.13 cover applications for over 2000V. When cable from 1/0 AWG to 4/0 AWG is used, the rung spacing is required to be 9". For this reason, 9" rung spacing is common.

The installation of the cable tray itself requires attention to grounding/bonding and supporting means. A cable tray is to be grounded the same way as other raceways and equipment enclosures. Certain installations of tray allow the tray to be used as the grounding conductor. NEC Section 392.60 covers the grounding and bonding of cable tray, and subsection B contains the requirements for using the tray as a grounding conductor. The NEC refers to the manufacturer's installation instructions for meeting the supporting requirements for the cable tray. The total weight of the cables to be installed in the tray is required in order to determine if the tray is supported adequately. Each manufacturer provides technical information on its cable trays, but Cooper B-Line has an additional section in its manual that covers the NEC and NEMA requirements for cable tray in great detail.

Conduit

There are several locations where conduit is used in substation designs. The most common one considered is conduit used to provide cable access to equipment, such as breakers, transformers, instrument transformers, and motor-operated disconnect switches located in the yard of the substation. Conduit can be a means by which direct buried cable gets from the ground to the equipment, or it can be run directly to cable trenches, manholes, or to the electrical equipment enclosure. Conduit is also used to run the wiring within the electrical equipment enclosure. Utilization wiring would include AC power cable used for lighting receptacles and HVAC. These uses of conduit are in all substations and have a straightforward application of the NEC. Another application of conduit in the substation is for the protection of medium-voltage circuits. Examples of these circuits include distribution cable leaving the substation and wind farm collector circuits entering the substation. This application of conduits results in some design challenges when applying the NEC.

Conduit types include many different materials, each having its own advantages and disadvantages. In general, there are metallic and non-metallic conduits. There are several types of each metallic and non-metallic conduit that are specifically detailed in the NEC. NEC Articles 342 to 362 pertain to each of the accepted types of conduit.

One common type of conduit used for the below-grade conduit in the substation is PVC. NEC Article 352 applies to PVC conduit. PVC conduit is corrosion resistant and therefore used for many below-grade applications. It can be direct buried or encased in concrete. Although PVC conduit can be used in exposed application as well, it is restricted to areas that are not subject to physical damage. There are

other limitations to using PVC conduit that the design engineer and installer must consider, such as the fact that it will become brittle and difficult to work with in cold temperatures. This is of particular concern in northern climates where maintaining systems that have PVC conduit installed in exposed areas is a challenge.

At substation equipment, a transition from a non-metallic conduit to a metallic conduit is usually made. Type RMC, or rigid metal conduit (generally galvanized steel), is used for the above-grade conduit connection to substation equipment in the yard. NEC Article 344 applies to rigid metal conduit.

In northern climates, another consideration for conduit installations to equipment in the yard is frost. Frost depths there can reach up to four feet deep. Heaving related to the frost can cause conduit to push or pull equipment cabinets. The NEC provides articles on the use of these types of installations (Sections 300.7(B) and 250.98).

A few examples that may help minimize the upward movement of conduit into enclosures include; using flexible conduit or expansion fittings, and site grading practices or local foundation correction (i.e. deep sand layer). The design engineer should consult with the requirements for frost depth in each state, as it can also impact the burial depth of the conduit.

While the substation design engineer will usually select the conduit type, routing, and sizing of the conduit used for the substation equipment in the yard, the conduit used within the electrical equipment enclosure will be selected and installed by the electrician or electrical equipment enclosure manufacturer. The type of conduit generally used for this application is electrical metallic tubing (EMT). EMT will generally be routed on the walls inside the electrical equipment enclosure. When installed with proper fittings, it can be used as the equipment grounding conductor. However, running a separate equipment grounding conductor with the phase conductor(s) to lights or receptacles within the electrical equipment enclosure is preferred. See Article 358 for requirements pertaining to EMT conduit.

The typical design of a conduit system will include conduit burial depth, bending radius, calculations on conduit fill, and determination of cable ampacity de-rating. Each of these criteria is covered in the NEC. Along with these design considerations, installation considerations are also addressed by the NEC, such as how the conduit is to be supported and secured.

Burial depth for conduit containing low-voltage wiring is covered under NEC Section 300.5 “Underground Installations.” This NEC section covers the burial depth for cable and conduit. While the NEC permits PVC conduit to be installed at a depth of 18”, consideration must also be given to local codes, frost depth, cable ampacity, and the conduit bending radius. The bending radius for each trade size of conduit is covered in Table 2 of Chapter 9 in the NEC. Circuits exceeding 600V have additional depth requirements and are covered under Section 300.50 of the NEC. PVC conduits used for circuits from 22kV to 40kV are required to be at least 24” deep. The increased depth must also be taken into account when calculating ampacity of the cables within the conduit, see NEC Section 310.60(C)(2).

Maximum fill percentages for conduit are covered in Table 1 of Chapter 9. For most substation applications, there will be more than two conductors in a conduit, so the maximum fill percentage will be 40%. It is important to consider the length of the conduit run and the number of bends in the conduit runs when determining the amount of fill that is acceptable. The maximum fill percentage will not guarantee an easy installation. Other considerations associated with the fill of the conduit and the ease of installation is the jamming ratio. While the NEC does not govern this, it does contain an informational note about its occurrence.

There are many different requirements for ampacity de-rating of cables, but specific to conduit is NEC Section 310.15(B)(2)(a), which addresses the number of current carrying conductors in a raceway.

Ampacity for cables can be required to be reduced to 35% of the original value. This section has several exceptions that should be examined for each application to reduce oversizing cable.

As mentioned above, there can be challenges when applying the NEC to larger underground medium-voltage circuits. In order to meet the fill requirements of the NEC, PVC conduit sizes larger than 6" are often required for the cable used. Many manufacturers produce 8" PVC electrical conduit, but the NEC specifically limits the size of conduit used for each type. The maximum size PVC conduit allowed by NEC is 6". While manufacturers do produce 8" conduit, it is not acceptable to use it in conjunction with the NEC, and it will not usually be UL listed. It is up to the engineer to work with the authority having jurisdiction to determine if the use of 8" conduit is acceptable. The NESC also contains a section on underground conduit systems in respect to the installation and maintenance of underground electric supply and communication lines that should be considered.

Station Service

Utilization equipment is defined in the NEC in Article 100 as equipment that utilizes electric energy for electronic, electromechanical, chemical, heating, lighting, or similar. The NESC defines utilization equipment in a similar fashion. The NEC contains many rules for the wiring of utilization equipment known as premises wiring. Specific NEC rules outline the design and installation of station service secondary conductors, cable ampacity ratings, conduit size, overcurrent protection device selection, conductor disconnecting means, and grounding/bonding of equipment. Knowledge of these rules is important for the proper design and installation of station service in substation applications.

The design of an AC station service begins with the selection of a station service transformer from information gathered and AC loading calculations. Once the transformer selection has been made, the design engineer can choose phase and neutral conductors from Table 310.15(B)(16) of the NEC. This table contains a listing of cable sizes and their ampacity ratings based on the cable insulation type and temperature rating. As previously mentioned, the design engineer will also need to look at any de-rating factors that may apply and account for them in the selection of cable sizing.

Next, the conduit can be selected based on the conduit fill from the selected secondary conductors. As previously mentioned, the maximum permitted conduit fill per the NEC is 40%.

The station service secondary conductors must terminate on a service disconnect prior to entering an automatic transfer switch (ATS). The service disconnect must be located in a readily accessible location either outside the enclosure or inside nearest the point of entrance of the service conductors (Section 230.70(A)).

If 800A or less, the NEC allows overcurrent protection at the disconnect to be selected such that the next higher standard overcurrent device rating above the ampacity of the conductors being protected to be used (Section 240.4(B)). This can be done since the conductors are not part of a branch circuit and if the ampacity of the conductors do not correspond with a standard ampere rating of a fuse or circuit breaker. Standard ampere ratings can be found in Section 240.6 of the NEC.

The conductors leaving the ATS terminate on an AC distribution panel for feeding utilization equipment. The same procedure outlined above can be used for selection of the cable, conduit, and panel board main circuit breaker sizing.

Example: Station Service Design for a 100 kVA station service transformer feeding a 400A, 240/120V, 1 Phase, 3 wire disconnect, ATS and two 225A panel boards. See Figure 2.

Full load amps (FLA) = $100,000 \text{ VA} / 240\text{V}$

FLA = 416A

Per Table 310.15(B)(16) assuming 75 °C equipment terminations and insulation, the minimum cable size from the table based on the required ampacity from the calculation above would be 500 KCMIL CU (good for 380A). For the purpose of this example, a full-sized neutral will be used. While the NEC does allow for de-rating of neutral conductors, if you have a larger volume of harmonic loads such as fluorescent lighting, power electronic, etc. using a fully rated neutral is generally a good practice and cheap insurance.

The minimum required PVC schedule 40 conduit size for three 500 KCMIL CU cables would be 3", resulting in a fill calculation of 29%. The use of a 2-1/2" conduit would not meet the requirements of the NEC as the fill calculation is 45%.

The maximum overcurrent protective device allowed base on the NEC rules mentioned above is 400A. This would require a 400A ATS and 400A fused disconnects, fused at 400A. One could choose to fuse the disconnect with a smaller fuse, but this example assumes that the full 400A is desired. A general rule of thumb is not to utilize more than 80% of the rating. Therefore, the connected load should not exceed 320A on the ATS assuming the main and branch circuit conductors are 80% rated versus fully rated. The cable and conduit for the 240/120V system would be the same as calculated above.

When branch circuit breakers from the 240/120V panel board are used to feed HVAC loads, the NEC (Article 440) requires the use of heating, ventilation, and air conditioning rated (HACR) circuit breakers. The design engineer should request data sheets for the HVAC units that are going to be installed in equipment enclosures. These vendor documents will list a minimum or sometimes a maximum overcurrent protective device that is to be installed based on Article 440.

When branch circuit breakers from the 240/120V panel board are used to feed lighting loads where the circuit breakers are meant to be used as the switching device, the NEC (Section 240.83(D)) recommends using HID/SWD rated breakers.

There are two types of circuit breakers available for switching lights, SWD and HID. SWD rated breakers are switching duty rated for fluorescent lighting circuits. HID rated breakers are breakers rated to interrupt higher current from High Pressure Sodium (HPS), Mercury Vapor (MV), or Metal Halide lighting circuits.

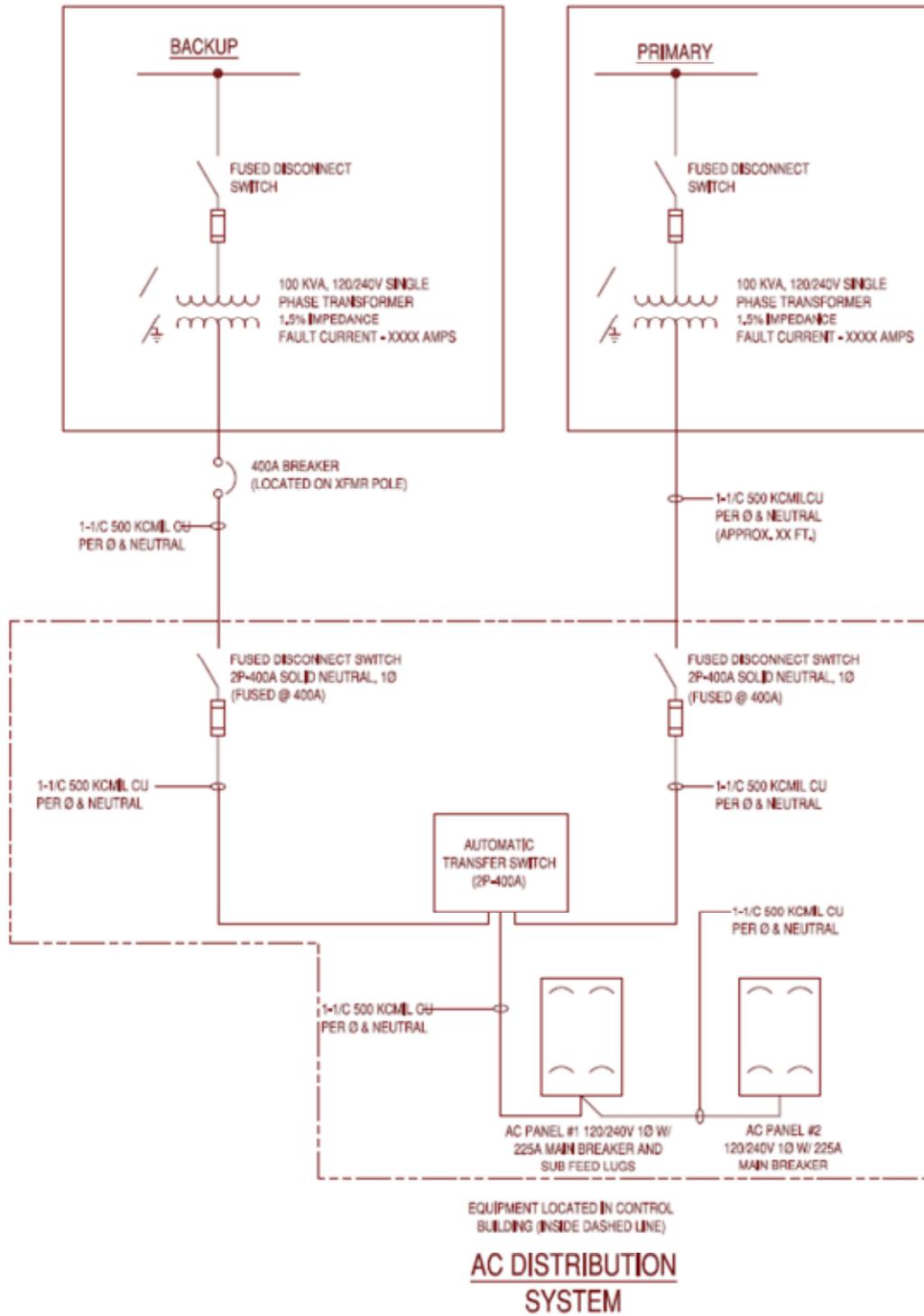


Figure 2: Station Service One-Line

Power Cable

Even the most basic substations can contain large amounts of power and control cables. These cables are located indoors and out. They can be in conduit, direct buried, in cable tray, or in other raceways. The varied application of cables in the substation requires the use of several different types of cable. The NEC defines the uses in which each type of cable is permitted. For conductor applications and insulations rated 600V and below, see Table 310.104(A) in the NEC. Typical location factors that need to be considered when selecting cable include whether the location is in a wet or dry environment, if it will be used in a cable tray, direct buried, and the temperature rise that the conductor will experience including ambient temperature. The electrical factors that need to be considered include the amount of current that the circuit will carry, the length of the circuit run for voltage drop, and voltage of the circuit.

The NEC contains articles for specific applications of some cable types. For example, cable that is to be used in a cable tray is detailed in NEC Article 336. Type TC cable is to be installed in a cable tray or other raceway. Type TC cable can satisfy additional requirements such as being sunlight-resistant or identified for direct buried applications. In most substation applications, tray rated cable will be required due to the use of cable tray within the electrical equipment enclosure. Since the cable extends beyond the electrical equipment enclosure into the yard, the cable will need to be rated for use in wet locations and in some instances may be required to be rated for direct burial.

Cables are rated based on their temperature capability. This rating is usually a product of the insulation that is used on the cable. Common temperature ratings are 60°C, 75°C and 90°C. Additional ratings beyond these temperatures are available and documented in the NEC. Temperature ratings of cable insulation, the terminations that are used on them, and ambient temperatures have a significant impact on the ampacity rating of a cable. Table 310.15(B)(16) has the allowable ampacities of insulated conductors for not more than three current carrying conductors in a raceway.

Example: De-rating of conductors

Assumptions for this example are: The AC equipment has 75°C terminations, no more than three current carrying conductors in the raceway, #10 AWG conductors, XHHW-2 insulation, an ambient temperature of 45°C, and a load of 29 amperes.

A copper #10, XHHW-2 cable is rated for 40 amps per the 90°C column in Table 310.15(B)(16). Since there are only three current-carrying conductors in the raceway, no de-rating is required for the number of conductors. We do need to de-rate for an ambient temperature of 45°C by multiplying 40 amps by 0.87 giving a new de-rated ampacity of 34.8 amps. The correction factors for ambient temperature are located in Table 310.15(B)(2). Since this new de-rated value is less than the 75°C column value, we can use the 90°C temperature rating of the conductor. If the ampacity was higher than the value provided in the 75°C column, we would need to increase the size of the conductor.

On the far left side of Table 310.15(B)(16), #14, #12 and #10 AWG conductors have a ‘**’ next to them which refers you to the bottom of the table where there is a reference to NEC Section 240.4(D). In the case of a #10 AWG conductor, Section 240.4(D) limits the maximum overcurrent protection device after any corrective factors for ambient temperature and number of conductors in a raceway to 30 amperes. Since our calculated ampacity of the cable is 34.8A, our load is 29A, and the maximum overcurrent protective device is 30A, a #10 AEG cable is sufficient. The result of this example is an installation that meets the de-rating factors and the maximum overcurrent protective device requirements of the NEC. One can see through the use of these NEC references that a #12 AWG conductor in this example would not meet the requirements.

This example shows it is important to know the ambient temperature, the temperature ratings of equipment, terminations, de-rating rules and cable type used for the installation.

Many substations are in rural settings where land costs allow low-profile designs that are spread out across a considerable amount of land. Even in more populous areas, where compact box structure designs are used, the amount of space required for a substation can be quite large. These large substations will require very long runs of control and power cable. Because of the length of the cable runs, voltage drop becomes a necessary calculation to perform. Although the NEC does not have any specific requirements for voltage drop, it does contain informational notes related to the amount of acceptable voltage drop. Informational note 4 of Section 210.19(A) and note 2 of Section 215.2(A) of the NEC describe the maximum voltage drop for a branch circuit as 3% and the total for a branch circuit and feeder as being 5%. In order to reduce the voltage drop for a circuit the cable size can be upsized to reduce the resistance in the circuit.

Example: Voltage drop calculation for heaters on an SF6 circuit breaker:

Total watts required:

$$\text{Tanks heaters} - 1600 \text{ Watts} * 3 = 4800 \text{ Watts}$$

$$\text{Cabinet heaters} - 400 \text{ Watts} * 2 = 800 \text{ Watts}$$

Current required:

$$I = (4800\text{W} + 800\text{W}) / 240\text{V} = 23.3 \text{ A}$$

Cable size used:

#10 AWG

Resistance of wire used (from Chapter 9 Table 8):

$$R = 1.24 \text{ Ohm/kFT}$$

Distance of breaker from AC panel:

$$L = 350 \text{ feet}$$

$$VD = \frac{2 * L * R * I}{1000}$$

$$VD = \frac{2 * 350 * 1.24 * 23.3}{1000} = 20.25 \text{ V}$$

$$\%VD = \frac{20.25}{240} = 8.4\%$$

As the calculation shows, even though a #10 AWG cable would be sufficient for the ampacity to supply the breaker heaters, the distance to the breaker results in a very high voltage drop. The results of this

voltage drop will be that the heater will not produce the expected amount of heat. If there is a convenience outlet in the control cabinet, any equipment plugged into it may be subjected to low voltage. In this case a #6 AWG would result in a more efficient design as the voltage drop would be 3.3%.

Substation designs require the use of many multi-conductor cables for control and monitoring of the system. These multi-conductor cables contain uniquely colored conductors within the cable to allow for identification of a termination by cable name and wire color. The two color code schemes commonly used are method K-1 and method K-2. Each of these methods defines the colors that will be contained in each cable. For example, the first four wires in any cable with a K-1 color code will be black, white, red and green. The first four colors in any cable with a K-2 color code will be black, red, blue and orange. The specific item to note here that applies to the NEC is that method K-2 does not contain a white or green. The NEC specifically defines that white is to be used on grounded conductors (the neutral) and green is to be used as a grounding conductor only. The NEC sections that cover the requirements for ground and neutral conductors are Section 200.6 and Section 250.119. The NEC does contain a provision for an insulated conductor in a multi-conductor cable to be permanently identified at the terminations as being a grounded conductor or a grounding conductor where the conditions of maintenance and supervision ensure that only qualified persons service the installations.

Conclusion

This paper introduced a number of NEC design considerations within utility substations. As previously mentioned, there is far more information available than could be presented in this paper. The most recent publications of the NEC (2011) and NESC (2012) have had a great deal of change relating to definitions and the inclusion of new information. Some of the changes and additions have brought the two codes closer together, while others continue to overlap. However, there remains a great deal of information contained in the NEC that can be applied within the substation design that is not explicitly covered in the NESC.

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