NEMA US 80017-2023

# *Design Considerations for Transformers in Data Center Applications*

**Disclaimer**

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## Introduction

Increased use of cloud-based storage and applications in many industries across the globe over the last five years has resulted in substantial investment in the construction and development of data centers. The U.S. Department of Energy estimates that data centers consume "…10 to 50 times the energy per floor space of a typical commercial office building," representing about 2% of total U.S. electricity use.[1] One prominent sector forecaster estimates a compound annual growth rate of over 8% in the data center industry through 2026.

Data centers vary in size, which means that sourcing and procurement needs will vary as well. But it is not uncommon for a single facility to employ hundreds, if not thousands, of transformers to ensure adequate, uninterrupted power. While purchasing specifications for these transformers should reference existing industry standards such as NEMA TR 1 or NEMA ST 20, there are special considerations for transformer design in data center applications.

The purpose of this paper is to provide guidance for data center developers and engineers to understand these design considerations and recommendations for incorporation into purchasing specifications.

## Available Fault Current on Terminals

In critical applications such as data centers, there is no allowable downtime for the power supply. This means that even when equipment (such as a transformer) is being serviced, the circuit will remain energized. This poses a hazard to maintenance personnel in the event of a fault as well as transformer longevity, but this hazard can be mitigated, at least somewhat, by reducing the available fault current on the primary and secondary terminals.

At the primary terminals of a transformer, ahead of the transformer coils, the natural impedance is limited to that of the bussing and/or conductors ahead of the transformer; therefore, the fault current will be significant (see Figure 1). This could have an impact on human safety as well as the life of the transformer. Partial range current limiting fuses (PRCLFs) inside the transformer will interrupt and clear the most significant fault currents associated with a minimal impedance internal fault, but these fuses must be coordinated with an internal expulsion fuse to ensure low-current secondary faults are also covered.

To mitigate the risk associated with faults at the primary terminal, we recommend the installation of two types of protective devices inside the transformer: an expulsion fuse and a partial range current-limiting fuse.

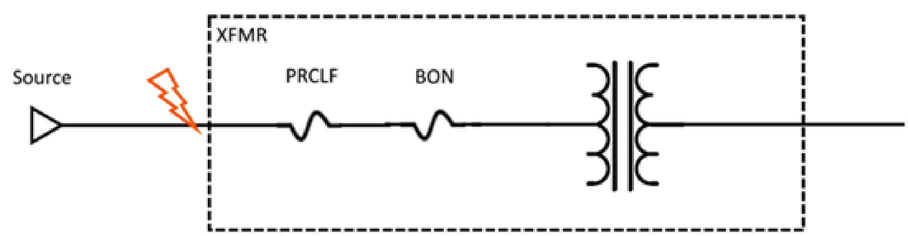


**Figure 1**

An expulsion fuse includes two subsets: a bayonet fuse and a cartridge fuse. Both types are installed near the primary terminal but will react to low currents from faults on the secondary side. The key difference is that bayonet fuses are externally accessible/replaceable while cartridge fuses are mounted

[1] "Data Centers and Servers," Office of Energy Efficiency & Renewable Energy, https://www.energy.gov/eere/buildings/data-centers-and-servers

on a rack *inside* the transformer. A partial range current-limiting fuse, on the other hand, is installed near the primary terminal but reacts only to high current internal faults.

Maximum let-through of available fault current at the secondary terminal also poses a concern for service personnel working downstream from the transformer as well as low-voltage equipment (see Figure 2). Additionally, secondary overcurrent faults will pull fault current through the transformer windings, causing significant electromechanical stresses in the core/coil, which may impact transformer lifetime. The maximum let-through of available fault current is determined by the level of impedance within the transformer and is calculated as (nameplate rated current) / (impedance), where impedance is expressed as a decimal.

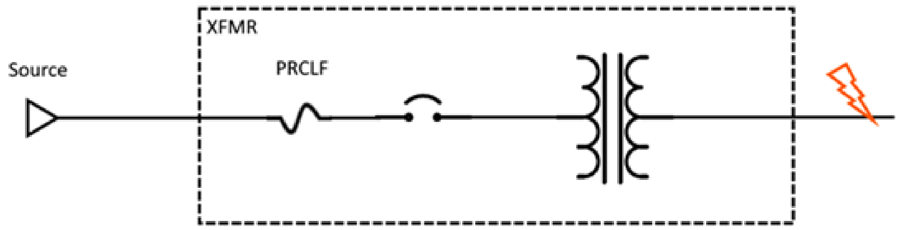


**Figure 2**

Most distribution transformers (including those used in data center applications) are designed to have somewhere in the range of 2-8% impedance.[2] This can be increased in order to reduce the maximum let-through vis-à-vis product design, though this may be a cost driver. In considering what level of impedance is appropriate for a given data center application, customers should be aware that several other dynamics of transformer design specifications also impact impedance. These[3] include:

- **Conductor material**: Copper has a lower impedance than aluminum
- **Temperature rise**: The lower the temperature rise, the lower the impedance
- **K factor ratings**: A higher rating will result in lower impedance
- **Loading percentage of the transformer**: A fully loaded transformer will have the highest possible impedance

It is important to note that design specifications for the above dynamics often specify characteristics that yield a lower impedance. In addition, industry experience demonstrates that data centers are often designed to avoid full loading. All of this should be taken into account for a fully informed decision about maximum let-through of available fault current.

## Harmonic Loads and Loading

With the use of power electronics and inductive loads such as motors in data centers, harmonics represent a real concern for engineers in these applications. While harmonics have an impact on power factor, there is minimal impact on transformer life. The health and preservation of the insulation material has a far greater impact on the transformer lifespan. Since temperature rise is a function of loading, this means that transformer loading has a much greater impact on transformer life.[4]

The above notwithstanding, there are certain cases where harmonics will have a material impact as well on transformer life: when the transformer is loaded at 80% or above. If this will be the case, the customer should specify a harmonic design of K4, K9, or K13.

[2] 10 CFR 431.192 Subpart K (see Tables 1 and 2)
[3] Transformer manufacturers have the ability to address the reduction of impedance caused by the dynamics discussed in the first three bullets through product design
[4] See IEEE C57.96 and C57.100 for further information about how transformer loading impacts life expectancy

## In-Rush Considerations

In data center applications, coordination between the breaker fuse trip curve and current in-rush is critical. When a transformer is energized, there is residual flux density in the core that causes current to spike. In-rush can either be: 25x for 0.01 seconds or 12x for 0.1 seconds. In most transformer applications, current in-rush is a primary consideration because it occurs to a material degree. At a data center, the current in-rush phenomenon regularly occurs because a transformer is de-energized and then re-energized because of maintenance/commissioning, power loss, or an open-source switch. If the breaker fuse trip is not calibrated to withstand the spike, the breaker will open, causing the transformer and downstream circuit to lose power. In order to avoid this, engineers should specify the breaker fuse trip curve to withstand anticipated in-rush.

## British Thermal Units (BTUs)

There is a common misconception that transformers need to be rated to the same BTU levels as HVAC units. Although there is a correlation between watt losses and BTU/hour, more often than not, this misconception results in unnecessary transformer over-design. Transformer OEMs supply losses in watts at 25%, 50%, 75%, and 100% loading; BTU/hr ratings should correlate to this data, NOT the HVAC BTU ratings.

## Transient Withstand

The frequent switching described above (see *In-Rush Considerations*) of data center transformers is one of several factors that put them at risk of transient voltages. Other factors include high power demand, high efficiency requirements, and spacing constraints. Switching of fast-acting breakers can create trapped fast transient currents that, in return, produce both multiple incoming chopped-wave voltage transients and the chance of harmonic resonance voltage amplification if the trapped waves excite transformer winding natural frequencies. Due to their reliance on air for dielectric clearances, the risk of transient voltages is greater for dry-type transformers than it is for liquid-immersed transformers. Customers should be aware of the likelihood of transient voltages, particularly in installations where the breaker is located close to the transformer and where the transformer is lightly loaded. In these cases, the transient will not have far to travel from the breaker to the transformer coil and the load will be insufficient to “pull away” the transient voltage.

In order to address this issue, customers/designers have three options. First, and most common, is the installation of RC snubbers, which are composed of a resistor and capacitor in series and connected just downstream of the interrupter. When a transient is created, the snubber is between the connection and ground and can smooth out the transient. The disadvantage to this solution is that it requires an understanding of system characteristics prior to design, additional floorspace, and added maintenance.

The second solution, and one that is common for dry-type transformers, is to install surge arresters at several key points in the high-voltage coil. Unlike the snubber option, surge arresters do not reduce the rate of voltage rise (dV/dT); however, they control and significantly reduce voltage magnitudes. The control of the voltage allows them to be used in any network system without need of understanding unique system characteristics. A disadvantage of integrated surge arresters is they add extra complexity to the transformer design and manufacturing.

A third solution is to change the resonant frequency of the transformer. Techniques such as increasing the basic insulation levels (BILs) through more insulation, adding winding shielding, and modifying the electrical shape of the transformer windings change the capacitance of the coil, which ultimately changes the resonant frequency of the transformer coils. These design techniques reduce the chance that the frequency does not match up with that of the vacuum switch, avoiding unwanted constructive interference and over-voltage. The disadvantage of this design technique is that it adds physical size to the transformer.

## Monitoring

We recommend that data center transformers include insulation and temperature monitoring capabilities to preserve performance. These characteristics will vary between liquid-immersed and dry-type, however.

To monitor temperature, engineers should consider employing a top-oil thermometer with Form A (simple open/close configuration) or Form C (three-sided open/close rotation) alarm contacts in liquid-immersed units. We recommend the threshold alarm temperatures for liquid-filled transformers be set at 60-90°C.

To monitor transformer insulation, we recommend employing the Dissolved Gas Test by pulling a sample of the oil and measuring the level of gas, the presence of which is an indicator for insulation breakdown.

Finally, we recommend employing a winding temperature indicator (WTI), which monitors winding current, via a current transformer, along with top oil temperature. It uses that information to predict the hottest spots in the active parts of the coils. The insulation paper is only rated up to a certain temperature, so it is important to be able to prevent any part of the coil from reaching that temperature.

In dry-type transformers, there is less to monitor because the air is the only medium for heat dispersion. One common monitoring solution for medium-voltage transformers is to employ a thermocouple in a hollow tube adjacent to the windings and tied into the transformer circuitry. The thermocouple wires, made of different materials, exhibit a correlation between the generated voltage and the temperature they experience. They can be used to measure the temperature of the winding and core, and send a signal to the fan or blower to trip on when the temperature reaches a threshold, or even for the transformer to shut down.

For low-voltage transformers, instead of the thermocouple solution discussed above, we recommend a normally closed (NC) thermal switch. For both low and medium, we recommend the alarm temperatures be set at 180-200°C.

## Contact Information

Please contact Jonathan Stewart (jonathan.stewart@nema.org) with comments or questions about this document or about NEMA's Transformers Section.

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