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Transformers in DC Applications: Design Spec Considerations and Recommendations

Disclaimer

Intro and Scope

Use cases for AC transformers within DC applications are becoming more common with the growth of renewable generation. For example, project developers might use a medium-voltage DC bus to directly interconnect solar PV and a battery energy storage system (BESS). Step-up and step-down transformers are required on both ends of the bus (≈1 kV – 24 kV). Grid planners might also connect a load center such as small towns/cities with MV DC connections to facilitate greater power flow control and facilitate renewable penetration. The links are generally in the 24-36 kV range.

In both of the above examples, configurations that involve AC transformers require the use of power conversion through an inverter or rectifier and may also entail interconnection directly with BESS. For these use cases, there are special design considerations for the AC transformer to ensure optimal performance. The purpose of this document is to provide guidance for developers and planners—anyone charged with specifying the transformer design—to better understand these considerations.

Table

The table below provides a brief overview of the design considerations for AC transformers in various applications that will be discussed throughout this document.

Design Considerations	**Applications**		
	Solar Inverter	**BESS**	**Drive/Rectifier**
Voltage Transients	X		
Electrostatic Shield	X		
Harmonic Currents		X	X
Harmonic Voltages	X		
Flux Density	X	X	
Grounding	X	X	X
Partial Discharge	X		

Voltage Transients and Electrostatic Shielding

One of the unique aspects of medium-voltage AC transformers connected to inverters in battery energy storage system (BESS) and/or solar photovoltaic applications is that the inverters connected to the low-voltage side of the transformer can cause fast transient voltages. This happens when the IGBTs of the inverter are firing to create a sinusoidal waveform (i.e., alternating current or voltage). These transients can have a dV/dt of 1600 V/µs or higher (2400 V/µs, etc.), with peak voltages of more than seven times the rated line-ground voltage of the winding. For these applications, we recommend specifying “inverter duty” insulation, suitable for operation while connected to a pulsed inverter and capable of handling differential-voltage-to-differential-time (dV/dt) surges. This is not a standard insulation level for a typical distribution application.

For a solar inverter application, we recommend adding an electrostatic shield between the high-voltage and low-voltage windings in order to isolate the high-voltage winding from the effect of the fast-rising voltage on the low-voltage winding. The electrostatic shield acts as an additional dV/dt filter and filters the voltage gradient of the pulsed inverter output. The electrostatic shield should have single-point grounding only to avoid circulating current within the shield. See Figure 1.

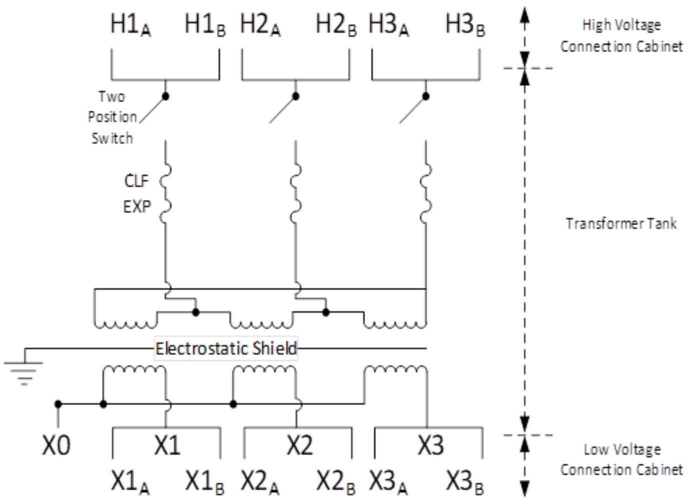

Figure 1
Schematic of the Transformer and Inverter Winding Appropriate for DC Applications

To validate that the transformer design is able to withstand these transient voltage levels, we recommend that a lightning impulse test be performed on the transformer design as a type test. We also recommend that an induced potential test be performed as a routine test on each transformer unit, with an induced voltage of two times the rated voltage of the transformer.

Harmonic Currents

For a BESS application or a rectifier/drive application, transformer loading is non-sinusoidal. The customer should specify a harmonic factor (i.e., “K-factor”) for the application as per ANSI/IEEE C57.110. It is common to specify the transformer with a factor of K-4, which accounts for some overheating caused by harmonics generated from the inverter.

Harmonic Voltages

For a solar inverter application, the transformer may be subjected to non-linear harmonic voltages, which cause additional heating in the transformer core and need to be addressed in the design. We recommend specifying a harmonic voltage factor that corresponds to the harmonic voltage generated by the inverter.

Flux Density

For solar inverter and BESS applications, flux density of the transformer core will vary in operation depending on the level of active and reactive loads on the transformer. In order to ensure that the transformer operating flux density does not exceed the saturation flux density of the core steel used in the transformer, product designers should source appropriate materials such as grain-oriented electric steel (GOES) or amorphous electrical steel for the transformer core. Saturation of the core would add additional harmonics to the system along with other negative consequences such as transformer heating and high noise levels.

To ensure minimum harmonic generation, the saturation flux density of the transformer should be higher than the maximum flux density reached during normal operation. This maximum flux density is obtained at the highest secondary voltage, at full capacitive power generation, and at the highest reference voltage, with minimum continuous frequency.

A 100% capacitive load will be connected on the secondary side of the transformer, which will raise the secondary voltage by a minimum of the inductive impedance of the transformer. Specifiers should target design flux density ≤ 1.8 T at a max. secondary voltage level.

Note that the flux density of the transformer should be calculated and evaluated for each possible voltage connection of the transformer if multiple voltage taps are included in the transformer design. This is especially critical for transformers where power will flow in both directions; changing the voltage tap will also change the volts-per-turn of the transformer in operation.

Guaranteed sound levels (to be measured per IEEE C57.12.90) should be at highest core and winding flux levels, maximum continuous operating voltage, and maximum current levels. In addition, the transformer supplier will calculate and submit the load sound level at top rated MVA base with fundamental current.

Grounding

Many transformers in DC applications have a delta connected high-voltage winding and a wye connected low-voltage winding. However, there are applications that may require a different connection configuration and corresponding grounding scheme. In any configuration, we recommend that the winding that is connected to the inverter or rectifier not be grounded, even if it is wye connected. This is because of common-mode noises and ground loops that can interfere with the operation of the inverter. The use of galvanic isolation allows for different grounding configurations on the different windings to achieve this.

The customer should specify separate galvanically isolated low-voltage windings. There are several benefits to galvanic isolation. For example, galvanic isolation minimizes the flow of common mode currents. It also minimizes the transfer of electrostatic noise between windings. A third benefit of galvanic isolation is that it blocks direct current from passing through the system to the AC lines. Finally, galvanic isolation minimizes the transmission of high-frequency harmonics and noise from one winding in the transformer to another (i.e., low to high or vice versa).

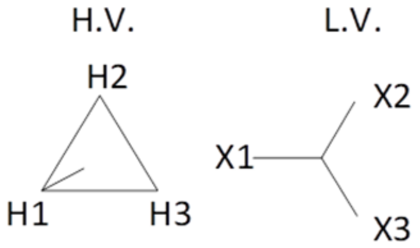

Figure 2
Typical Vector Diagram of Galvanically Isolated Transformer Connection

Partial Discharge (Internal) and Corona Discharge (External)

Insulation on power transformers breaks down over time because of corona discharges, potentially releasing hydrogen and ultimately leading to transformer failure. There is a potential for this to occur anywhere there is a sharp point on the energized metallic parts like lugs, connectors, or conductor splices.

In renewable applications, where power conversion is necessary, customers usually specify lower partial discharge (PD) limits for higher quality transformers. Many customers believe that the lower they specify the PD, the longer the transformer will last. This is true but only to a point. For example, if the specifications call for extremely low PD limits, the accessories installed on the transformer (such as dead front connections with solid bushings) will have a higher PD limit than the actual transformer. This results in a requirement for alternative testing configurations other than a routine test and increases the cost and time to delivery. Specifically, if the PD limit is specified to less than 50 pC, the whole system will likely not pass the routine test and will need to be tested in such a configuration that the dead front bushings are removed from the test circuit. As mentioned, this can result in additional cost and test time because of special test configurations to remove the bushings from the test circuits.

Instead of specifying a routine test for the induced/partial discharge test, we recommend that customers specify a type test that will only be performed for the first unit of a specific design where specified PD is less than 50 pC.

Other Special Features

Because of the complexities and variability of renewable generation, in some DC applications there is a higher risk of faults and surges that originate both within and without the transformer. Specifiers should account for these by adding protective devices. For example, at a minimum, we recommend specifying a current-limiting fuse on the high-voltage side of the transformer to protect the transformer and inverter from system fault currents and surges. Specifiers should also consider adding an internal expulsion fuse in the transformer to protect the inverter from internal transformer faults.

For applications with more frequent switching, we recommend specifying a load break switch or dedicated circuit breaker on the high-voltage side of the transformer. This would still provide the overcurrent protection while also providing a higher level of operational flexibility needed for frequent switching.

Three-winding transformers need to be connected to two separate inverters (i.e., one high-voltage winding with two separate low-voltage windings, each connected to a separate inverter). Four-winding transformers (i.e., two high voltage + two low voltage) are sometimes used in storage applications. Both configurations represent an asymmetric load for the transformer when only one of the two inverters is operating. Accordingly, these transformers must be designed for up to 100% asymmetric loads.

Thermal design of transformers is important for certain DC applications (such as BESS), as these transformers can be run at continuous (near) full rating while charging during the day and discharging at night, for example. Further, in solar applications, the transformer will likely be located in high ambient temperature environments. Specifiers must provide the expected ambient temperature ranges so that the manufacturer can incorporate that into the thermal design.

For further questions or further information on this topic, please contact Jonathan Stewart (jonathan.stewart@nema.org).

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