A Comparison of Grid Simulator Topologies for LVRT/HVRT Testing: Transformer-Pre-Positioned/Transformerless VS. Transformer-Post-Positioned

Low-Voltage Ride-Through (LVRT) and High-Voltage Ride-Through (HVRT) tests are critical verification procedures for assessing the grid adaptability of grid-connected power generation equipment. Their effectiveness is highly dependent on the transient performance of the test power source. This paper compares two mainstream grid simulator topologies—the output-side integrated line-frequency transformer (postpositioned transformer) topology versus the transformer-pre-positioned or transformerless topology—with a focus on their transient response mechanisms. The solution with a line-frequency transformer on the output side poses an inherent risk of deep core magnetic saturation during deep voltage step tests. This risk can lead to severe output voltage waveform distortion and uncontrolled recovery dynamics, thereby severely compromising the validity and accuracy of the test.

Test Background and Requirements

According to core standards such as IEEE 1547-2018, IEC 61400-21, and GB/T 37408, LVRT/HVRT tests require the Device Under Test (DUT) to remain grid-connected and provide the required dynamic reactive power support during and after specified deep voltage sags (e.g., to 0%) or swells (e.g., to 120%), as well as during the subsequent linear or step recovery process. The test power source must be capable of accurately and repeatably reproducing the stringent voltage transient waveforms defined in the standards, especially rapid voltage changes within the millisecond range.

Inherent Defect of the Output-Side Line-Frequency Transformer Topology: Analysis of the Transient Magnetic Saturation Mechanism

Grid simulators that use an output-side line-frequency transformer for voltage regulation perform well in steady-state tests. However, when faced with the rapid, deep voltage steps required for LVRT/HVRT testing, their physical structure leads to a fundamental flaw that is difficult to avoid.

- **Inevitability of Magnetic Saturation**

The core flux of a line-frequency transformer is designed based on steady-state sinusoidal excitation. A voltage command that drops from its rated value to near-zero residual voltage within milliseconds, or vice versa, is equivalent to applying a voltage impulse to the primary winding that contains a large DC component or an extremely high dv/dt. According to Faraday's law of electromagnetic induction, the core flux integrates this sudden voltage change, quickly exceeding the linear magnetization region of the material and entering a state of deep saturation.

- **Chain Reaction of Failures Caused by Saturation**

Once the core is saturated, the electromagnetic characteristics of the transformer change dramatically:

Surge in Magnetizing Current: Saturation causes a sharp drop in magnetizing inductance, and the magnetizing current can instantly spike to tens of times its rated value, exhibiting a sharp impulse characteristic.

Loss of Control and Distortion of the Output Voltage Waveform: The transformer loses its normal voltage transformation capability, and its output voltage is no longer controlled by the commands from the preceding power stage. The expected sinusoidal waveform during the recovery phase exhibits severe clipping or distortion, with a significant increase in harmonic content.

Severe Lag in Transient Recovery: It takes a considerable amount of time for the core to demagnetize from its saturated state and re-establish a steady-state alternating flux, often lasting several to dozens of power frequency cycles. During this period, the power system's ability to control the RMS value and waveform of the output voltage is essentially lost.

Figures 1 and 2 show measured waveforms from a wind farm LVRT test where a transformer-post-positioned grid simulator was used for a voltage sag to 20%.

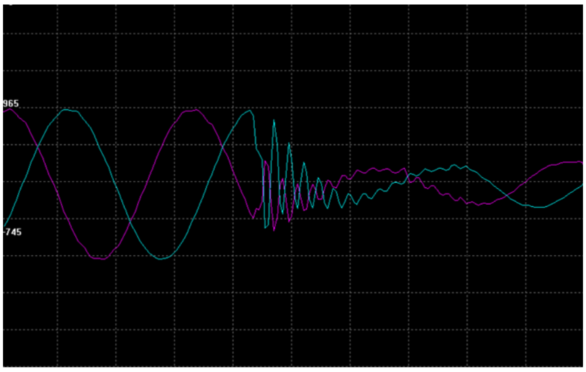

Figure 1 Voltage Drop Waveform

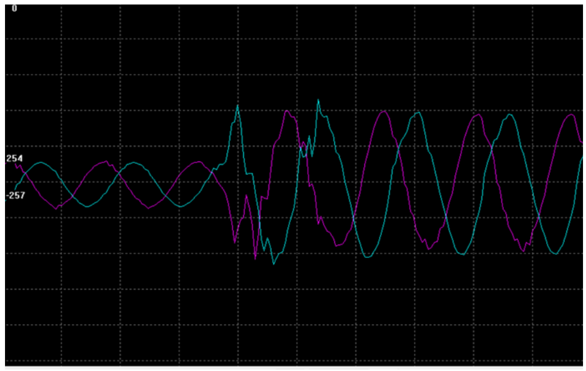

Figure 2 Voltage Recovery Waveform

As can be seen from the figures, when using the transformer-post-positioned grid simulator, the output voltage waveform is significantly distorted. The actual recovery time is as long as approximately 200ms.

Severe Impact on Test Validity

The aforementioned defects directly cause the applied test conditions to deviate from the standard definitions, leading to several consequences:

- **Non-Standardized Test Conditions**

The actual voltage waveform applied to the DUT severely deviates from the ideal recovery curve (e.g., a linear ramp) specified in the standards, undermining the uniformity of the test baseline.

- **Potential for Misjudgment**

Harmonics, low-frequency components, and slow recovery dynamics generated by the power source's own distortion may abnormally trigger the DUT's protection mechanisms (e.g., overcurrent, over-harmonic protection) or cause its control loop to become unstable. This can cause a device that complies with real grid conditions to fail the test (false negative risk). Conversely, it might also mask a device's deficiencies under rapid, real fault clearing (false positive risk).

- **Distorted Assessment of Dynamic Reactive Support**

The device's reactive current injection strategy during voltage anomalies relies on the precise perception of the grid voltage's phase angle and magnitude. The distorted and unpredictable dynamics from the power source's output make the assessment of the device's reactive support performance unreliable.

Recommended Solutions and Topology Selection

To ensure the precision, reliability, and standard compliance of LVRT/HVRT tests, the following grid simulator topologies are recommended:

- **Transformer-Pre-Positioned or High-Frequency Isolation Topology**

This structure places the line-frequency transformer on the input side or uses high-frequency isolation, with the output stage generating voltage directly through an LC filter via fully-controlled power devices (e.g., IGBTs). This structure fundamentally eliminates the possibility of saturation in the outputside core during testing.

- **Direct Transformerless Topology**

This approach uses technologies such as multilevel or H-bridge cascades to generate high-quality AC voltage without a line-frequency transformer, offering extremely fast dynamic response (microsecond level).

Grid simulators with these advanced topologies can:

- Accurately reproduce the full range of standard test waveforms from zero voltage to overvoltage.
- Achieve sub-millisecond voltage step and linear ramp responses.
- Provide pure sinusoidal waveforms with extremely low Total Harmonic Distortion (THD).
- Possess four-quadrant operation capability, realistically simulating the source/load characteristics of the grid.