

ABSTRACT

Increasing renewable-energy integration and the growth of large electrical loads are reshaping power-system operation and interconnection planning. Converter-interfaced resources change how voltage and frequency support are provided, while electronic loads, including AI data centers and electrified industrial facilities, can impose substantial and rapidly varying demand. Load-origin ramps and oscillations can propagate toward the upstream grid. In the opposite direction, grid-side voltage disturbances can disrupt sensitive equipment and cause a sudden reduction in demand when loads disconnect or transfer to backup supplies. Bidirectional inverter-based resources operating in grid-following or grid-forming modes can influence how these disturbances propagate across the connection. Their use also calls for reliable synchronization, controlled energization of connected equipment, including power transformers, and effective dynamic operation after connection.

This dissertation advances the modeling, control, and assessment of bidirectional inverter-based resources from initial connection through large-load operation. It first addresses synchronization through a current-based method that obtains grid-phase information from switching-cycle current measurements while controlling startup current. Because connection can also require energizing power transformers, the research develops a complementary method that combines pre-fluxing, coordinated startup-angle selection, and virtual resistance to suppress inrush and damp residual transients. Laboratory demonstrations support both methods.

The dissertation then examines large, rapid changes in load demand. Considering a grid-following inverter, an integrated electromagnetic-transient (EMT) model combines a bidirectional inverter, a prescribed load ramp, and the upstream network. As demand changes, a load-related command adjusts the inverter's active-power reference to counter the ramp, leaving a residual power excursion at the grid connection. Given the complexity of these detailed models, an analytical approximation has been developed to predict the peak excursion as a function of the load ramp rate, ramp duration, and the inverter's response, characterized by its rise time. Comparisons with the EMT simulations evaluate the prediction's accuracy by quantifying the percentage error in the peak grid-power excursion.

Moreover, large electronic loads can also exhibit smaller oscillatory variations around an operating level. The dissertation therefore examines how a grid-forming inverter responds to these variations while its active-power reference remains fixed. Its natural power response and electrical coupling determine how much of each fluctuation is buffered locally and how much reaches the upstream grid. The EMT study considers a detailed dynamic data-center load model that includes rectifier, DC-link, UPS, computing, and cooling dynamics. A small-signal, circuit-derived analytical model predicts frequency-dependent power sharing for variations in actual terminal demand. Variations in virtual inertia, damping, and active-power droop show how tuning shapes that response.

Complementary frequency scans assess disturbance propagation in both directions on the integrated network. For load-origin fluctuations, perturbations to the computing command measure both the resulting terminal demand and the active-power oscillations reaching the grid, allowing comparison with the analytical power-sharing prediction. For grid-side voltage variations, paired upstream voltage-magnitude and phase perturbations identify the site's terminal admittance and assess coupled point-of-common-coupling (PCC) voltage sensitivity. Matched magnitude perturbations also quantify the resulting PCC-voltage oscillations. A unified small-signal network formulation connects load-power propagation with PCC-voltage sensitivity, while sampled loop-eigenvalue and multiloop disk calculations assess grid-site interaction under the stated assumptions.

The results show how inverter control governs connection, energization, and subsequent dynamic support of large loads. Grid-following response characterization enables prediction of residual grid power during finite-duration load ramps. Under grid-forming operation, the inverter reduces grid-facing active-power oscillations at several studied frequencies and reduces PCC-voltage oscillations under the studied grid-side magnitude variations. Controller tuning and network coupling shape these responses, with trade-offs among disturbance attenuation, damping of reduced modes, and sampled coupled-system robustness. Together, the research provides methods for assessing bidirectional inverter-based resources from initial connection through large-load operation.