Probabilistic Assessment of Inverter-Based Flexibility in Distribution Grids

A Monte Carlo based Load Flow Study in a Swiss LV Grid with High DER Penetration

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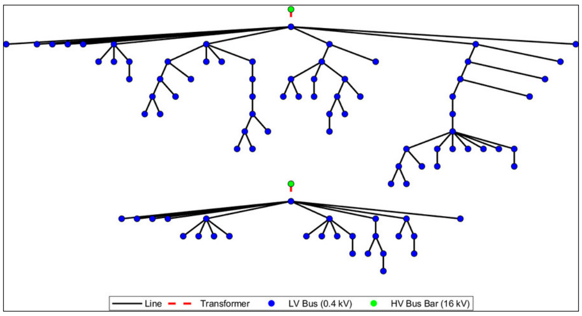
Introduction: The transition toward a decentralized and decarbonized energy system accelerates the integration of distributed energy resources (DERs), particularly photovoltaic (PV) systems, into low-voltage (LV) distribution grids. This development challenges conventional grid planning practices, which typically rely on static worst-case assumptions and deterministic reinforcement strategies. In response to these limitations, this thesis develops a probabilistic simulation framework to evaluate the impact of DERs on the operational state of a Swiss LV grid, focusing on voltage quality, thermal loading, and the role of inverter-based control strategies.

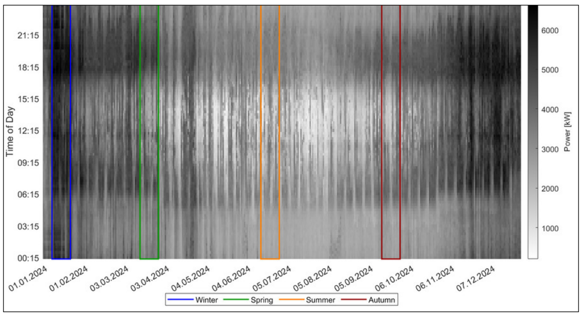
Approach: The study examines a representative Grid Level 7 (GL7) grid operated by Technische Betriebe Würenlos (TBW), using real geospatial and electrical infrastructure data. A modular simulation pipeline, implemented in Python using pandapower, enables automated time-series simulations that incorporate measured or synthesized load and generation profiles, spatial allocation of rooftop PV systems, and local inverter controls. Three control strategies are compared: (i) no control, (ii) Volt-Watt control (P(U)), and (iii) Volt-Var control (Q(U)). Monte Carlo Simulation (MCS) is used to capture uncertainties in DER allocation, irradiance, and load behavior. Each iteration evaluates constraint violations via a power flow calculations at 15-minute resolution.

Result: The results show that uncontrolled PV feed-in frequently causes voltage violations and transformer overloads, particularly in summer. Both P(U) and Q(U) improve stability: P(U) curtails peak voltages but reduces active power output, while Q(U) maintains compliance with minimal energy loss. The probabilistic analysis highlights seasonal risk patterns and the limitations of static planning under high DER variability. Inverter-based control thus emerges as an effective non-wires alternative (NWA), aligned with recent Swiss regulatory changes. This supports a shift toward flexibility-first planning using adaptive controls and data-driven tools.

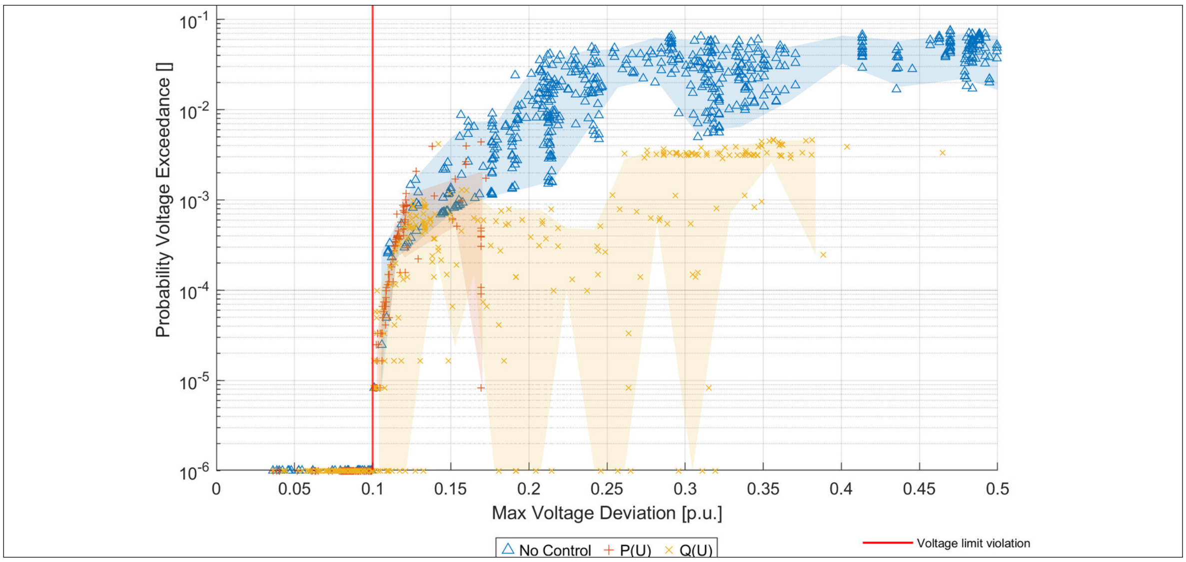
Analyzed subgrids of the TBW grid.
Own presentment



Time-series heatmap of active power injection at the grid interface (2024), with selected seasonal windows highlighted.
Own presentment



Joint distribution of maximum voltage deviation and voltage limit exceedance probability for each control strategy
Own presentment



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