Doctoral Dissertation
Doctoral Program in Electrical, Electronics and Communications Engineering
(36^{th} cycle)

Clustering-based Categorization of Power Systems Based on Dynamic Responses

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Politecnico di Torino
September 2025

Summary

Energy sustainable transition is a crucial and urgent pathway for ensuring a sustainable future. This transformation focuses on shifting the global energy sector from a heavy dependence on fossil fuels to a broad implementation of zero-carbon resources. This shift is not just desirable, but essential for addressing the pressing challenges of climate change and environmental degradation. The widespread utilization of Renewable Energy Sources (RES) is fundamental in this context, as RES play a critical role in decarbonizing the energy sector, significantly reducing CO_2 emissions, which is essential for mitigating the adverse impacts of climate change. In this context, the electricity sector has a primary role in the energy transition process, undergoing deep changes that disrupt its longstanding paradigms. Traditionally, electrical generation is based on conventional power plants, that are synchronous and centralized. The transition disrupts this paradigm, involving a shift to non-conventional RES that are non-synchronous and decentralized. This shift poses significant challenges in managing transmission systems, requiring innovative solutions and a deeper understanding of new operational dynamics. In this context, understanding the complex frequency dynamics at the network nodes is becoming more and more important, as it directly impacts the stability and reliability of the power grid.

This dissertation aims to address these challenges by illustrating the use of clustering algorithms to group power system nodes based on their dynamic responses to large disturbance events. Clustering, a data-driven approach, helps identify patterns and similarities in the dynamic behavior of different nodes, which can provide insights into the overall stability and performance of the power grid. A comprehensive review of the scientific literature has been performed, to identify the limitations and weaknesses of various clustering approaches, particularly when applied to real-world case studies and practical applications. An analytical framework is presented, beginning with the selection of disturbance events to analyze. The features used as inputs to the clustering procedure are then defined, ensuring they capture the

essential aspects of the dynamic responses at the system nodes. These features include parameters derived from the node dynamic responses and distance matrices calculated from various metrics such as electrical distance, Euclidean distance, and global distances like Hausdorff and Wasserstein.

A thorough and statistically significant analysis is conducted to determine the optimal number of clusters. This involves comparing the results obtained from different clustering algorithms, particularly those that involve random elements in their solution process. The analysis is aimed at ensuring robustness and reproducibility of the clustering outcomes. The calculations are performed using the dynamic model of the Great Britain 36-bus electricity transmission network, which provides a realistic and complex testbed for validating the clustering approach.

Furthermore, a second test case has been developed, based on the model of the Italian electricity transmission network, so that the method could be tested on a system with a larger number of nodes.

The most significant findings of this study are obtained by implementing the spectral clustering algorithm with inputs derived from the Wasserstein distance matrix. Spectral clustering is chosen for its ability to handle complex and high-dimensional data, making it suitable for capturing the intricate dynamics of power system nodes. The Wasserstein distance, in particular, is effective in measuring the dissimilarity between the probability distributions of the node dynamic responses, providing a more nuanced understanding of their behavior.

In conclusion, this dissertation contributes to the field of power system analysis by providing an effective methodology for clustering power system nodes based on their dynamic responses to disturbances. The insights gained from this approach can inform the design and management of more resilient and stable power grids, facilitating the smooth integration of RES and supporting the broader goal of a sustainable energy future. The findings underscore the importance of advanced analytical techniques in addressing the challenges of the energy transition and highlight the potential of clustering algorithms in enhancing the understanding of power system dynamics.