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Resilience Analysis For The Electric Power Transmission Grid With A Criticality Measure Based On Cascade Simulations

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Electricity transmission system operators (TSOs) are responsible for maintaining the security of the power system, while the security of electricity supply is the most important objective of the European Union (EU) electricity sector regulations (ENTSO-E, 2009; COMMISSION REGULATION, 2017). Both may be threatened by forced outages (TEIAS, 2015; Behnert and Bruckner, 2018; ENTSO-E, 2021; Stankovski et al., 2023), whether they are intentional (e.g. intentional incident) or not (e.g. weather-related or technical incidents).

Every TSO should prepare and adapt the power system to provide a reliable and uninterrupted energy supply to its control area. Considering the increasing complexity of the electric power system operation, the "deterministic" N1 rule should be extended (or even replaced) with methods that better take into account the variability of the system states (Wawrzyniak et al., 2018; Wawrzyniak et al., 2020). Practical consideration of the interconnected and synchronized European power system requires modelling the whole power system or a significant part thereof, at least at the highest voltage levels. This translates to a requirement of handling tens of thousands of power lines, thousands of buses and transformers.

The first step towards this is to identify which network elements (substations, transmission lines, transformers, generators, etc.) are the most critical for the security of electricity supply. Identification of such elements of the power system may be expressed by relevant criticality measures and calculated in extensive simulations.

The simulation should include both events resulting from an intentionally forced outage ("incident"), as well as normal changes of the system state, resulting from e.g. renewable generation level (Beyza and Yusta, 2021), energy import and export, maintenance-related planned outages and non-intentional grid incidents (resulting from e.g. technical issues or human error). The simulation should then follow the coinciding initiating events through a possible cascading sequence triggered (Panel, 2021; Portante et al., 2011; Portante et al., 2014), through the post-cascading states, such as islanding or a blackout, to the system restoration actions. Such processes could last from minutes to months. The actions required during the restoration are a consequence of the cascading sequence. Therefore, it may be assumed that the incident and cascade simulation provide enough information to assess the criticality of network elements.

We propose a detailed multi-stage simulation approach, as well as incident impact measures and a resulting criticality measure for network elements. The impact measure represents the influence of forced outages modelled by the energy not served (ENS) due to the incident. The criticality measure of each network element is defined based on risk assessment methods, by taking into account the information on all the cascading simulations from different incidents affecting that network element, and recognized under different power system conditions (exogenous and endogenous).

This criticality definition is meant to support a TSO in deciding where to improve the resilience of the power system, in particular by minimizing the risk in one of the following ways:

- reducing the vulnerability to the incident, by increasing the physical security of the network elements;
- reducing the impact of an incident (impact measure), by improving the network with investments which affect the power flow, consequently lowering the value of the impact measure;
- and reducing both vulnerability and impact, by increasing redundancy of selected network elements.

This work is aimed at providing a semi-automated tool capable of calculating the network element criticality to support the strategic process of identification of the critical elements of the power system.

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