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The impact of increased decentralised generation on the reliability of an existing electricity network

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HIGHLIGHTS

- Adding significant amounts of DGs can seriously reduce network reliability.
- The networks become more reliable when the strategy improves the local power balance.
- Communication and effective power control mechanisms are shown to be crucial.

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ABSTRACT

This study evaluates the impact of decentralisation on the reliability of electricity networks, particularly under stressed conditions. By applying four strategies to add decentralised generators to the grid, the impact on network reliability has been assessed, where the blackout impact has been defined as the product of the relative blackout size and the relative blackout frequency. The general approach taken to decentralise the network is to replace the aggregated generation capacity at an existing node with three new nodes representing the total generation capacity of multiple decentralised generators. Two different networks have been used: a reduced and aggregated version of the electricity network of Great Britain (GB) and the IEEE 39 network, and each of them has been assessed for decentralisation based on conventional energy sources and for decentralisation based on intermittent renewable energy sources. The results suggest that adding significant amounts of DGs, especially if it is intermittent, can seriously reduce network reliability; however, various approaches regarding the decentralisation strategy and management of the resulting network can mitigate the negative effects.

1. Introduction

The future of electricity generation will become more and more decentralised. This is primarily due to the increasing amount of wind and solar energy systems, supplemented by the installation of other smaller-scale generation facilities (e.g. hydro, anaerobic digestion and combined heat and power (CHP) systems) [1]. Since the decentralisation changes the traditional centralised power supply, the network operators tend to have less control over the power generators. Moreover, the existing electricity network will be used in a different way than was envisaged during its original design, since surplus power in a distribution grid might reverse the direction of power flow. In general, the grid is required to become more flexible in order to balance the supply and demand [2,3].

It is well-known that a national electricity system consists of multiple networks with different voltage levels which are interconnected by transformers; in the UK, these levels include a high voltage (HV) transmission network (400 kV, 275 kV and 132 kV), a medium voltage (MV) distribution network (33 kV and 11 kV) and a low voltage (LV) distribution network (230 V). DGs directly connected to the distribution grid such as rooftop PV are defined as distributed generators [4]. Distributed generators will mainly result in a lower electricity demand in the HV grid, since part of the demand will be met by these local generators [5]. However, under the influence of cost reductions in renewable power generation technologies combined with policies favouring low carbon generation, the share of distributed energy systems will likely increase further. With higher shares of distributed energy systems, it becomes more likely that a surplus of power generated in a distribution grid will be transferred to the MV and eventually the HV grid.

The Paris agreement aims to keep the "global temperature rise this century well below 2 Celsius above pre-industrial levels and to pursue

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efforts to limit the temperature increase even further to 1.5 degrees Celsius" [6]. To meet this goal, it is likely that governments will decide to develop more large-scale energy projects such as offshore wind farms. These (grouped) DGs will be connected to the HV grid, which will change the power flow distribution in the HV grid. Eventually, current fossil fuel based power plants will be phased out. The combination of distributed energy systems, decentralised energy systems and the phasing out of existing fossil fuel based generators will lead to different load profiles of the HV grid. For distributed energy systems like rooftop PV, it might be hard to plan and control the locations of the installations, unless the regulatory practice changes dramatically in order to cope significant network management challenges. For large scale energy projects such as wind farms, the locations can be more readily planned. It is therefore interesting to know what the impact of the locations of new DGs will be on the reliability of the grid, so that system planners could take this into account.

In this study, we are interested in the impact of the above future changes on the reliability of the power supply of a nationwide system. Consequently, we will focus on the HV transmission grid to evaluate the impact of introducing DGs, through changing the level (and, in the case of renewable DGs, the temporal pattern) of supply at the affected transmission nodes, on the reliability of the existing network structure.

For electricity grid operators, the reliability of the network, which relates to the security of supply for customers, is one of the most critical concerns. Since society depends increasingly on electricity, power outages should be minimised in order to avoid major disruptions to normal daily life potentially leading to high societal costs [7–9]. The main objective of network operators is to ensure a reliable electricity supply while minimizing the operating costs.

Network operators use economic dispatch (ED) models to minimize the operating costs of a network subject to network constraints. To account for risks of failing network components, such as generator and line outages, the system operators extend the ED models by including additional security constraints [10]. These models are known as security-constrained economic dispatch models (SCED) [10–13]. Typically, network operators will make sure that a network satisfies the N-1 condition, meaning that uninterrupted electricity supply is still guaranteed if a single network component fails [10,14,15]. To improve the network, network operators have multiple ways to address reliability issues. One of these is transmission expansion planning (TEP) [16], which studies which transmission lines should be upgraded and where it makes sense to create extra lines. For example, the inclusion of wind power in the grid has to be taken into account in TEP [17,18].

Historically, the HV grid has been very reliable due to safeguards such as the N-1 condition and capacity margins in both generation and line capacities. Currently, the reliability of the electricity networks in Western Europe are very high and blackouts are therefore very unlikely, for example the reliability of UK's national grid has been 99.999998% during the financial year 2015/16 [19]. However, future developments and changes such as the decentralisation of electricity supply might change load profiles leading to different stresses in the network. At the same time, highly unlikely events do occur, in November 2016 a boat's anchor caused serious damage to the France-UK interconnection cables, which typically supply about 5% of UK's electricity [20]. Likewise, accidents with defense helicopters hitting transmission cables are rare, but have happened occasionally [21]. If such events happen when the electricity system is already strained by high inputs of renewables, this might lead to large blackouts.

A lot of research has been focused on the reliability, vulnerability or robustness of a power network. A study by Koç et al. [22] presents a metric to quantify the network robustness with respect to cascading failures. The metric takes both flow dynamics and network topology into account. In another paper, the same authors use the effective graph resistance as a metric to assess the robustness of a network topology against cascading failures by targeted attacks [23].

Few studies use simulations to quantify this impact. On the connection between decentralisation and network stability, Rohden et al. [24] studied the self-organised synchronization of the nonlinear dynamics of complex power networks with increasing decentralisation of the British power grid, and found that more decentralised grids may have moderately lower dynamic stability, but that they become more robust to structural failures at the same time due to the increased self-organised synchrony. Zerriffi et al. [25] evaluated network robustness and costs of centralised and distributed gas and electric power distribution systems for different failure modes. They applied a modified IEEE reliability test system and evaluated the availability of the individual generating units as a key variable in their Monte Carlo simulation, with the loss of energy expectation as the metric to assess the reliability of various networks. They found that electric power systems with DGs improve reliability. However, they assumed that power lines in the central part of the grid experience no line outages and their approach did not include power flow dynamics and thus no cascading failures.

To assess blackout dynamics in power networks, Carreras et al. [26] developed the ORNL-PSerc-Alaska (OPA) model. Using the well-known DC power flow model, the core of the simulation includes slow and fast dynamics. During the slow dynamics, the energy demand and generation capacity will be increased by a small amount. The fast timescale represents the actual operation of the network, particularly the power line outages by relay protection[1] which includes some probability of operating incorrectly, redistribution in flows following outage and subsequent further line outages (a phenomenon known as the cascading effect). The authors examined the sensitivity of several network structures by varying model parameters. They found that "although the size of the network affects the sizes of the cascading events, it appears to have little impact on the frequency of the events" [26].

Mei et al. [27] adapted the OPA model of Carreras et al. by introducing two changes to be consistent with practical systems, namely decreasing the "tripping" probability of an overloaded line, and including a planning function inside the slow dynamics part of the simulation. This planning function increases the line capacities of overloaded lines based on an initial power flow simulation before the actual power flow will be simulated.

Focusing on the impact of increasing decentralisation on power network reliability, this study is designed to quantify, through simulation studies, the blackout behaviour for electricity networks with different levels of decentralisation considering both power flow dynamics and network structural features, which has not been carried out before. The novelty of this study is to apply an existing power flow model - which has been developed to analyse blackout dynamics in a grid - to an electricity network which will be decentralised incrementally, in order to analyse the reliability of decentralisation. By applying different strategies, the results can give insights on the best approaches to increase the reliability of a highly decentralised power network. In particular, reliability in this study is quantified by the blackout size and frequency, with a focus on line failures, not on generator failures.

Note that in a real system, the risks of the same blackout frequency and size can be different, because of dissimilar economic or social ties related to specific nodes [28], however, this study simplifies some of these real-world complexities, to allow focus on a set of key technical attributes of the decentralisation process.

This paper is organised as follows. The next section will present the methodology, which starts with a general description of electricity grids and a more specific description of the two applied electricity networks. Subsequently, the power flow model and the modelling of DGs will be discussed. The latter will distinguish two cases: (1) conventional DGs and (2) renewable DGs. The results are presented in Section 3, which is followed by a discussion section. The paper concludes with the main

[1] Power lines are protected by relays which can trip a circuit breaker when a fault is detected (e.g. over-current or over-voltage).