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Designing reliable and resilient smart low-voltage grids

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ABSTRACT

The electric power grid is a critical infrastructure that delivers electricity from power generation sources to consumers. At this time, renewable and distributed sources of electricity as well as new technologies that introduce large loads are significantly changing load profiles in low-voltage grids. This trend calls for reassessing the structure of low-voltage grids to examine if they can safely accommodate the new load profiles. The future smart grid will also rely on information and communications networks to support decentralized power distribution. The information and communications network nodes may depend on the grid for power supply, leading to bidirectional interdependence between the two types of networks that could affect the reliability of the power grid.

This paper focuses on the problem of enhancing the reliability of future low-voltage grids by improving their structure and dealing with their interdependence with information and communications networks. The paper investigates the structural features of a low-voltage grid and assesses their influence on the ability of the grid to handle new load profiles. Concepts from complex networks theory are used to derive relevant structural metrics that characterize the structural properties of low-voltage grids and performance metrics are proposed to assess their operational performance. Several low-voltage networks are analyzed under various loading scenarios to observe the influence of structural metrics of a low-voltage grid on its operational metrics. Based on this analysis, a constraint programming formulation is proposed for the cost-optimal and robust structural design of a low-voltage grid. In addition, a design algorithm is proposed that considers the interdependence of information and communications network nodes on power grid nodes to increase the reliability of the grid.

1. Introduction

In the traditional electric power system, power is produced by large-scale generators. The generated power is stepped up to a high voltage (typically 110–380 kV) and transported over long distances by the high-voltage transmission grid to transmission substations. At the transmission substations, electric power is stepped down to medium voltage, typically in the range of 10–20 kV. The power is then transported over the medium-voltage grid to medium-voltage to low-voltage (MV/LV) transformers, where the power is further stepped down to low voltage (typically 230 V) that is suitable for end consumers. The low-voltage grid distributes power to the end customers.

In a classical low-voltage grid, end consumers are connected to a transformer in a radial structure as shown in Fig. 1. This radial structure is designed for unidirectional supply of power

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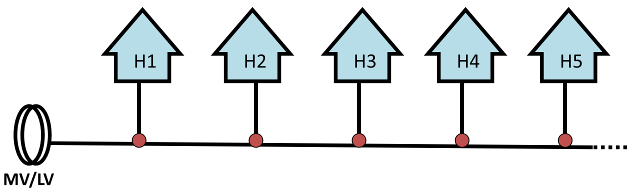

Fig. 1 – Typical radial low-voltage grid.

from the transformer to end consumers with small loads (e.g., households with small appliances).

To safely operate a low-voltage grid, the voltage levels at all the nodes and loads in all the cables should be maintained within their operational boundaries. In a low-voltage grid, the voltage level at the transformer is stable while the voltage levels at the other nodes may vary depending on the power flows. During normal operation, the voltage level at each node should remain within the range of 90–110% of 230 V (the standard in most European countries). In addition, each cable in a low-voltage grid has a maximum load capacity that should not be exceeded. Violations of these constraints can lead to the deterioration of the quality of the power delivered and, possibly, network breakdowns. As it turns out, the node voltages and cable loads are easily maintained within their operational ranges because the low-voltage grid connects households with conventional appliances that present small loads to the grid.

However, the power grid is undergoing a major transformation. The push towards green energy, energy efficiency and energy security, has resulted in the incorporation of distributed power sources such as solar panels, wind turbines and micro-CHPs (combined heat and power plants) in the electric power grid. As a result, end consumers are becoming “prosumers” who locally generate electric power and feed their surplus power back to the grid. Moreover, new devices such as electric vehicles and heat pumps that introduce large loads are becoming increasingly common. As more distributed resources become available, decentralized energy exchanges will take place in the power grid. The decentralized exchanges will involve information flow between different elements in the grid. Indeed, information and communications networks will be deployed at all levels of a power grid to support information flow [37]. Thus, a low-voltage grid would depend on information and communications networks and the information and communications network nodes themselves would depend on the power grid for power supply.

These new developments will revolutionize low-voltage grids because they are the portion of the power grid that would incorporate the vast majority of distributed energy sources and new devices. Although low-voltage grids have traditionally been a passive part of the power grid to which small-scale consumers are connected, its role and relevance will increase with the new developments.

These trends raise certain concerns. One concern is that low-voltage grids that were originally designed to supply power to traditional passive consumers might not be able to support the new load profiles. In particular, there is concern if low-voltage grids can maintain safe operational boundaries of node voltages and cable loads. Although the classical residential loads usually do not cause significant voltage drops and stresses on cables, the power injected back to the grid by prosumers and the large loads imposed by electric vehicles and heat pumps could cause significant voltage deviations and cable overloads, leading to reduced power quality and infrastructure constraint violations. The problem will become even more critical when households consume a lot of power or inject a lot of power back into the grid.

Another concern is that the mutual interdependence between a low-voltage grid and its supporting information and communications network could negatively impact power grid reliability [15,26]. For example, the failure of an information and communications network node could lead to inaccurate decisions about power flows, which may result in the voltage levels at some nodes of the low-voltage grid violating their operational boundaries. Also, the failure of power grid nodes could, in turn, lead to failures in one or more information and communications network nodes, and vice versa.

This paper attempts to address the two major concerns discussed above with the goal of improving the reliability of future low-voltage grids. The focus is on improving the structure of low-voltage grids as well as dealing with their interdependence with information and communications networks. In order to improve the structure of a low-voltage grid, the paper examines how its topological structure can affect operational performance. Concepts from complex networks theory are employed to characterize the topological structure of a low-voltage grid. Operational performance indicators are used to capture how well the node voltages and cable loads are maintained within their operational boundaries. Moreover, certain resilience metrics are engaged to analyze the robustness of a low-voltage grid to attacks. Based on these findings, a constraint programming formulation is proposed to optimize the critical structural features of a low-voltage grid. Additionally, the impact of the interdependence of a low-voltage grid and its supporting information and communications networks on the operational performance of the power grid is analyzed under different scenarios and an algorithm is proposed for dealing with the interdependence to enhance power grid reliability and resilience.

2. Related work

In complex network analysis, real networks are represented by graphs and their dynamics are analyzed statistically to identify characterizing network features. Several studies have been conducted on the power grid (see, e.g., [1,3,7–9,11,13,14,16,17,19–22,27,29–31,33–35]) following the major blackouts that occurred in North America and Italy in 2003. These studies have focused on developing appropriate graph models of the power grid (e.g., [13,35]), specifying graph metrics that characterize the power grid (e.g., [9,27]) and analyzing power grid vulnerabilities (e.g., [1,31]). Most of the studies characterize the power grid in terms of classical topological metrics such as network connectivity; however, some of the studies employ topological metrics that reflect the electrical properties of the power grid. While most of the work related to complex network analysis has involved the high-voltage grid, recent research by Pagani and Aiello [27] on the structure of medium-voltage and low-voltage grids has identified the influence of the topological structure of a grid on the cost of decentralized power trading.