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Power grid complex network evolutions for the smart grid

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HIGHLIGHTS

- Network design for smart grid.
- Complex network for power grid design.
- Effects of topology on the cost of electricity distribution.
- Complex network literature topologies comparison for smart grid.

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ABSTRACT

The shift towards an energy grid dominated by prosumers (consumers and producers of energy) will inevitably have repercussions on the electricity distribution infrastructure. Today the grid is a hierarchical one delivering energy from large scale facilities to end-users. Tomorrow it will be a capillary infrastructure at the medium and low voltage levels that will support local energy trading among prosumers. We investigate how different network topologies and growth models facilitate a more efficient and reliable network, and how they can facilitate the emergence of a decentralized electricity market. We show how connectivity plays an important role in improving the properties of reliability and path-cost reduction. Our results indicate that a specific type of evolution balances best the ratio between increased connectivity and costs to achieve the network growth.

1. Introduction

Something is changing in the way energy is both produced and distributed, due to the combined effects of technological advancements and the introduction of new policies. In the last decades a clear trend has invested the energy sector: that of *unbundling*. This is, the process of dismantling monopolistic and oligarchic energy system, by allowing a greater number of parties to operate in a certain role of the energy sector and market. The goal of unbundling is that of reducing costs for the end-users and providing better services through competition (e.g., Refs. [1,2]). From the technological perspective, new energy generation facilities (mainly based on renewable sources) are becoming more and more accessible. These are increasingly convenient and available at both the industrial and the residential scale [3]. The new actors operating in this scenario, who are both producers and consumers of energy, also known as *prosumers*, are increasing in number and will most likely demand a market with total freedom for energy trading [4]. In this future setting, the main role of the high voltage grid will change, leaving more space and relevance for the distribution grid (i.e., medium voltage and low voltage). In fact, the energy interactions between prosumers will increase and occur at a rather local level, therefore involving the low and medium voltage grids, inevitably calling for an upgrade of the enabling distribution infrastructure in order to facilitate local

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energy exchanges. This vision for the infrastructure is comparable to a ''peer-to-peer'' system on the Internet, rather than the current strictly hierarchical system. But how will the infrastructure evolve or change to enable and follow this trend?

The starting point of our study is to assume that the infrastructure must change to accommodate the new way of producing and distributing energy [5]. The tool for our investigation is that of Complex Network Analysis (CNA) [6–9]. In particular, in the present case we use CNA as an engineering tool to synthesize networks using topological models coming from the literature of modeling the evolution of technological, infrastructural and social network. Our goal is to provide a methodology to support the change by statistically looking at how the current infrastructure should evolve and estimating the benefits of the evolutions while keeping an eye on the associated costs. In a nutshell, we intend to provide the foundations for a decision support system for high level planning the upgrade of the distribution network. We base our study on actual samples of the Dutch grid and previous results that provided an initial economic analysis of the possible barriers from an infrastructure point of view to delocalized trades [10]. The present paper considers growth models for network topologies providing an analysis of which models suit best the purpose of local energy exchange. In order to evaluate the adequacy of the generated networks, we develop a set of metrics, based on CNA literature and our own experience, that capture the various aspects that networks suited for small-scale energy exchange need to satisfy. It is then quite straightforward to compare the results of the synthetic models with the real samples and, on that ground, propose network models that best suit a prosumer-based local energy exchange. Finally, a quantitative evaluation of how the improvement in the topology directly influences electricity transport prices is then possible considering the metrics defined in the literature. In simple words, we look at the possible evolutions of the current grid that would make most sense to achieve the vision of a smart grid from the point of view of the prosumer. The study is statistical and can provide a budgeting and decision support tool for governments and utilities.

We remark the novelty of this proposal with respect to previous CNA studies of the power grid. In the survey work [11], it is emphasized that the use of CNA is mainly on the high voltage networks to get information on resilience to failures, while the medium and low voltage grids have been mostly neglected. Another novelty is the use of CNA not as a tool for pure analysis of the existing infrastructure, but to exploit it as an infrastructure design tool. Using Graph Theory in the design of distribution systems is not completely new, several studies have incorporated Graph Theory elements in operation research techniques for grid planning [12], but never, to the best of our knowledge, has Graph Theory been combined with global statistical measures to design the grid. In addition, we ground the design methods into investments by taking into account the costs of grid cabling based on the types of cables typically used in real distribution networks (i.e., Northern Netherlands medium and low voltage network samples). The exploitation of the advancement in network studies and topology provides a new way of looking at the development of the power grid infrastructure. A future grid that will have much of its production decentralized will call for an adequate infrastructure whose topology and development has to take advantage of the modern development of network models and network metrics to analyze its properties. In addition to the physical constraints dictated by the Kirchhoff's laws, the grid will have to obey a set of metric and constraints coming from the scientific approach at studying networks to have an efficient and optimized infrastructure. In summary, the paper discovers which topologies according to CNA-based metrics are best suited in terms of performance and reliability of the infrastructure for a local energy exchange, gives an estimation of the cabling cost for the realization of such topologies and assesses the advantages from the electricity distribution point of view of the proposed topologies compared to the current ones. From the point of view of Power Systems, we propose a new way to look at distribution grid planning. Our proposal is to consider statistical tools for estimating benefits and costs of upgrading the infrastructure. This can be a high-level decision-support tool in the hands of grid planners and governmental organizations. To the best of our knowledge, this type of approach to power grid planning, called for by the shift towards decentralized generation, is novel.

The paper—which is a condensed version of the on-line available and unpublished technical report [13] to which we refer for detailed simulation data—is organized as follows. Section 2 describes the main properties of the network models considered, while the metrics utilized to compare the properties of the various generated graphs are described in Section 3. The analysis and discussion of the results is presented in Section 4. The economic aspects of denser networks are evaluated in Section 5, while an overall discussion of the evolution of topologies is in Sections 6 and 7 reviews the related work, while concluding remarks are in Section 8. Appendix provides definitions of the metrics used in the evaluation of the models.

2. Modeling the power grid

We resort to complex network analysis, a branch of Graph Theory having its root in the early studies of Erdős and Rényi [14] on random graphs and considering statistical structural properties of very large graphs. CNA is a relatively young field of research. The first systematic studies appeared in the late 1990s [15,16] having the goal of looking at the properties of large networks with a complex systems behavior. Afterwards, CNA has been used in many different fields of knowledge, from biology [17] to chemistry, from linguistics to social sciences [18], from telephone call patterns [19] to computer networks [20] and the web, to virus spreading [21], logistics and also inter-banking systems [22]. Men-made infrastructures are particularly interesting to study under the CNA lenses, especially when they are large scale and grow in a decentralized and independent fashion, thus not being the result of a global, but rather of many local autonomous designs. The power grid is a prominent example. In this work, we consider a novel approach both in using CNA tools as a design instrument (i.e., CNA-related metrics are used in finding the most suited medium and low voltage grid for local energy exchange) and in focusing on the medium and low voltage layers of the power grid. In fact, traditionally, CNA studies