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From the grid to the smart grid, topologically

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HIGHLIGHTS

- Network evolution for Smart Grid.
- Complex Network for Power Grid design.
- Effects of topology on the cost of electricity distribution.
- Strategy comparison for link addition in networks.

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ABSTRACT

In its more visionary acceptation, the smart grid is a model of energy management in which the users are engaged in producing energy as well as consuming it, while having information systems fully aware of the energy demand-response of the network and of dynamically varying prices. A natural question is then: to make the smart grid a reality will the distribution grid have to be upgraded? We assume a positive answer to the question and we consider the lower layers of medium and low voltage to be the most affected by the change. In our previous work, we analyzed samples of the Dutch distribution grid (Pagani and Aiello, 2011) and we considered possible evolutions of these using synthetic topologies modeled after studies of complex systems in other technological domains (Pagani and Aiello, 2014). In this paper, we take an extra important step by defining a methodology for evolving any existing physical power grid to a good smart grid model, thus laying the foundations for a decision support system for utilities and governmental organizations. In doing so, we consider several possible evolution strategies and apply them to the Dutch distribution grid. We show how increasing connectivity is beneficial in realizing more efficient and reliable networks. Our proposal is topological in nature, enhanced with economic considerations of the costs of such evolutions in terms of cabling expenses and economic benefits of evolving the grid.

1. Introduction

The power grid traces its roots in the late 18th century. Then, it involved large production facilities and a hierarchical grid composed of high (transmission), medium and low voltage (distribution) grids to transport and distribute the power to the end users. Traditionally, the power industry has been a sector characterized by being a (state-owned) monopoly. Nowadays there is a strong trend for innovation driven by the need of making the infrastructure more reliable, open, and to accommodate for new technology, both in term of renewable energy generation and digital infrastructure. The technological

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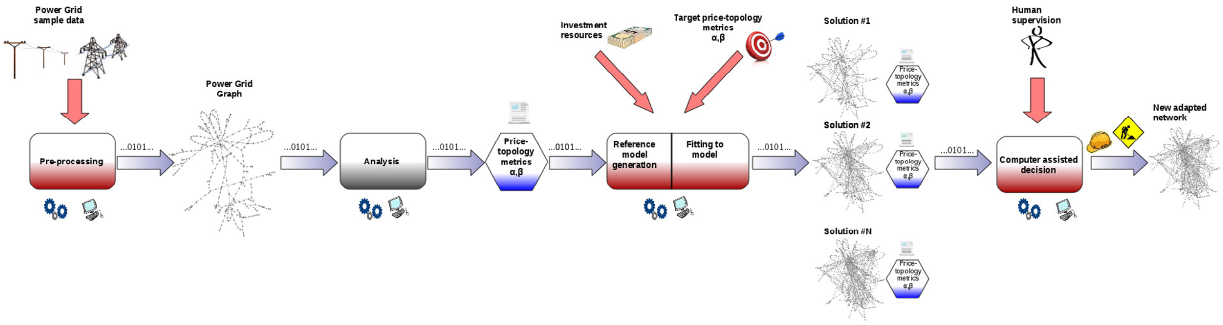

Fig. 1. Engineering process for medium and low voltage grid optimized for prosumer-based energy exchange.

innovation and the political pressure for a new power grid often go under the name of *smart grid*, which though has no unique definition [1]. One of the prominent aspects that the smart grid will enable is the participation of small producers in the energy distribution. It is already possible today for an end user to produce energy with small-scale units such as solar panels, small wind turbines, and micro-Combined Heat Power generators (mCHP). The energy produced is sold back to the local energy distributor. More efficiency and perhaps sustainability can be achieved if the producers would have access to an open energy market where they can auction their over-production and buy energy in a truly competitive market. Local energy production and distribution will change the traditional way power systems have been considered so far: the low voltage layer of the grid will go from being a passive layer, to an active segment with multi-directional energy flows. This trend will inevitably affect the physical structure of the medium and low voltage grid, also topologically. The reason for this is that the cost of distribution will be of primary importance in enabling or repressing a local market of energy.

Assuming the need for an enhancement of the physical low voltage grid, our aim is to realize a decision support system to guide distribution operators, policy makers, and utilities to evaluate scenarios of network improvement and to realize more efficient distribution grids. We propose a process to analyze, design, and adapt existing distribution networks based on statistical models of the power grid as a weighted network. A visual representation of the process is presented in Fig. 1. In the figure, several phases and inputs are considered to plan the evolution of the infrastructure where local energy exchange is the guiding principle. It starts with a pre-processing phase where the input data of the grid is converted into a graph; the output of this initial phase is a power grid graph. The following phase consists of the analysis of the topological properties characterizing the graph. The output of this phase consists of a set of values representing the metrics related to the power grid that influence the price of electricity (α and β metrics in the figure). The process continues with the generation of a network model. The number of nodes and edges of this reference model are provided according to the targets for the cost-related parameters (α and β) and the will to invest of the stakeholders. Based on the theoretical model identified, the physical network under assessment is then fitted into a topological structure similar to the one of the model. Several solutions are provided that differ in the topology and the economic efficiency of power distribution. All these solutions are then input to an interactive module that presents the benefits/costs of the evolution of the network; an expert is involved in the selection of the evolution to be implemented among the most promising candidates built by the computer. Once the decision is made, the adaptation of the physical grid can be planned in details following traditional power system engineering techniques.

We covered the initial steps of the process in our previous works. In Ref. [2], we performed a topological analysis of samples from the Dutch medium and low voltage power grids. We developed a set of metrics based on weighted topological properties to assess the influence on the cost of electricity distribution for a set of real Dutch medium and low voltage Grids. In the following Ref. [3], we evaluated known (reference) models of technological networks to evaluate how they would perform for local energy exchange. We found that an increase in connectivity from the current value of average degree of two to higher values such as four and higher is beneficial in improving the efficiency and reliability of the network. We also found that the small-world model with average degree $\langle k \rangle \approx 4$ provides a very promising compromise between performance improvement and the thrift in the realization (i.e., cost for cabling). Although the generation from scratch of a network topology is interesting from a modeling and theoretical perspective, it is not common to design a distribution grid from scratch. In this paper, we take a practical step in evaluating how to evolve the current distribution grid to a more interconnected network taking into account the existing network and the physical constraints. We keep the basis of our statistical approach to weighted network evolution and apply it to Dutch samples of the medium voltage networks. We not only assess the benefits in terms of pure topology, but also the costs for cabling of the evolved networks, and the benefit in terms of costs of electricity distribution. The are several novelties with this approach. First, techniques typical of complex network analysis are employed as design tools; second, given that the smart grid mostly concerns the distribution grid, we focus on these networks which are topologically quite different from the high voltage grids typically studied in the literature [4]; third, we provide the basics for a decision support system that works in the large and not for individual subcomponents of the grid, as is typical for power system engineering tools.

The rest of the paper is organized as follows. We open by describing the motivations and the need that drive an upgrade of the grid (Section 2), then we dive into the evolution strategies followed in upgrading the samples of the distribution grid