



European representative electricity distribution networks[☆]

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ABSTRACT

In Europe there is a great diversity of distribution grids and distribution system operators (DSOs) and a consolidated and shared knowledge of their techno-economic features is missing. This fact represents a major hindrance for fully assessing the performances of distribution grids evolving towards Smart Grids (SG) embedding low-carbon technologies, digital services and emerging actors. In order to contribute to bridge this knowledge gap, this paper presents a methodology to build representative distribution networks. Starting with real data provided by 79 large European DSOs, several network indicators have been firstly devised to extract the required information. Later, based on these, nine representative networks have been built through the proposed methodology. The built networks are of two major types: large scale and feeder type networks. All the network models are made available to allow researchers to overcome confidentiality and intellectual property constraints and to perform in-depth analyses on distribution network models realistically mimicking portions of the EU distribution system. Finally current applications and future improvements are also discussed.

1. Introduction

A representative (or reference) network is a theoretical network that can be used as proxy for actual grids. Depending on the methodology followed to construct the representative networks, these can be broadly classified into: (i) large-scale and (ii) feeder-type networks. The former include thousands of consumers connected to various voltage levels, and are normally obtained through large-scale distribution planning models that require geographical information. These models are known in literature as reference network models (RNMs) or norm models.

Based on the concept of least cost or quasi-optimal network, RNM are also referred to as adapted networks. The first mention to adapted networks that can be found in the literature was applied to transmission grids for network pricing [1], whereas the first kind of reference network model to regulate distribution companies was presented in Ref. [2]. Since then, RNMs have been proposed and used to provide regulators with an estimation of the efficient costs to be undertaken by a distribution company to supply a certain geographical area. This approach has been used in fact by several countries such as Spain [3–8], Sweden [9,10–12] and Chile [13,14]. It is worth also mentioning that they have been applied to regulate overall distribution costs in Brazil through the so-called primary elementary distribution systems or PEDS as described in [15].

From a different perspective, network models are typically used by researchers to compare the computational performances of different algorithms (e.g. power flow, grid topology estimation, etc.).

For this scope, feeder-type grids are typically used. They comprise tens of consumers at a single voltage level and are most commonly built by manually selecting few feeders based on expert knowledge or by applying clustering techniques on a large sample of real distribution grids [16]. At the moment IEEE test feeders are the most common topologies used to test algorithms [17]. CIGRE has also released a set of benchmark networks in [18] and representative distribution networks of Italy have been released in [19]. However, none of the aforementioned networks is both large-scale and representative of European Union (EU) distribution networks.

There are significant differences between U.S. and European networks [20]. In Europe, due to the existence of single-phase loads, phase unbalance can be caused by an uneven distribution of load connected to each phase or due to differences in the time when each load is consuming. Nonetheless, distribution companies always try to minimize these unbalances as much as possible when deciding the phase to which connect any new consumer.

On the other hand, in the U.S. phase unbalance is typically caused by the structural design of the grid itself, since three-phase trunk feeders with single-phase laterals are very common there. On the other

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side, in Europe the feeders are mainly three-phase, and it is directly the single-phase loads which can be connected to one phase or another (especially in low voltage). At the same time in Europe the medium to low voltage (MV/LV) transformers are typically three-phase while in the U.S. there are a few three-phase MV/LV transformers, but the majority are single-phase centre tapped MV/LV transformers.

It is this difference, meaning that the networks themselves are mainly three-phase in Europe, which has lead us to model balanced three-phase networks in Europe. However, the unbalance nature of the loads could also be taken into account in future, and is proposed as a future line of research. This may be more important in future, with the additional connection of photovoltaic units and electric vehicles in the low voltage networks [21].

In this work, a Reference Network Model¹ [3,22,23] has been used to build several representative networks which are based on real technical data provided by 79 large European DSOs.^{2,3} The proposed approach intends to overcome the confidentiality problems that could appear when disclosing publicly the gathered DSOs' data. With this in mind, the typical topologies of EU distribution networks have been modelled. The voltage levels that have been considered go from high voltage (HV) at 132 kV to low voltage (LV), lower than 1 kV, passing through medium voltage (MV) levels which cover the range 1–36 kV.

The constructed representative networks can be categorized into two major groups:

- (1) **Large-scale networks**, which model the network from a high voltage to medium voltage (HV/MV) substation to LV consumers including MV consumers, MV-LV feeders and MV/LV substations.
- (2) **Feeder type networks**, which represent common feeder topologies divided into: (a) MV feeder networks, (b) LV feeder networks.

All the networks are three-phase and balanced. The selected topologies and types of networks represent typical cases of EU distribution networks but other alternatives and variants could also be considered for specific analysis depending on objective and scope.

This paper is among the first steps to obtain European representative networks, including large-scale distribution systems, which cover both MV & LV and to the best of our knowledge, such a set was not previously available in the literature. In fact, in the expanded set of IEEE Distribution test feeders [17] there is a large-scale network (the 8500-Node test feeder), but it represents U.S. networks, which have different characteristics. There is also an IEEE European Low Voltage Test Feeder, but it is not large-scale. EPRI and PNNL have also released several distribution feeders, but they model U.S. systems [24,25]. The networks presented in [18,19,26,27] describe European distribution systems, but they are not large-scale. The cited contributions have shown to have a huge impact on the research community, being the results often used by many researchers. Thus besides the methodological contribution, the paper presents nine representative networks (three large scale and six feeder-type) which are openly available for researchers willing to carry out analysis on European-type distribution grids.^{4,5} Additionally, based on the interest shown and thanks to the feedback provided by almost 50 among universities and

research centres, more concrete examples on the applications of the representative networks are discussed.

The remainder of this paper is organized as follows: Section 2 briefly describes the information collected from DSOs to build the European DSO network indicators. Section 3 explains the methodology used to build the EU representative networks from the obtained indicators. Sections 4 and 5 summarize the built large-scale representative networks and the feeder type networks, respectively. Finally, Section 6 illustrates a number of works which already use our networks and Section 7 concludes the paper.

2. European DSOs dataset

In Europe DSOs connect around 260 million customers by operating 10 million of km of power lines and supplying 2700 TWh of energy per year [28]. A rough estimate hovers at the moment around 2400 DSOs of different size operating their distribution grids in Europe. From this number, 190 serve more than 100,000 customers and are requested to comply with the Electricity Directive 2009/72/EC on unbundling. Our analysis is focused on this restricted but still representative sample of large DSOs in Europe.

Data has been collected through an extended online questionnaire, filled by European DSOs. Such a collection has been carried out by JRC in line with previous works (see also [29,30]). The database covers 74.8% of total connected customers in the European Union, which is indeed a good representation of the DSOs population (42% of the larger DSOs).

Finally, a series of indicators has been elaborated from the DSO collected database, which provides a deeper understanding of the structural similarities and differences among DSOs across the EU [31].

2.1. Indicators

The comparative analysis of the DSOs is split in three categories: network structure, network design criteria and distributed generation connected to the DSOs' grid.

The network structure part covers those data that for a DSO are given, the inputs, (e.g. the number of connected consumers, number/size/energy of distributed generation, areas of supply and distributed annual energy) and those which result from the operation and planning of the DSO, the outputs (at each level LV, MV and HV), such as circuit length per voltage level, number and capacity of substations. Based on this categorization, four possible ratios can be defined: Input/Input (I-I), Input/Output (I-O), Output/Input (O-I) and Output/Output (O-O). The number of consumers and the covered area supplied by the DSOs have been selected as the most relevant inputs to build the network structure indicators. Based on that invariant ratios O-I or I-O have been calculated, e.g. LV circuit length per LV consumer or area covered per HV/MV substation. These types of indicators in fact relate for instance the structure of the demand (or the DG) with the installations that the DSO uses to supply that demand (or to connect that DG).

Additionally network structure indicators of type O-O or I-I have been also calculated. The O-O indicators (such as capacity of MV/LV substations per capacity of HV/MV substation), provide a better understanding of the criteria used by DSOs when sizing their network installations. The I-I ratio indicator (such as consumers per area) highlights the structure of demand and DG that DSOs must connect to the network. Note that DSOs have no control on these kind of indicators (I-I), while their planning decisions can affect the rest of indicators (O-I, I-O, O-O).

The network design indicators refer mainly to substations and feeders. This information sheds some light on the typical parameters that DSOs use for sizing and designing distribution installations. For instance, the analysis addresses which is the typical transformation capacity of the HV/MV and MV/LV transformers, how many MV/LV substations are connected to a MV feeder, and which is the average

¹ <http://www.iit.comillas.edu/technology-offer/rnm>

² 'Distribution System Operator' according to the European Directive 2009/72/EC, is defined as 'a natural or legal person responsible for operating, ensuring the maintenance of and, if necessary, developing the distribution system in a given area and, where applicable, its interconnections with other systems and for ensuring the long-term ability of the system to meet reasonable demands for the distribution of electricity'.

³ Such data collection has been part of the DSOs Observatory project led by the Joint Research Centre (JRC) of the European Commission.

⁴ The constructed networks are described in MATLAB®/MATPOWER format, including additional data such as consumer coordinates and switching devices (circuit breakers and line switches) in Excel format.

⁵ The networks are available on request on JRC website <http://ses.jrc.ec.europa.eu/distribution-system-operators-observatory>.

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