Review and Classification of Published Electric Steady-State Power Distribution System Models

Steffen Meinecke\textsuperscript{a,*}, Leon Thurner\textsuperscript{b}, Martin Braun\textsuperscript{a,b}

\textsuperscript{a}Department of Energy Management and Power System Operation (e\textsuperscript{2}n), University Kassel, Germany
\textsuperscript{b}Fraunhofer Institute for Energy Economics and Energy System Technology (IEE), Kassel, Germany

Abstract

Publicly accessible grid data with static equivalent circuit models are crucial for the development and comparison of a variety of power system simulation tools and algorithms. Such algorithms are essential to analyze and improve the integration of distributed energy resources (DERs) in electrical power systems. New technologies and changing law, standards and guidelines cause recurrently changing grids and research. As a result, the number of grid datasets which are used in research increases. On top of that, the used grids are generated by different methods and intentions. This paper gives orientation within this development. First, it provides an overview of well-known publicly accessible grids. Second, background information is reviewed to characterize how the grid datasets are compiled. Third, widespread terms to describe grids are assembled and reviewed, and recommendations for the use of these grid terms are made.

Keywords: benchmark grid; generic grid; representative grid; reference network; terminology; methodology

1. Introduction

For the purpose of an sustainable and ecological energy supply, electrical energy systems are changing. This is characterized in particular by the increase of decentralized renewable energy generation. Many studies are conducted in this field of research, e.g. to estimate the impact of distributed energy resources (DERs) integration into grids, to analyze new methods for cost-efficient and secure grid planning for grids with volatile energy resources or to simulate new solutions for smart grid operation. These power system simulations are usually based on power system analyses which of course require datasets of the respective grid models. The fact that power system operators treat their grid data as confidential is a challenge for the scientific community, which relies fundamentally on the reproducibility of scientific studies. To make power system research more accessible and comparable, a large body of openly available grid datasets has accumulated in the public domain that can be used for research purposes.

However, power systems are constantly changing, be it due to increasing DERs penetration, new technologies or changing legal and regulatory frameworks. As a result, existing grid datasets may become obsolete and no longer suitable for testing new algorithms or conducting power system studies. New publicly accessible grid datasets are therefore recurrently needed and published.

To give an overview over the different grids, terms such as reference network, representative grid or benchmark grid are often used to classify the grids. However, since these terms are not clearly defined, they are not always used consistently in literature. This can lead to misunderstandings and make it difficult to chose a fitting dataset for a given research purpose.

This paper has three main objectives: First, to give an overview of existing distribution grid datasets as a starting point for researchers (Section 2). Second, to present background information of these grid datasets, such as intended use cases and grid compilation methodologies, to help researchers conceiving existing datasets and to give insight into how new datasets can be derived (Section 3). And third, to propose a consistent nomenclature for common grid terms to enable clear communication between researchers (Section 4). A summary and conclusion is given in Section 5.

2. Available Grid Datasets

Using publicly accessible distribution grid data makes studies easily comparable to other work. When selecting an appropriate existing grid dataset, it is necessary to get an overview of the available grid and their properties. There are already different resources available for researchers to get an overview of existing datasets \cite{1, 2, 3}. An overview of available grids is also given in Table 1.

While this paper focuses mostly on distribution grids, four prominent transmission system datasets have been added to the grid selection to give an outlook for the expandability of the overview.

The overview provides information about the year in which the different grids were published and about elec-
| Grids         | Year Published | Voltage Levels | Number of Buses | Switch Models | Dynamic Models | OPF Analysis | Reliability Analysis | State Estimation | Unbalanced Power Flow | Short Circuit Calculation | GIS Data | Time-series Data |
|--------------|----------------|----------------|----------------|---------------|----------------|--------------|----------------------|-------------------|------------------------|---------------------------|----------|-----------------|
| Atlantide [4, 5, 6] | 2012           | MV             | 97-103         | ✓             | ✓              | ✓            | ✓ - - - - - - - - - - |
| Baran’s System [7]  | 1989           | MV             | 33             | ✓             |                |              | - - - - - - - - - - |
| CIGRE Systems [8]   | 2009           | LV, MV, EHV    | 13-44          | ✓             | ✓ G, EN, T, (L)-L | - ✓ ✓ ✓ ✓ ✓ |
| Cinvalar’s System [9] | 1988           | MV             | 14             | ✓             | - - - - - - - - - - |
| Dickert’s LVDNs [10] | 2013           | LV             | 1-150          | ✓             | - L            | - - - - - - - - - - |
| ELVTF [11, 12]     | 2015           | LV             | 906            | ✓             | - T            | - - ✓ ✓ ✓ ✓ ✓ |
| EREDNs [13]        | 2016           | LV, MV         | 13-6921        | ✓             | - V, T, L      | - - - - - - - - - - |
| IEEE LVNTS [14, 12] | 2014           | LV, MV         | 342d           | ✓             | - T, (L)       | - ✓ ✓ ✓ ✓ ✓ ✓ |
| IEEE 8500 NTF [15, 12] | 2010          | LV, MV         | 8500d          | ✓             | - T, L         | - ✓ ✓ ✓ ✓ ✓ ✓ |
| IEEE Case 30 [16]  | 1974           | HV             | 30             | ✓             | - ✓ ✓ ✓ ✓ ✓ ✓ |
| IEEE DTFs [17, 18, 19, 12] | 1991, 2002, 2010 | MV             | 4-123          | ✓             | - T            | - - ✓ ✓ ✓ ✓ ✓ |
| IEEE NEV [20, 21, 12] | 2008           | LV             | 21d            | ✓             | - T, L         | - ✓ ✓ ✓ ✓ ✓ ✓ |
| ICPSs [22, 23, 24, 25] | 1968, 1974, 1981, 1982 | -               | 11, 13, 43     | -             | - - - - - - - - - - |
| Kerber Grids [26]  | 2011           | LV             | 10-386         | ✓             | - V, T, L      | - - - - - - - - - - |
| Salama’s System [27] | 1993           | MV             | 34             | ✓             | - (L)          | - - - - - - - - - - |
| SimBench [28, 2]   | 2019           | LV, MV, HV, EHV | 15-380         | ✓             | - V, G, T, L   | ✓ ✓ ✓ ✓ ✓ ✓ ✓ |
| Su’s TDG [29]      | 2005           | MV             | 84             | ✓             | - ✓ ✓ ✓ ✓ ✓ ✓ |
| UKGDSs [30, 31]    | 2011           | MV, HV         | 52-413         | ✓             | - ✓ ✓ ✓ ✓ ✓ ✓ |
| IEEJs [32]         | 2000           | HV             | 236-933        | ✓             | - T, L         | ✓ ✓ ✓ ✓ ✓ ✓ |
| IEEE Case 9 [33]   | 1980           | EHV            | 47-115         | ✓             | G, (L)         | ✓ ✓ ✓ ✓ ✓ ✓ |
| IEEE RTS [34]      | 1979           | HV, EHV        | 24             | ✓             | - C, G, T, L   | ✓ ✓ ✓ ✓ ✓ ✓ |
| PEGASE Cases [35, 36] | 2015           | HV, EHV        | 89-13659       | ✓             | ✓ ✓ ✓ ✓ ✓ ✓ |
| RTE Cases [35]     | 2016           | MV-EHV         | 1888-6515      | ✓             | ✓ ✓ ✓ ✓ ✓ ✓ |

a Complete grid names: Dickert’s LV Distribution Networks (Dickert’s LVDNs), European LV Test Feeder (ELVTF), European Representative Electricity Distribution Networks (EREDNs), IEEE 342-Node LV Networked Test System (IEEE LVNTS), IEEE 8500-Node Test Feeder (IEEE 8500 NTF), IEEE Distribution Test Feeders (IEEE DTFs), IEEE Neutral-to-Earth Voltage Test Case (IEEE NEV), Ill-Conditioned Power Systems (ICPSs), Su’s Taiwanese Distribution Grid (Su’s TDG), United Kingdom Generic Distribution Systems (UKGDSs), Grids of the Institute of Electrical Engineers in Japan (IEEJs), IEEE Reliability Test System (IEEE RTS)

b EHV > 145 kV ≥ HV > 60 kV ≥ MV > 1 kV ≥ LV
c C: cost data, V: voltage limits, G: generator limits, EN: external net limits, T: transformer limits, L: line limits, (L): line types
d Nodes are counted, i.e. any single electrical point is counted (relevant definition at inconsistent phase systems)
e GIS data exist, but are not publicly accessible
tactical properties, such as voltage level and the number of buses. Since modeling of switches is an important factor for many analysis in distribution systems, the level of detail in the switch models is also given. Therein, switch models are divided into three categories: no modeling ( ), simple marking of the switchable lines ( ( )) and indication of the position of the switch between nodes and branch elements and possibly annotation of the switch type ( ).

The table also provides specific information on which analysis types the grid data are suitable for. The analysis is assumed to be possible ( ), if the relevant input parameters are included in the grid dataset. For example, state estimation relies on measurement data and optimal power flow (OPF) analysis relies on information about generation costs and operational limits for the different electric elements.

Furthermore, it is stated whether geographic coordinates (GIS) are available, as these are relevant for network expansion planning, for example. Finally, the overview includes whether time series data of loads and generators are given ( ) or at least an exemplary plot corresponding to the grid is drawn ( ).

The original datasets are often modified or enhanced with additional information to allow further analysis. For example, dynamic models are available for the IEEE RTS [37, 38] and OPF data has been provided for the IEEE Case 9 [39]. As there are multiple and sometimes conflicting derivatives of the original datasets, the overview in Table 1 only considers the data contained in the initial publication.

Comparing SimBench to the other presented grid datasets reveals that it is the only one that includes all four voltage levels from LV to EHV and information on state estimation. As one of few it also offers extensive GIS and time series data.

3. Compilation Process of Grid Datasets

Table 1 gives an overview of the electric parameters and possible analyses methods. To check the suitability of a dataset for a specific use case, it can however also be relevant to know how and with what intention the grid was compiled. While grid models and their parameters can be specified clearly by mathematical formulas and numerals, this type of background information is more difficult to communicate. This section introduces an overview of different use cases, data origins and compilation methodologies.

3.1. Intended Use Case

Use cases are often the starting points of compiling grid data. The intention in generating grids can range from compiling a simple test grid to the compilation of grids that represent certain specialized applications or use cases.

A frequently occurring use case is the compilation of a grid that is representative of a region or a specific kind of power system structure. Usually, the intention in this case is to extrapolate from this grid to other, unknown grids of the same type.

Even though the intended use cases are usually specified in the documentation or accompanying publication, the grids are often applied in different contexts than originally intended [41, 42, 43, 44]. In this case, it is up to the researcher to decide, whether the application of the grid in this use case allows to draw valid conclusions.

The intended use cases of all grids from Table 1 are specified in the first column of Table 2.

3.2. Grid Data Origin

The origin of the grid is relevant information to classify grids. On one side, grids are allocated to geographical regions, since different power system structures and voltage levels prevail in these regions. On another side, grids can be compiled in a synthetic way (e.g. manually, rule based), originate from real grid models (e.g. as they are, modified, simplified) or in a hybrid way.

Unfortunately, several grid documentations do not specify this information extensively. Especially in case of simple grids for testing, this is often skipped. In the case of real grid data, privacy concerns can also lead to the omission of the data origin. As a result, some origin and methodology information remain unclear in Table 2. In contrast, SimBench provides the most detailed documentation of the compilation process of the presented selection [28].

3.3. Grid Generation Methodologies

The methodologies used to compile grids are highly correlated to the grid data origins. Here, three different, common methodologies are presented.

Figure 1 illustrates the relation between the distribution of existing grid data (top) and resulting, published grids (bottom) for the three methodologies discussed below. For a clear illustration of the methodologies, the figure is two-dimensional. In practice, more than two grid parameters are usually used to describe and classify grids. Which parameters are suitable for this and actually label the axes depends on the use case.

A common method is to select grids based on expert selection decisions (see Figure 1, left). The grids are selected based on the data requirements derived from the intended use case. While small adjustments might be made to the grid to better fulfill the requirements, the created grids are of real origin. This method is often used in transmission systems, where the number of grids is relatively low and experts have a good overview of the parameters of different grids. It has also been applied within the CIGRE Benchmark System process [8].

A method to compile grid data based on urbanization classes is shown in the center of Figure 1. The approach separates the grids into urbanization classes, such as rural, suburban, urban or commercial. These classes are defined
# Table 2: Overview of intentions, generation methodologies and origins of publicly accessible, widely used grids

| Grids                  | Intended Use Cases                                                                 | Data Origin*                | Information on Methodology                                                                 |
|-----------------------|-----------------------------------------------------------------------------------|----------------------------|------------------------------------------------------------------------------------------|
| Atlantide             | representative distribution grid models                                           | Italy, real                | as Figure 1 Method 3.I                                                                   |
| Baran’s System        | test system for loss reduction and load balancing via network reconfiguration    | NA, ?                     | ?                                                                                       |
| CIGRE Systems         | benchmark system for issues of grid operation, planning, power quality, protection, stability | NA & EU, adapted and simplified real grids | use case driven approach adjusting real grids (Figure 1 Method 1)                         |
| Cinvalar’s System     | illustrating the problem of switch positioning for minimum distribution grid losses | NA, synthetic             | ?                                                                                       |
| Dickert’s LVDNs       | LV benchmark grids representative of German feeders                              | DE, synthetic              | principal component and clustering analysis (Figure 1 Method 3.II)                       |
| ELVTF                 | typical test feeders                                                             | EU, ?                     | ?                                                                                       |
| EREDNs                | large-scale distribution grids representative of EU                              | EU, synthetic              | greenfield reference network model                                                       |
| IEEE LVNTS            | to test solver with highly meshed LV system                                       | NA, ?                     | ?                                                                                       |
| IEEE 8500 NTF         | representative of full-size distribution system with suitable complexity          | NA, derived from commercial software | ?                                                                                       |
| IEEE Case 30          | test case for optimal load flow with steady-state security                          | ?, simple approximation of real grid | adaption of existing test case                                                          |
| IEEE DTFs             | to test new power flow solution methods for unbalanced systems                    | NA, ?                     | ?                                                                                       |
| IEEE NEV              | to examine the voltage rise on the neutral conductor                               | NA, ?                     | ?                                                                                       |
| ICPSs                 | ill-conditioned sample systems for power flow methods                              | ?, synthetic              | ?                                                                                       |
| Kerber Grids          | to enable estimating LV grids hosting capacity                                     | DE, manually selected real grids | as Figure 1 Method 2                                                                   |
| Salama’s System       | application example for the VAr control problem                                   | NA, ?                     | ?                                                                                       |
| SimBench              | benchmark dataset with multiple voltage levels and data of time series and study cases to compare innovative solutions of multiple use cases based on power flow analysis | DE, derived from open data and compared with real grids | use case driven approach deriving grids from available data and validating the grids [40] |
| Su’s TDG              | example grid for network reconfiguration                                          | Taiwan, real              | ?                                                                                       |
| UKGDSs                | representative distribution grids to test and evaluate new concepts                | UK, ?                     | ?                                                                                       |
| IEEJ                  | to test power supply restoration planning and reliability analysis algorithms       | Japan, derived from a commercial software package | ?                                                                                       |
| IEEE Case 9           | small test system for classical stability studies                                  | NA, synthetic              | ?                                                                                       |
| IEEE RTS              | to test or compare methods for reliability analysis                                | NA, ?                     | ?                                                                                       |
| PEGASE Cases          | to develop new tools for control and operational planning of the pan-European transmission network | EU, derived from real grid data and partly sampled | generated by the platform iTesla                                                        |
| RTE Cases             | to enable validating mathematical methods and tools                                 | French, snapshots from real grid data | come from French SCADAs via Convergence software                                          |

* NA: North America, EU: Europe or European Union, UK: United Kingdom, DE: Germany

b Presumably, due to the simple grid structure
with regard to non-electrical parameters, such as floor-space index, site occupancy index or buildings per area. For each class grids are synthesized using the knowledge about the grid parameters. The approach is based on the assumption that the grids can be classified by the supply task, especially by the urbanization character. This method has for example been applied to generate grids to be representative of LV grids for estimating hosting capacity [26, 45, 46].

A third method based on clustering is shown on the right of Figure 1. In contrast to the before mentioned method, the grid classes are not defined beforehand, but compiled with mathematical clustering analyses. Multivariate, heuristic methods such as k-means or ward’s method allow to analyze (dis-)similarities and appropriate groupings of the set of objects. While the resulting clusters might be interpreted as grid types such as “urban” or “rural” afterwards, the methodology only analyses the mathematical similarities. After finding a number of grid classes or clusters, there are two methods for obtaining the grids, each representative of one class:

I) The best existing real grid of each class is selected, i.e. the grid with the least distance to the cluster center [47, 48, 49].

II) The parameter values of the cluster centers are used to generate synthetic grids with grid parameters that are typical for the respective cluster [10, 50]. Typically, a few assumptions about the topology or missing parameters are required to create the grids.

Although a clustering analysis is appropriate as an unbiased, mathematical classification method there are disadvantages, for example, compared to make use of expert knowledge when considering causality. To avoid this problem, mathematical analysis and expert knowledge can also be combined [40, 51].

4. Terminology to Characterize Grid Models

As the previous section has shown, properly describing the methodology and intended use case of grid datasets can be a complex task. Researchers therefore often use short and succinct terms, such as reference grid, synthetic grid or test case to describe grid datasets. While this can facilitate the communication, it can also lead to misunderstandings if the terms are not clearly defined. This section gives an overview of the meanings of widespread network terms and how they are used in literature, as well as a recommendation for the terminology\(^\text{1}\).

\(^{1}\)The discourse on grid terms is about the terms describing the grid rather than the terms system, network, grid or case. These four terms are considered as synonyms and are applied in common usage in this paper.
4.1. Review of Grid Term Nomenclature in Literature

This section gives an overview of common grid terms and their usage in literature.

4.1.1. Synthetic Grids

Grids are called synthetic to describe the data origin, e.g. in [3]. Such grids are neither models of real grids nor directly derived from such. They are artificially created, for example by green field methods [52]. In [52, 53], a number of synthetic grids are generated to achieve study results with validity. That is because simulation results can be more relevant if the algorithms run with several (types of) grids or because a large number of grids can be used to extrapolate results to real grid areas.

4.1.2. Example & Test Grids

Many research projects require grid data to exemplify or validate case studies. Well known example data are the IEEE Case 9 [33], Baran’s, Cinvalar’s and Salama’s systems [7, 9, 27] as well as the ICPs [22, 23, 24, 25]. Both are named test network, real grids [54, 55] and synthetically generated grids [52, 56]. Likewise, the number of buses varies widely depending on the use case [39]. Often, the dataset qualification for more than one use case is not considered since the test case creation have subordinate priority compared to the focus of the study.

4.1.3. Benchmark Grids

Benchmarking does not originate from the field of electrical power supply but from testing and comparing the performance of business processes or software tools based on trusted procedures or datasets [1]. The IEEE test feeders are called test cases or test feeders, but the intention clarifies that they should serve as a benchmark for different algorithms, such as unbalanced power flow, calculation of full-size distribution systems or handling of highly meshed LV grids [17, 18, 19, 12, 15, 20, 21, 14, 11]. In references [8, 10, 57], the grids themselves are named benchmark networks while having the same intention to be appropriate to be used as a dataset to benchmark algorithms and methods.

Besides the widespread consideration of developing software tools or methods in the field of electrical power supply, in which a benchmark grid is the trusted dataset, there is another conceivable way of understanding the term benchmark grid. Since system operators of several countries are regulated and incentivized to be efficient, grid planning and operation management is often viewed from a financial perspective. Thus, a grid with which other grids are to be financially compared is named benchmark grid or, as mentioned in Section 4.1.7, reference network [58]. However, usually the process of comparing the performance of system operators, which is subject to some challenges, is called benchmarking rather than the network itself [59].

4.1.4. Representative Grids

Representative is used to express a relation of a grid to real grids. Comparing algorithms gets more convincing by performing the algorithms on grids with reference to reality, i.e. on representative grids [8, 6]. Furthermore, representative grids are used to elaborate technical conclusions, recommendations and estimative projections about real grids [26, 60, 53]. Often several representative grids are created, each representing a different class. These classes of grids could be a subset of all grids distinguished between geographic, urbanization or grid parameter aspects, e.g. coastal grids, rural grids or grids with long lines. With these findings, the Methods 2 and 3 of Figure 1 clearly belong to representative grids.

4.1.5. Generic Grids

The intrinsic meaning of the term generic pretty much is general or universal. Thus, generic grids should be characteristic of (a class of) grids to bring a large number of grids together.

In [61], for instance, a specific system is introduced which is intended to be particularly suitable for testing dynamic wind studies. The steady-state parameters are stated while the proposed parameters of the dynamic models are open for modifications. In [62], the generic distribution grid models denote several grids of different types, generated with varying parametrization.

There are also term usages that do not fit the intrinsic meaning of the word. For example, using generic for a grid which is derived from a real grid to allow analyzing algorithms for DER integration, as in [63]. The UKGDSs intended use cases and data correspond better with representative grids than with the word meaning of generic. This is not resolved in referring papers [64, 65], too.

4.1.6. Typical Grids

Grids, named typical, are also described as representative [66] or generic [64]. Parameters with the most frequent occurrence are described as typical. Composing these parameters, a typical grid can be formed. In [67], the IEEE 13-Node Test Feeder [11] is also named typical. However, since this grid is very small, generated to test common features of distribution analysis software and originally named as test feeder, it is more closely related to the other IEEE test feeders than to other grids named typical.

4.1.7. Reference Grids

The term reference network is also used differently. To conclude these understandings, it is used as:

a) Synonym for representative grids [6, 55, 5, 66]
b) Synthetic network, planned optimally from greenfield [68, 13, 58]
c) Simplified test case [69, 50]
d) Best or worst case grid (to compare to), derived from representative grids by optimal choice of variable parameters [70]
4.2. Recommended Terminology

The previous section showed, that many terms are used inconsistently throughout the literature. To eliminate ambiguities and improve the communication in scientific language, we propose the following terminology:

1. The term *synthetic* grids should be used for grids that either do not model real grids or that are not obtained by simplifying or modifying real grid models.

2. The term *example* grid or *test* grid should be used for grids that are simply created and used for basic testing, validation or demonstration of one issue only. Transferring quantitative conclusions from these to conditions in real grids is doubtful.

3. The term *benchmark* grid should be used when grids are used to compare the efficiency or validity of algorithms. When using a benchmark grid, the object of investigation is the algorithm rather than the grid itself.

4. The term *representative* grid should be used for grids that are representative for a large number of grids. Since one grid can hardly be representative for all grids, there are usually multiple representative grids to cover different clusters of similar grids.

5. The term *generic* grid should be used for grids with variable parameters that allow to synthesize different grids through parametrization. While representative grids use multiple grids with fixed parameters to represent different grid states, generic grids cover multiple states through parameter variation of one grid.

6. The term *typical* grid should be used for a grid with common parameters. While representative grids intend to represent a wide range of possible grids, typical grids only claim to cover a common or normal grid type, so that outliers and extreme cases have little or no influence on a typical grid.

7. The *reference* grid should be used for a grid that is optimal with regard to a specific criterion, like in understandings b) and d).

To exemplify this terminology the introduced widespread grid datasets are assigned to the discussed grid terms from the steady-state power flow perspective. A distinction is made between a well-suited term (✓), a partially fitting term ((✓)), and an inappropriate term (-). Furthermore, as in Table 2, information is missing to assign the term *synthetic* to every grid (?)

For Baran’s, Cinvalar’s and Salama’s System as well as for the IEEE Case 9, which are classified as example/test cases in Table 3, it can be discussed whether these are benchmark grids (too), since they are used as such nowadays. But as stated in Section 2, the intentions of the initial publications are considered here.

| Grids          | Synthetic | Example/Test | Benchmark | Representative | Generic | Typical | Reference |
|----------------|-----------|--------------|-----------|----------------|---------|---------|-----------|
| Atlantide      | -         | -            | ✓         | -              | -       | -       | -         |
| Baran’s System | ?         | ✓            | -         | -              | -       | -       | -         |
| CIGRE Systems  | -         | -            | ✓         | -              | -       | -       | -         |
| Cinvalar’s System | ✓       | -            | -         | -              | -       | -       | -         |
| Dickert’s LVDNs | ✓        | -            | ✓         | ✓              | -       | -       | -         |
| ELVTF          | ?         | -            | ✓         | -              | -       | -       | -         |
| EREDNs         | ✓         | -            | ✓         | ✓              | -       | -       | -         |
| IEEE LVNTS     | ?         | -            | ✓         | -              | -       | -       | -         |
| IEEE 8500 NTF  | -         | -            | ✓         | -              | -       | -       | -         |
| IEEE Case 30   | -         | -            | ✓         | -              | -       | -       | -         |
| IEEE DTFs      | ? (✓)    | ✓            | ✓         | -              | -       | -       | -         |
| IEEE NEV       | ?         | -            | ✓         | -              | -       | -       | -         |
| ICPSs          | ✓         | -            | ✓         | -              | -       | -       | -         |
| Kerber Grids   | -         | ✓            | -         | -              | -       | -       | -         |
| Salama’s System | ?        | ✓            | -         | -              | -       | -       | -         |
| SimBench       | (✓)      | -            | ✓         | ✓              | -       | -       | -         |
| Su’s TGD       | - (✓)    | ✓            | ✓         | -              | -       | -       | -         |
| UKGDSs         | ?         | ✓            | ✓         | ✓              | -       | -       | -         |
| IEEJs          | ?         | -            | ✓         | -              | -       | -       | -         |
| IEEE Case 9    | ✓         | ✓            | ✓         | -              | -       | -       | -         |
| IEEE RTS       | ?         | -            | ✓         | -              | -       | -       | -         |
| PEGASE Cases   | -         | ✓            | ✓         | -              | -       | -       | -         |
| RTE Cases      | -         | ✓            | ✓         | -              | -       | -       | -         |

* Presumably, due to the simple grid structure

It should be noted that the intrinsic meanings of the grid terms and therefore the recommendations do not address all types of information, mentioned in Section 3, at the same time. For example, *synthetic* specifies the data origin whereas benchmark expresses the intention to be used as database to compare algorithms. As a result, terms might also be combined and grids are assigned to multiple terms. The EREDNs derived in [13], for instance, can be classified as synthetic reference grid, since they are synthetically created and optimally planned by a greenfield planning approach. In the same way, the same grid can be applied in several ways. Hence, different terms might apply depending on the context. For example, a grid that was intended to be a generic grid to derive scientific conclusions about grid stability, can also be used as a benchmark grid to compare the performance of two optimization algorithm without any intention to derive an insight about the grid itself.
5. Conclusion

Many publicly accessible grids already exist, but new studies, especially regarding the change of power systems towards a high share of renewable energy, continue requiring new or modified grid data. To first examine whether existing grids are suitable for a new study, this paper provides an overview of many well-known and widespread publicly accessible grids. This includes fundamental information, possible power system analyses and descriptive information on intention, methodology and data origin. In this way, this paper helps to avoid working with inappropriate grid data. As a consequence, less supplementary data and assumptions must be added which is time consuming and hinders transparency and comparability, in case of incomplete documentation.

Moreover, relevant methods for creating grid models are presented to help new studies generating improved or new grid datasets.

Compared to the presented grid datasets, SimBench is outstanding in terms of the level of detail of the documentation, the provided and interconnectable voltage levels, the switch models as well as the extensive data of GIS coordinates, time series and for state estimation analysis.

Short descriptive terms are common to inform about the type of grid data. But these terms are used inconsistently. Therefore, in this paper the usage of grid terms in the literature is reviewed. Regarding that and the terms intrinsic meanings, we provide recommendations for grid term usage to improve scientific communication on steady-state power distribution systems. In this way, the proposed terminology can be a valuable first step for future standardization activities such as performed in [71] or by IEC working group [72]. The terminology is exemplified by assigning the defined terms to the reviewed grid datasets. Therein, since the grid terms do not completely characterize a grid, multiple terms may fit to a grid and describe different attributes.

Acknowledgment

This work was supported by the German Federal Ministry for Economic Affairs and Energy and the Projekträger Jülich GmbH (PTJ) within the framework of the project SimBench (FKZ: 0325917A). The authors are solely responsible for the content of this publication.

References

[1] J. Bialek, E. Ciapessoni, D. Cirio, E. Cotilla-Sanchez, C. Dent, I. Dobson, P. Henneaux, P. Hines, J. Jardim, S. Miller, M. Panteli, M. Papic, A. Pittro, J.Quiros-Tortos, D. Wu, Benchmarking and validation of cascading failure analysis tools, IEEE Transactions on Power Systems 31 (6) (2016) 4887–4900.
[2] Project, SimBench - Simulation data base for a consistent comparison of innovative solutions in the field of grid analysis, grid planning and grid operation management, www.simbench.net [Accessed: Mar. 13, 2020].
[3] R. D. Christie, Power systems test case archive, University of Washington, http://www2.ee.washington.edu/research/psnc/ [Accessed: Feb. 20, 2020] (1999).
[4] F. Pilo, G. Pisano, S. Scaliari, D. D. Canto, A. Testa, R. Langella, R. Caldon, R. Turri, Atlantide - digital archive of the italian electric distribution reference networks, in: CIRED 2012 Workshop: Integration of Renewables into the Distribution Grid, 2012, pp. 1–4. doi:10.1049/cp.2012.0783.
[5] G. Celli, F. Pilo, G. Pisano, G. G. Soma, Reference scenarios for active distribution system according to atlantide project planning models, in: 2014 IEEE International Energy Conference (ENERGYCON), IEEE, 2014, pp. 1190–1196.
[6] A. Bracale, R. Caldon, G. Celli, M. Cocco, D. Dal Canto, R. Langella, G. Petretro, F. Pilo, G. Pisano, D. Proto, S. Scaliari, R. Turri, Analysis of the italian distribution system evolution through reference networks, in: 2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe), IEEE, 2012, pp. 1–8.
[7] M. E. Baran, F. F. Wu, Network reconfiguration in distribution systems for loss reduction and load balancing, IEEE Transactions on Power Delivery 4 (2) (1989) 1401–1407. doi:10.1109/61.25627.
[8] K. Strunz, N. Hatzigiayriou, C. Andrieu, Benchmark systems for network integration of renewable and distributed energy resources, Cigre Task Force C6.04.02 (Apr. 2009).
[9] S. Civanlar, J. J. Grainger, H. Yin, S. S. H. Lee, Distribution feeder reconfiguration for loss reduction, IEEE Transactions on Power Delivery 3 (3) (1988) 1217–1223. doi:10.1109/61.193906.
[10] J. Dickert, M. Domagk, P. Schegner, Benchmark low voltage distribution networks based on cluster analysis of actual grid properties, in: PowerTech, 2013 IEEE Grenoble, IEEE, 2013, pp. 1–6.
[11] IEEE PES AMPS DSAS Test Feeder Working Group, Test feeders resources, http://sites.ieee.org/pes-testfeeders/resources/ [Accessed: Mar. 12, 2020].
[12] K. P. Schneider, B. A. Mathier, B. C. Pal, C. Ten, G. J. Shirek, H. Zhu, J. C. Fuller, J. L. R. Pereira, L. F. Ochoa, L. R. de Araujo, R. C. Dugan, S. Matthias, S. Pauldy, T. E. McDermott, W. Kersting, Analytic considerations and design basis for the IEEE distribution test feeders, IEEE Transactions on Power Systems 33 (3) (2018) 3181–3188. doi:10.1109/TPWRS.2017.2760011.
[13] C. Mateo, G. Prettico, T. Gómez, R. Cossent, F. Gangale, P. Frias, G. Fulli, European representative electricity distribution networks, in: Electrical Power and Energy Systems, 2018. URL https://www.sciencedirect.com/science/article/pii/S014206151731801X.
[14] K. Schneider, P. Phanivong, J. Lacroix, IEEE 342-node low voltage networked test system, in: 2014 IEEE PES General Meeting — Conference Exposition, 2014, pp. 1–5. doi:10.1109/PESGM.2014.6939794.
[15] R. F. Arritt, R. C. Dugan, The IEEE 8500-node test feeder, in: IEEE PES T D 2010, 2010, pp. 1–6. doi:10.1109/TDC.2010.5484381.
[16] O. Alas, B. Stott, Optimal load flow with steady-state security, IEEE transactions on power apparatus and systems (3) (1974) 745–751. doi:10.1109/TPAS.1974.29397.
[17] W. H. Kersting, Radial distribution test feeders, IEEE Transactions on Power Systems 6 (3) (1991) 975–985. doi:10.1109/59.119237.
[18] W. H. Kersting, Radial distribution test feeders, in: Power Engineering Society Winter Meeting, 2001. IEEE, Vol. 2, 2001, pp. 908–912 vol.2. doi:10.1109/PESW.2001.96993.
[19] W. H. Kersting, A comprehensive distribution test feeder, in: IEEE PES T D 2010, 2010, pp. 1–4.
[20] W. G. Sunderman, R. C. Dugan, D. S. Dorr, The neutral-to-
earth voltage (nev) test case and distribution system analysis, in: 2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008, pp. 1–6. doi:10.1109/PES.2008.4596812.

[21] D. R. R. Penido, L. R. Araujo, S. Carneiro, J. L. R. Pereira, Solving the new test case using the current injection full-newton power flow, in: 2008 IEEE/PES Transmission and Distribution Conference and Exposition, 2008, pp. 1–7. doi:10.1109/TDC.2008.4517250.

[22] S. Tripathy, G. D. Prasad, O. P. Malik, G. S. Hope, Load-flow solutions for ill-conditioned power systems by a newton-like method, IEEE Transactions on Power Apparatus and Systems PAS-101 (10) (1982) 3648–3657. doi:10.1109/TPAS.1982.317050.

[23] K. Zollenkopf, Load-flow calculation using loss-minimisation techniques, Proceedings of the Institution of Electrical Engineers 115 (1) (1968) 121–127. doi:10.1049/piee.1968.0019.

[24] B. Stott, O. Alsac, Fast decoupled load flow, IEEE Transactions on Power Apparatus and Systems PAS-93 (3) (1974) 859–869. doi:10.1109/TPAS.1974.293985.

[25] S. Iwamoto, Y. Tamura, A load flow calculation method for ill-conditioned power systems, IEEE Transactions on Power Apparatus and Systems PAS-100 (4) (1981) 1736–1743. doi:10.1109/TPAS.1981.316511.

[26] G. Kerber, Aufnahmefähigkeit von Niederspannungsverteilnetzen [Hosting capacity of low-voltage distribution grids for small scaled PV systems], Ph.D. thesis, Technische Universität München (2011).

[27] M. M. A. Salama, A. Y. Chikhani, A simplified network approach to the var control problem for radial distribution systems, IEEE Transactions on Power Delivery 8 (3) (1993) 1529–1535. doi:10.1109/61.252679.

[28] S. Meinecke, S. Drauz, A. Klettke, D. Sarajlic, et al., Simbench documentation - electric power system benchmark models, Tech. Rep. EN-1.0.0, University of Kassel, Fraunhofer IEE, RWTH Aachen University, TU Dortmund University (Jan. 2020).

[29] www.simbench.net

[30] C.-T. Su, C.-F. Chang, J.-P. Chiou, Distribution network reconfiguration for load reduction by ant colony search algorithm, Electric Power Systems Research 75 (2) (2005) 190 – 199. doi:https://doi.org/10.1016/j.epsr.2005.03.002. URL http://www.sciencedirect.com/science/article/pii/S0378779605001021

[31] Centre for Sustainable Electricity and Distributed Generation (SEDG), UKGDS: United Kingdom Generic Distribution System, https://github.com/sedg/ukgds [Accessed: Feb. 15, 2020] (Apr. 2020).

[32] M. Klaee, A. Cruden, D. Infield, Demand side management using alkaline electrolyser within the ukdgs simulation network, in: CIRED - 21st International Conference on Electricity Distribution, Frankfurt, 2011.

[33] N. Uchida, K. Kawata, M. Egawa, Development of test case models for japanese power systems, in: 2000 Power Engineering Society Summer Meeting (Cat. No.00CH37134). Vol. 3, 2000, pp. 1633–1638 vol. 3. doi:10.1109/PESS.2000.868773.

[34] P. M. Anderson, A. A. Fouad, Power System Control and Stability, Iowa State University Press, 1980.

[35] P. M. Subcommittee, IEEE reliability test system, IEEE Transactions on Power Apparatus and Systems PAS-98 (6) (1979) 2047–2054. doi:10.1109/TPAS.1979.319398.

[36] C. Josz, S. Fliscounakis, J. Maeght, P. Panciatici, AC power flow data in MATPOWER and QCQP format: iTesla, RTE snapshots, and PEGASE, preprint (2016). URL https://arxiv.org/abs/1603.01533

[37] S. Fliscounakis, P. Panciatici, F. Capitanescu, L. Wehenkel, Contingency ranking with respect to overloads in very large power systems taking into account uncertainty, preventive, and corrective actions, IEEE Transactions on Power Systems 28 (4) (2013) 4909–4917. doi:10.1109/TPWRD.2013.2251015.

[38] B. Porretta, D. L. Kiguel, G. A. Hamoud, E. G. Neudorf, A comprehensive approach for adequacy and security evaluation of bulk power systems, IEEE Transactions on Power Systems 6 (2) (1991) 433–441. doi:10.1109/59.756684.

[39] C. Grigg, P. Wong, F. Albrecht, R. Allan, M. Bhavaraju, R. Billinton, Q. Chen, C. Fong, S. Haddad, S. Kuruganty, W. Li, R. Muherji, D. Patton, N. Rau, D. Reppen, A. Schneider, M. Shahidehpour, C. Singh, The IEEE reliability test system-1996. a report prepared by the reliability test system task force of the application of probability methods subcommittee, IEEE Transactions on Power Systems 14 (3) (1999) 1010–1020. doi:10.1109/59.780914.

[40] R. D. Zimmerman, C. E. Murillo-Sánchez, R. J. Thomas, Matpower: Steady-state operations, planning, and analysis tools for power systems research and education, IEEE Transactions on power systems 26 (1) (2011) 12–19.

[41] S. Meinecke, N. Bornhorst, M. Braun, Power system benchmark generation methodology, in: NEIS-Conference Hamburg, 2018.

[42] C. Li, Z. Dong, G. Chen, F. Luo, J. Liu, Flexible transmission expansion planning associated with large-scale wind farms integration considering demand response, IET Generation, Transmission Distribution 9 (15) (2015) 2276–2283. doi:10.1049/iet-gtd.2015.0579.

[43] H. Wang, Z. Chen, Q. Jiang, Optimal control method for wind farms to support temporary primary frequency control with minimised wind energy cost, IET Renewable Power Generation 9 (4) (2015) 350–359. doi:10.1049/iet-rpg.2014.0045.

[44] S. Pazouki, A. Mohsenzadeh, S. Ardalan, M. Haghifam, Optimal place, size, and operation of combined heat and power in multi carrier energy networks considering network reliability, power loss, and voltage profile, IET Generation, Transmission Distribution 10 (7) (2016) 1615–1621. doi:10.1049/iet-gtd.2015.0888.

[45] H. Xing, H. Cheng, Y. Zhang, P. Zeng, Active distribution network expansion planning integrating dispersed energy storage systems, IET Generation, Transmission Distribution 10 (3) (2016) 638–644. doi:10.1049/iet-gtd.2015.0411.

[46] G. Kerber, R. Witzmann, Statistical distribution grid analysis and reference network generation, eW (2008) 22–26.

[47] J. U. Scheffler, Bestimmung der maximal zulässigen Netzanschlussleistung photovoltaischer Energiewandlungsanlagen in Wohnsiedlungsgebieten [Determination of the maximum permissible power of photovoltaic power plants in residential areas], Ph.D. thesis, Technische Universität Chemnitz (2002).

[48] K. P. Schneider, Y. Chen, D. Engle, D. Chassin, A taxonomy of north american radial distribution feeders, in: 2009 IEEE Power Energy Society General Meeting, 2009, pp. 1–6. doi:10.1109/PESS.2009.5275906.

[49] B. Broderick, J. Williams, K. Munoz-Ramos, Clustering method and representative feeder selection for the california solar initiative, Tech. rep., Sandia National Laboratories (Feb. 2014).

[50] G. Waller, A.-K. Krausz, S. Eilenberger, W. Schweinfurt, S. Tenbohlen, Entwicklung eines standardisierten Ansatzes zur Klassifizierung von Verteilnetzen, in: VDE-Kongress Frankfurt, 2014.

[51] R. Bhakar, N. P. Padhy, H. O. Gupta, Development of a flexible distribution reference network, in: IEEE PES General Meeting, 2010, pp. 1–8. doi:10.1109/PES.2010.5589867.

[52] S. Breker, J. Rentmeister, B. Sick, M. Braun, Hosting capacity of low-voltage grids for distributed generation: Classification by means of machine learning techniques, Applied Soft Computing 70 (2018) 195 – 207. doi:https://doi.org/10.1016/j.asoc.2018.05.007. URL http://www.sciencedirect.com/science/article/pii/S1568494618302680

[53] H. Rui, M. Arnold, W. H. Wellssow, Synthetic medium voltage grids for the assessment of smart grid techniques, in: 2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe), 2012, pp. 1–8. doi:10.1109/ISGT-Europe.2012.6465639.

[54] P. Larscheid, M. Maercks, S. Dierkes, A. Moser, S. Patzack, H. Vennegeerts, J. Rolink, E. Wieben, Increasing the hosting ca-
pacity of res in distribution grids by active power control, in: International ETG Congress 2015; Die Energiewende - Blueprints for the new energy age, 2015, pp. 1–7.

[54] X. Han, S. You, F. Thorodson, D. Victor Tackie, S. Merete Ostberg, O. Michael Pedersen, H. Bindner, N. Christian Nordentoft. Real-time measurements and their effects on state estimation of distribution power system, 2013, pp. 1–5. doi: 10.1109/ISGTEurope.2013.6695324.

[55] A. Bracale, R. Caldon, G. Celli, M. Coppo, D. Dal Canto, R. Langella, G. Petretto, F. Pilo, G. Pisano, S. Ruggeri, S. Scalari, R. Turri. Active management of distribution networks with the atlantide models, in: 8th Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion (MEDPOWER 2012), IET, 2012, pp. 1–7.

[56] A. Seack, J. Kays, C. Rehtanz. Generating low voltage grids on the basis of public available map data, in: CIRED Workshop, Rome, Italy, Vol. 11, 2014.

[57] Q. Zhou, J. W. Bialek. Approximate model of european interconnected system as a benchmark system to study effects of cross-border trades, IEEE Transactions on Power Systems 20 (2) (2005) 782–788. doi:10.1109/TPWRS.2005.846178.

[58] H. Fan, M. Wang, X. Ning, Y. Liu. Transmission network expansion based on reference network concept, in: 2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), 2016, pp. 1405–1408. doi:10.1109/APPEEC.2016.7779720.

[59] E. Mayer. Benchmarking performance levels of distribution companies, in: 2001 Power Engineering Society Summer Meeting, Conference Proceedings (Cat. No.01CH37262), IEEE, 2001. doi:10.1109/pess.2001.979081.

[60] A. Scheidler, R. Bolgryn, J. Ullfers, J. Dassenbrock, D. Horst, P. Gauglitz, C. Pape, H. Becker, M. Braun. DER integration study for the german state of hesse – methodology and key results, in: CIRED 2019 (25th International Conference on Electricity Distribution), Madrid, 2019. URL: https://www.researchgate.net/publication/333651664_DER_INTEGRATION_STUDY_FOR_THE_GERMAN_STATE_OF_HESSE_-_METHODOLOGY_AND_KEY_RESULTS

[61] A. Adamczyk, M. Altin, O. Göksu, R. Teodorescu, F. Iov. Generic 12-bus test system for wind power integration studies, in: 2013 15th European Conference on Power Electronics and Applications (EPE), 2013, pp. 1–6. doi:10.1109/EPE.2013.6634758.

[62] S. Garske, C. Blaufuß, M. Sarstedt, L. Hofmann. Reactive power management analyses based on generic distribution grid models, in: 2017 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), 2017, pp. 1–6. doi:10.1109/ISGTEurope.2017.8260248.

[63] M. Kraiczy, T. Stetz, M. Braun. Parallel operation of transformers with on-load tap changer and photovoltaic systems with reactive power control, IEEE Transactions on Smart Grid (99) (2017). doi:10.1109/TSG.2017.2712633.

[64] I. Hernando-Gil, H. Shi, F. Li, S. Djokic, M. Lehtonen. Evaluation of fault levels and power supply network impedances in 230/400 v 50 Hz generic distribution systems, IEEE Transactions on Power Delivery 32 (2) (2017) 768–777. doi:10.1109/TPWRD.2016.2609643.

[65] A. Shafiu, N. Jenkins, G. Strbac. Measurement location for state estimation of distribution networks with generation, IEEE Proceedings - Generation, Transmission and Distribution 152 (2) (2005) 240–246. doi:10.1049/ip-gtd:20041226.

[66] K. A. b. Ibrahim, M. T. Au, C. K. Gan. Generic characteristic of medium voltage reference network for the malaysian power distribution system, in: 2015 IEEE Student Conference on Research and Development (SCOReD), 2015, pp. 204–209. doi:10.1109/SCOReD.2015.7449324.

[67] X. Chen, J. Lin, C. Wan, Y. Song, S. You, Y. Zong, W. Guo, Y. Li. Optimal meter placement for distribution network state estimation: A circuit representation based milp approach, IEEE Transactions on Power Systems 31 (6) (2016) 4357–4370. doi:10.1109/TPWRS.2015.253429.