Power System Benchmark Generation Methodology

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***Abstract*—Benchmark grids are power system parameter datasets, that are suitable for testing, publishing and comparing network planning and operation solutions and algorithms. A large amount of benchmark grids already exists. However, due to continuous development of new technologies and associated power systems changes, e.g. inverter-coupled distributed energy resources (DER) or controllable medium voltage (MV)-low voltage (LV) transformers, extended or new benchmark grids are required recurrently. To easily generate appropriate future benchmark grids, detailed descriptions of benchmark grid generation methodologies are required. Existing benchmark publications, however, lack such descriptions. Therefore, in this paper, an appropriate and comprehensible methodology to generate current and future benchmark grids is proposed. First results from the first application of the methodology in the project SimBench demonstrate its ability to generate an open-source, up-to-date, benchmark dataset that can be upgraded in future using the methodology.**

***Index Terms*—benchmark, methodology, comparability, reproducibility**

I. Introduction

As described in definitions of benchmarking, e.g. in [1], power system benchmark grids enable performance comparisons of one tool to another via tested datasets. Due to its availability, scientists use benchmark grids for testing, validating and publishing new algorithms.

A large number of elaborated and useful grid datasets exists. Several activities provide overviews of common public power system test cases [1], [2], and provide datasets in consistent formats that often can be used in common open or commercial power system analysis tools [3]–[5]. Although many available grid datasets are used to test and publish new algorithms, the original intention for generating the datasets often differs from above mentioned benchmark purposes. Besides *benchmark* grids, such as “IEEE Reliability Test System” [6], “CIGRE Benchmark Systems” [7] and “RTE/PEGASE cases” [8], [9], there are *example* and *test* grids, for instance “Nine-Bus System” [10] and “Baran’s System” [11], as well as grids with the focus to be *representative* for a larger amount of grids, e.g. “New England Test System” [12] and grids derived from clustering analysis [13]–[15]. The objective and the data origin of existing benchmark grids are described in literature. However, a step by step description of the design process is missing.

The period in which test cases were created shows that there is a recurrent need to generate new test cases. This is because benchmark grids should address real power system challenges and satisfy algorithm requirements while frequent novel technologies and developments lead to changes of power systems as well as new methods and solutions, especially for the grid integration of renewables. To satisfy the resulting recurrent need via generation of new benchmark datasets, a suitable methodology is required to make existing benchmark grids adaptable to future changes and challenges. To the best of our knowledge, however, no appropriate methodology is described in detail so far in literature.

In the project SimBench, a new benchmark grid generation methodology has been developed wherewith a benchmark grid dataset is currently being developed [2]. The methodology is presented in this paper. The dataset itself will be published later in a succeeding paper and will include tested combinations of all common German voltage levels, load and generation profiles as well as grid evolution scenarios.

This paper is organized as follows: A new general and suitable methodology is derived and introduced in Section II. In Section III, the application of the methodology in the SimBench project is presented along with exemplary results. Finally, conclusions are drawn in Section IV.

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II. Benchmark Grid Generation Methodology

The general methodology developed in SimBench is presented in this section. Development requirements of the methodology are appropriateness, applicability, scientificity and comprehensibility. As a result, the methodology is suitable to create new benchmark grid datasets appropriate for today’s and future benchmark grid requirements. The flowchart in Figure 1 illustrates the new methodology. An iterative loop of Step 5 and 6 is a key aspect to ensure appropriateness, applicability and comparability and improves the dataset to be developed. Each of the six steps is described in the following along with examples. Some descriptions in this section may seem abstract for the reader, but should become clearer when the exemplary results are presented in Section III.

1) Formulation of the objectives: For many reasons, e.g. to get orientated, motivated, coordinated and communicable with the outside, a benchmark activity should start with a clear formulation of the objectives. This includes estimating the user community and defining the use cases for which the benchmark dataset is supposed to be applicable. As an example, the objective could be to generate a German-like, static and balanced modeled low voltage (LV) grid, appropriate to study the use cases “voltage control” and “active power curtailment”. Step 1 further consists of the establishment of

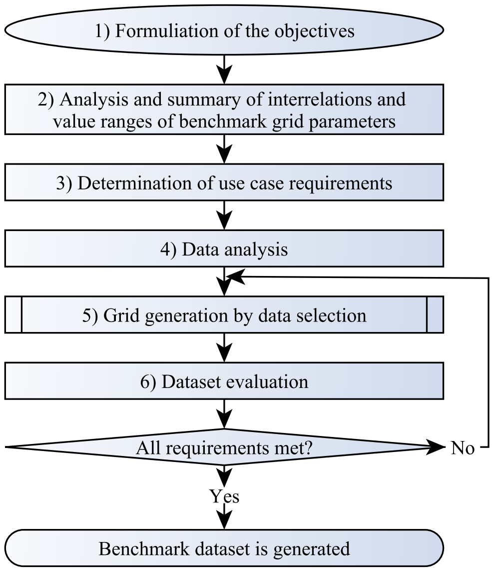

Figure 1. Flowchart of the benchmark generation methodology

fundamental criteria for an appropriate benchmark dataset such as:

- Complete data for all addressed use cases
- Real and future challenges are included
- Appropriate state of the benchmark system for analysis and fair comparisons

Based on these criteria, during the benchmark generation process, a catalog of requirements should be compiled. This catalog lists precise recommendations how to compose a benchmark dataset and implement individual parameters. Omitting a methodology step risks the compliance of the criteria.

The smaller the scope of use cases, the more similar the requirements can be. Some studies of new tools, solving these use cases, can possibly be calculated and analyzed automatically. However, if one is interested in a benchmark grid for a wide range of use cases, usually some use cases cannot be formulated fully mathematically. As further elaborated in Subsection II-5, in this case, expert knowledge is required to design the grid. As another consequence of satisfying many different requirements, benchmark grids become tendentially hybrid and atypical [16].

It may occur that the project objective includes several use cases whose requirements favor opposing parameter choices. In this methodology, except for multiple iterations of Step 5 and 6, each step is performed only once, considering all addressed use cases in parallel. That is in contrast to a serial methodology approach, where each step is performed multiple times, once for each use case. The parallel approach avoids that the benchmark dataset is optimized for the first use case in a first iteration while a second iteration reveals that the dataset is not appropriate for the second use case, and so on. Thus, competing use cases can be weighed against each other through simultaneous consideration and opposing requirements are revealed more quickly with less iterations. Among others, this is taken into account in Steps 2 and 3 which are described in the following. Step 2 focuses on grid parameter settings from a general perspective while in Step 3, use case specific aspects and interrelations between use cases are considered.

2) Analysis and summary of interrelations and value ranges of benchmark grid parameters: In Step 2, the expected influence of the dataset parameters is analyzed along with the range, which these parameters should exhibit. The main contribution to this step can be provided by a literature review. In this way, established practices can be used with or without revision. Line lengths and types are two exemplary parameters which should be assumed appropriately since they are important to analyze grids voltage profiles and power flow limits. While line lengths are distributed continuously, there are only a few used standard line types. Some information on the line types and their electrical parameters as well as line length distributions can be found in literature, e.g. in [17], [18].

3) Determination of use case specific requirements: For each use case, this step determines input and output variables as well as most important dataset manipulating parameters to achieve a useful benchmark grid.

Let us consider line lengths as an exemplary parameter for opposite use case interests. For the use case “voltage control”, long lines at the beginning of a feeder create a challenging scenario with high voltage drop or rise. To ensure “n-1 security” in ring-main systems, it is the same for supplied and supplying feeders. However, long lines at the end of feeders to be resupplied by another feeder intensify the challenge because in n-1 case, the long lines are located in the middle of the new long feeder and need to carry more power. In general, if the lines are chosen too long, they do not bear reference to real grids.

Literature can help to identify missing benchmark data and qualified assumptions. Summarizing all relevant benchmark information and design advices in a concrete catalog of requirements significantly supports Step 5 to select grid parameters.

4) Data analysis: Preserving and estimating the benchmark grid closeness to reality is a key challenge which is tackled in the data analysis step. To this end, the parameter ranges estimated in Step 2 are validated and completed using real data.

First, the parameters to be analyzed must be defined. These can be the full set or a subset of the intersection of relevant variables from Step 2 and 3 and available real data. Exemplary grid characteristic describing parameters are the transformer rated power $S_{N,Trafo}$, the sum of consumer active power $\sum P_{Load}$, the sum of distributed energy resources (DER) rated power $\sum S_{DER}$, the mean line length $\bar{l}_{Line}$ and the degree of cabling $\sum l_{Cable} / \sum l_{Line}$. Second, the data analysis is to be executed. Various analysis procedures are available. These include data collection and evaluation by questionnaires filled in by consulted experts, simple statistical analysis of grid

Table I
POSSIBLE PROCEDURES OF DATA ANALYSIS WITH REGARD TO AVAILABLE DATA QUANTITY AND QUALITY AS WELL AS CORRESPONDING CHALLENGES

Minimum data requirement			Possible procedures	Implementing and result interpretation challenges
Quantity	Assigned to individual grids	Calcu-lable		
Many grids	Yes	Yes	Full-scale analysis of many grids from automated use cases	Automation of use cases Do benchmark results fit to real data results?
Many grids	Yes	No	Determine grid classes and correlations via clustering, discriminant analysis, principal component analysis, support vector machines	Appropriate and comprehensible choice of analysis parameters and result interpretation
Many grids	No	No	Statistical parameter analysis from dataset extract or questionnaire	Appropriate and comprehensible choice of analysis parameters
Few grids	Yes	Yes	Test comparability of various algorithms	Do benchmark results fit to real data results? Reason the relevance of results and the appropriateness of analyzed grids
One grid	Yes	Yes	Detailed analysis of one real grid	Reason the relevance of results and the appropriateness of the analyzed grid

parameters, determination of parameter correlations and more complex procedures such as clustering. The selection of the best methods depends on the parameters and especially on the amount and level of detail of the available data. An increasing extent and level of detail of the accessible data enables further possible procedures, which generally generate better outcome quality. In Table I, this is presented with regard to data allocation to grids and feasibility of power flow analysis, starting with the lowest minimum data requirement at the bottom of the table up to the highest minimum data requirement at the top. As an example, analyzing a few grids, whose parameters are not only a data collection but are assigned to the corresponding grids and calculable in power flow analysis, enables testing comparability of various algorithms. The method given in the bottom line of Table I is also applicable since one calculable grid is also covered. In terms of including real challenges to benchmark data, it is highly recommended to analyze at least a few calculable grids.

Note that data from multiple system operators usually represents existing grid diversity better than data from a single system operator. This is because a system operator usually applies consistent criteria to design, operate and extend its networks, but these criteria may differ from other system operators. In addition, system operators may have to meet only homogeneous political and geographical requirements if for example the operator's grid is small enough. Therefore, it is recommended to consider data from different system operators, although this requires more effort, e.g. to convert data into a consistent format.

Depending on the reliability and data completeness, data from publicly available sources may be used in addition or as an alternative. Common sources are openstreetmap data [19], grid describing data published by system operators [20] and energy, power, or population data from governments or many other sources, e.g. reference [21].

5) Grid generation by data selection: This step combines the assessed variable space of Step 2 and 4 with the benchmark design advice of Step 3 to propose a sophisticated data selection. This is done by weighting the benchmarking knowledge and catalog of requirements. The complete selection of grid parameter data corresponds to creating the grid since the grid is then completely defined.

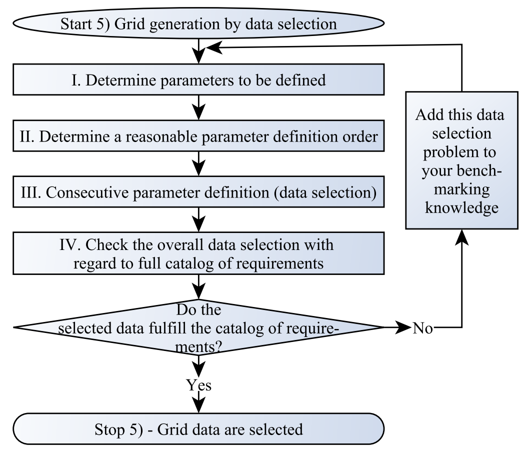

Figure 2. Data selection flowchart (Step 5)

Figure 2 depicts a simple and clear course of data selection. In Step 5-I, the parameters to be defined are selected. These include all variables in the first iteration of the overall methodology. After ordering this set in Step 5-II, e.g. starting with the parameter which is most fundamental for other depending parameters, the parameters are finally determined in Step 5-III. In the first iteration of the benchmarking methodology, the data selection can start with an initial parameter set from Step 2 or 4 or a mixture of both. Such initial parameters are literature based or real grid data based information. The conventional approach is to use and manipulate real grid data. Recently, further approaches based on clustering methods [13], [14], or on openstreetmap data [22] or additionally with green

Table II
EXCERPT OF SIMBENCH USE CASE CATALOG

Transmission grid operation	**Distribution grid operation**	**Network planning**	**Grid simulation**
Voltage control	Voltage control	Conventional network planning	State Estimation
Central reactive power control	Central reactive power control	Innovative network planning	Probabilistic power flow analysis
	Reactive power supply	Multi-voltage network planning	Accelerated and modified power flow analysis
Loss minimization	Loss minimization		
Redispatch simulation	Local congestion management Active power curtailment		
Topology optimization			

field planning tools [18], called reference network models, have been proposed. In Step 5-IV, a high-level check of overall data selection can cause an intuitive redefinition of grid parameters. However, to examine whether a dataset is suitable for benchmarking purposes also on a more detailed level, an evaluation of the generated dataset for all addressed use cases and based on benchmark grid requirements is required. This is performed in Step 6. The evaluation results, which can extend both, the benchmarking knowledge and the catalog of requirements, must be included in the data selection in the next iteration. To consider use case depended requirements, no procedures currently exist which are not based on expert knowledge. That is because many use case results cannot be evaluated automatically, but must be interpreted. Nevertheless, a detailed documentation enables a comprehensible benchmark development.

6) Dataset evaluation: This step is particularly important to ensure and enhance the suitability of a dataset as a benchmark. In this step, the created dataset is evaluated and a decision is made whether the dataset is of sufficient quality or it has to be improved based on the evaluation result. Here, it has to be evaluated whether the benchmark dataset fulfills all three fundamental criteria mentioned in Step 1 for all addressed use cases as described in the following.

The completeness is distinctly evaluated via implementing all considered use cases.

The comparison to the results of Step 4 shows whether the output of Step 5 is realistic. Experts or many assumptions are needed to assess benchmark inclusion of real and future challenges. To answer this question, an advisory team, e.g. with experienced system operators, is helpful.

To analyze whether the benchmark dataset provides a fair comparison of competing methods, different schemes, whose performance is known, can be applied to the benchmark dataset. Afterwards, the performances of the schemes achieved on the benchmark dataset is compared to their expected performances. Known advantages and disadvantages should be easily identified using the benchmark dataset. As an example for the use case “voltage control”, different voltage control strategies are applied to the benchmark grid and it is analyzed, if the different strategies yield different results, i.e., whether comparability is guaranteed. A local voltage control strategy should yield worse results than a centralized optimal power flow strategy.

In the following, the interaction of Step 5 and 6 by means of the use case “protection design at LV level” is discussed. The approaches to select initial parameters proposed in Subsection II-5 prevent the selection of a special case benchmark. However, since some use cases are only relevant in extreme grids, such an initial compilation of predominant typical grid parameters may not be appropriate in the first iteration for certain use cases like the “protection design at LV level”. For this use case, the initial compilation will agree with the majority of LV grids which can easily guarantee a minimum short circuit current for protection devices. However, due to extremely low short circuit current, especially extreme grids including long stub lines are worth investigating for this use case. Nevertheless, the above approaches for initial parameter selection are convenient as in this way the benchmark is only extreme if it is explicitly required by use cases.

III. SIMBENCH RESULTS OF MV BENCHMARK GRIDS

In this section, recent results of the first application of the methodology of Section II to generate one SimBench dataset consisting of benchmark grids at MV level are presented.

1) Formulation of the objectives: In SimBench, about 40 use cases are collected in Step 1. Table II highlights a choice of those, divided in four categories. The categories distribution grid operation, network planning and grid simulation concern the MV benchmark grid development.

The focus of the model is set on Germany, but due to similar conditions in many other countries, SimBench datasets are internationally applicable.

2) Analysis and summary of essential interrelations of the benchmarking development: Among many collected important quantities there is, for example, grid topology, which is fundamental for n-1 security and sectioning point optimization. Furthermore, the voltage level is an important parameter to design assets and coordinate network operation principles, but is missing in some existing benchmark grids or data formats, e.g. “case14”, “case57” and “New England Test System” [5], [12]. Another example is the degree of cabling, because cables and overhead lines (OHL) have fundamentally different electrical parameters which influence on line overloadings and voltage stability. In contrast to that, a consideration of different controls of reactive power compensation systems in German MV grids can be neglected because of rare appearance and unfavorable cost benefit ratio.

SimBench data covers symmetrical power system models because this simplification is valid for most investigations in the target region Germany.

3) Determination of use case specific requirements: As a result of use case analysis, SimBench data is limited to static power system models as dynamic models would increase the project scope immensely, whereas only a few of the collected use cases require dynamic models. On the contrary, for several use cases, e.g. “topology and sectioning point optimization”, “short circuit calculation with innovative switch control” or “power system restoration”, bus-branch-modeling is not sufficient. Hence, basic switch models are considered in SimBench. To cover future challenges, technologies like storages, electric mobility or high voltage (HV) DC lines are modeled as well.

4) Data analysis: At MV level, we focused on analyzing real data in SimBench. In contrast to extra high voltage (EHV) and HV, for MV the available open data from openstreetmap [19] or other sources is not sufficient for an analysis. Moreover, whereas at LV level, grids may be deduced from open information like building distribution, population information and road maps, combined with assumptions based on planning and operation principles, it is more difficult and uncertain for MV.

Relevant information to create the benchmark grids are derived from power flow analysis and statistical parameter analysis of real grids. Distributions and correlations of grid parameters of 74 separately operated MV grids are analyzed. These grid data include a line length sum of about 11.000 km and come from five system operators. Figure 3 exemplary illustrates the line cross-section distribution and line lengths for cable and OHL. The deployed cable and OHL cross-sections closely correspond to the different maximum line currents. The right diagram of the lengths boxplots gives an overview of MV line lengths and shows that OHL are frequently used for long lines. Since the lower OHL bars of the left diagram signify that the share of OHL is only 19.8 %, the boxplot of all lines is very similar to the cables boxplot. Likewise, other parameters and correlations are determined, e.g. DER position in feeder or MV/LV substations per HV/MV substation capacity ratio.

5) Grid generation by data selection: In particular, the selection of the number of different network types is challenging but essential. As explained in Step 1 of this section, the SimBench dataset is supposed to cover a large number of use cases, each of which has its specific requirements to be met by the SimBench dataset. Meeting the large number of requirements can be achieved by selecting different types of feeders and grids for the benchmark dataset. The more grid types in the dataset, the better the total amount of all existing grids can be represented. However, a high complexity due to a large number of grid types hinders comparability since results are only comparable if the same grid is used. This trade-off results in a number of four carefully chosen MV grid types. In spite of the limitation to four grid types, the dataset is appropriate for a sufficient number of use cases via choosing

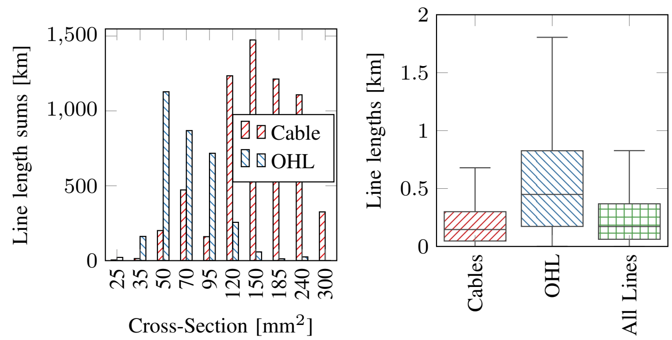

Figure 3. Example results of data analysis: cross-section distribution (left) and line length boxplots (right) by line type in real MV grids

Table III
QUALITATIVE CHARACTERIZATION OF SIMBENCH MV GRIDS

Grid	1	2	3	4
$S_{N,Trafo}$	low	medium	high	medium
$\sum P_{Load}$	low	medium	high	medium
$\sum S_{DER}$	very high	high	medium	medium
$\bar{l}_{Line}$	long	medium	short	high
$\sum l_{Cable} / \sum l_{Line}$	low	medium	high	medium

fundamentally different characteristics, topologies and levels of control variables for the different grid types. Table III provides an basic overview of the grid describing parameters from Subsection II-4 for the four different MV grid types of the SimBench dataset.

Figure 4 provides a schematic and simplified visualization of the topologies of the SimBench MV grid types. Grid 1 is connection to the HV level via simple H-arrangement and a single transformer. Starting from the MV busbar, simple rings with sporadic stub lines are operated separately. Grid 2 contains more complex ring structures, like triple-systems with cross-link connection. Similar to all other depicted MV grids, the rings at Grid 2 are operated separately under normal operating conditions. Due to historical reasons, topologies of Grid 3 and 4 also appear in reality. In addition to complex ring structures, Grid 3 includes a base station and Grid 4 a remote station both without HV supply. By means of two parallel transformers and a double busbar as well as the single busbars with longitudinal buscouplers at the substation, base and remote station, these grids have a huge number of switching possibilities to satisfy the n-1 criteria or improve operation.

These four grids are categorized as consecutively rural, suburban, urban and commercial (from Grid 1 to Grid 4).

6) Dataset evaluation: The SimBench group currently performs the evaluation step. Within the evaluation step, the benchmark grids are evaluated with regard to completeness, applicability, and comparability, based on a selection of the use cases from Subsection III-1. Within this step, some detailed requirements are deduced and added to the requirement catalog. For a first example requirement, let us consider the challenge of placing DER units in the grid such that compa-

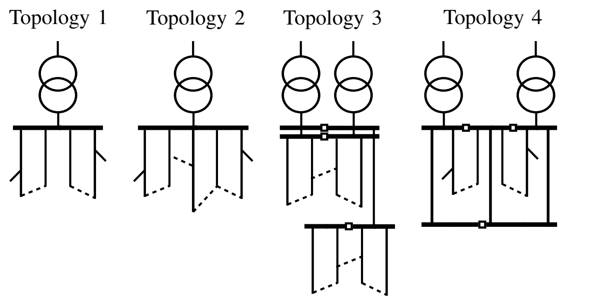

Figure 4. Schematic diagram of the four SimBench MV grid topologies

rability is guaranteed. For the comparison of several voltage control strategies, DER units at the beginning and the end of feeders yield different comparison results while resulting in the clearest differences between controller performances. DER units in the middle of a feeder do not yield clear differences. As a second example, for comparing various active power curtailment strategies, the strategies can only achieve different results if there are multiple, similar sized DER units to control in the critical, analyzed feeder. In addition, topologies from Figure 4 are found to be as already sufficient for n-1 calculation methods. Simple n-1 algorithms can show their advantages in the simple Topology 1 whereas n-1 algorithms must be gradually extended to consider all possibilities and solve n-1 calculations in Topologies 2, 4 and 3.

IV. Conclusion and Outlook

In literature, the documentation of benchmark grid generations lack a general power system benchmark generation methodology. In this paper, we bridge this gap by proposing a stepwise methodology for generating benchmark datasets, considering basic criteria. The proposed methodology contains an iterative improvement of the dataset to meet benchmarking requirements. Experiences and results of the first application in the project SimBench are presented. The created dataset is not yet completed and will be further evaluated and refined. Expectedly by the end of 2018, the dataset will be freely available online at [2] and will include not only MV, but also LV, HV and EHV grids.

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