Benchmark Models for Low-Voltage Networks: a Novel Open-Source Approach

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***Abstract*—This paper presents a novel benchmark system for the simulation of low-voltage networks. Two different versions are provided for dynamic simulations over short time intervals and for power flow studies over longer time horizons. The model description is accompanied by a comprehensive open-source documentation in order to facilitate the utilisation, tuning and expansion of the model by external users. This documentation includes the model implementation files in a Matlab/Simulink environment and a detailed description of the network and its components according to the PreCISE methodology. Finally, the model is extensively tested in simulation, considering two distinct test cases from the Erigrid 2.0 test case library.**

***Index Terms*—Benchmark models, low voltage networks, microgrids, simulation**

I. Introduction

Environmental concerns and the introduction of ambitious decarbonization targets are radically changing the traditional operational paradigm and structure of power systems, leading to a fast increasing penetration of renewable generation and of new flexibility technologies (e.g. storage). A significant research effort is being made to ensure that the electricity networks of the future will be able to operate securely and efficiently, dealing with increased uncertainty and complexity through smart and distributed control actions. The effectiveness of analytical and simulative studies on this topic cannot prescind from the availability of accurate benchmark models that capture the fundamental features and dynamics of the new electricity networks.

In this regard, it is important to underline the activity carried out by international technical organizations on this topic. For example, IEEE published its first test feeder model in 1991 [1], managing its updates [2] and developing other models for ad hoc analyses, from reliability [3] to small signal oscillations [4]. Similarly, the benchmark models developed by CIGRE in 2014 [5] have been customized and widely utilised by the research community [6], [7]. In the last few years, a substantial amount of research has focused on the development of benchmark models for low voltage (LV) networks, where some of the most significant developments and transformations are expected to take place. Different works have analysed the possibility to develop benchmark models that are based on real networks and data [8], [9] or are tailored on specific topics, such as frequency response analysis [10] or Power Hardware-In-the-Loop simulations [11], [12]. A significant number of benchmark models for Microgrids (MG) have also been developed, considering their operation in LV networks [13], the impact of local generation and storage devices [14], or analyzing particular cases such as networked MGs [15].

This wide range of models constitutes an important resource for the simulation and analysis of LV networks and MGs. However, their implementation and usage is generally not straightforward, as most of the cited works only provide network topologies and relevant parameters of the considered components. There are some exceptions: for example, among the cited works, network model files are provided in RTDS/RSCAD [12] and Simulink [16] environments, and relevant datasets are made available by [8], [9]. Nonetheless, to the best of our knowledge, there are not many works that provide an holistic and comprehensive description of the benchmark models, with the objective of facilitating their efficient and flexible replication and utilization. This paper aims at addressing this research gap, proposing a complete and open-source description of a new LV network model for the analysis of MGs and Distributed Energy Resources (DERs). The key novelty of the proposed approach is that, in addition to the typical technical description of the model (accompanied by validation in simulation and sharing of the associated Matlab/Simulink files), a complete and exhaustive model documentation is also produced. Such documentation has been developed following an ad hoc framework that allows to present, in a structured and consistent manner: i) a general hierarchical overview of the system, with high-level information on topology and parameters and ii) a description of the single network components, with information for their testing and validation. The proposed methodology not only streamlines the implementation and utilization of the developed network, but it also constitutes a relevant paradigm that

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can be easily replicated with other benchmark models.

II. Model Development

The development of the benchmark models was based on some preliminary design principles that were determined in the initial planning phase:

- Sizing of the network (in terms of number of components), aimed at achieving a desirable trade-off between network complexity and simulation speed.
- Inclusion of circuit breakers at relevant points of the network, in order to test different kinds of disconnections but also to consider, through proper switching, various network topologies (both radial and meshed).
- Modelling of inverters as controllable voltage sources and inclusion of the associated control schemes, to better evaluate their behaviour in a wide range of different scenarios.
- Inclusion of a microgrid, in order to assess its role and impact within the larger LV network and its capability to operate in islanded mode.
- Modelling of at least two different DER technologies (e.g. photovoltaic generation, PVs, batteries) to test their behaviour and interactions with synchronous generation.
- Inclusion of a distribution MV/LV transformer equipped with an On-Load Tap Changer (OLTC), in order to test its behaviour under different system conditions.

In order to accommodate all these elements and to enable simulations over different time horizons, two distinct versions of the benchmark model were designed. The ‘dynamic’ version includes detailed models of the power electronic components and is specifically tailored for dynamic simulations over short time intervals. On the other hand, the ‘phasor’ version is more suitable for power flow studies over longer time horizons. The modelling of these two networks was carried out in the Matlab/Simulink environment and the development of the different grid components tapped into the expertise and collaboration of many partners of the ERIGRID 2.0 project, including Tecnalia, RSE and OCT.

A. The ‘dynamic’ Network Model

The ‘dynamic’ version of the model includes all the network components that are relevant for dynamic simulations over short time intervals (from milliseconds to a few seconds): a Medium Voltage (MV) grid equivalent voltage source, an MV/LV transformer with OLTC, a synchronous generator, an asynchronous motor, a grid-following inverter, resistive-inductive loads, LV lines, and a microgrid composed of a grid-forming inverter and a resistive load. The model is represented in its Simulink implementation in Fig. 1 and its main parameters and characteristics are reported below:

- *Network*: A 20 kV voltage source is used to represent the Medium Voltage (MV) grid. The source is connected, through a MV/LV transformer equipped with OLTC, to a 420 V LV grid composed of 6 lines, 8 buses and 6 circuit breakers.
- *Loads*: Two RL static loads (both drawing 10 kW of active power and 1 kVAr of reactive power) and an asynchronous squirrel-cage motor with a nominal power of 80 kVA.
- *Generation*: A synchronous machine with rated power of 60 kVA and a renewable source, modelled as a grid-following inverter with maximum active power of 50 kW.
- *Microgrid*: Composed by a grid-forming inverter and one resistive load (drawing 2 kW of active power).

B. The ‘phasor’ Network Model

In order to accommodate some of the design objectives highlighted at the beginning of this section, an alternative version of the benchmark network (named ‘phasor’ version) was developed. This model, represented in Fig. 2, can be simulated with a phasor method and was developed to run ‘energetic’ types of scenarios on longer time scales (e.g. hours or days).

With respect to the initial ‘dynamic’ version, the synchronous generator and the motor were removed, while the inverters were replaced by alternative models of different components, i.e. a battery storage device, PV panels and a residential load. Since this ‘phasor’ model is tailored for simulations over longer time horizons, the fast dynamics of the inverters are now neglected but, on the other hand, the key operating features of the DER resources are taken into account, considering daily time-varying power profiles for load and generation and the charge/discharge activity of the storage.

III. Open-Source Documentation

The main objective of this paper is to guarantee a straightforward replication and easy utilization of the proposed benchmark models for LV electrical networks in modern power systems studies. Hence, a detailed and comprehensive open-source documentation of the models was made available to ensure that each benchmark network can be easily replicated by the interested parties, reducing the requirements for basic modeling of single network components. In particular, the overall idea lies on interested partners being able to investigate the phenomena or components they are interested in, using a freely available simulation setup, i.e. without having to start from scratch.

The documentation of the proposed electrical benchmark network can be divided into three-main categories: i) the networks description, ii) the components description and iii) the simulation files, which are also available. Regarding the networks and components description, the “Approach for preparing concise information for simulation experiments (PreCISE)” has been followed [17]. The rationale of the PreCISE approach is to facilitate collaborative work between professionals with different expertise, through an efficient documentation based on template documents. Hence, it can also facilitate the documentation of all the components of the benchmark networks of this paper, which are very diverse. For further information about the PreCISE approach, the reader is

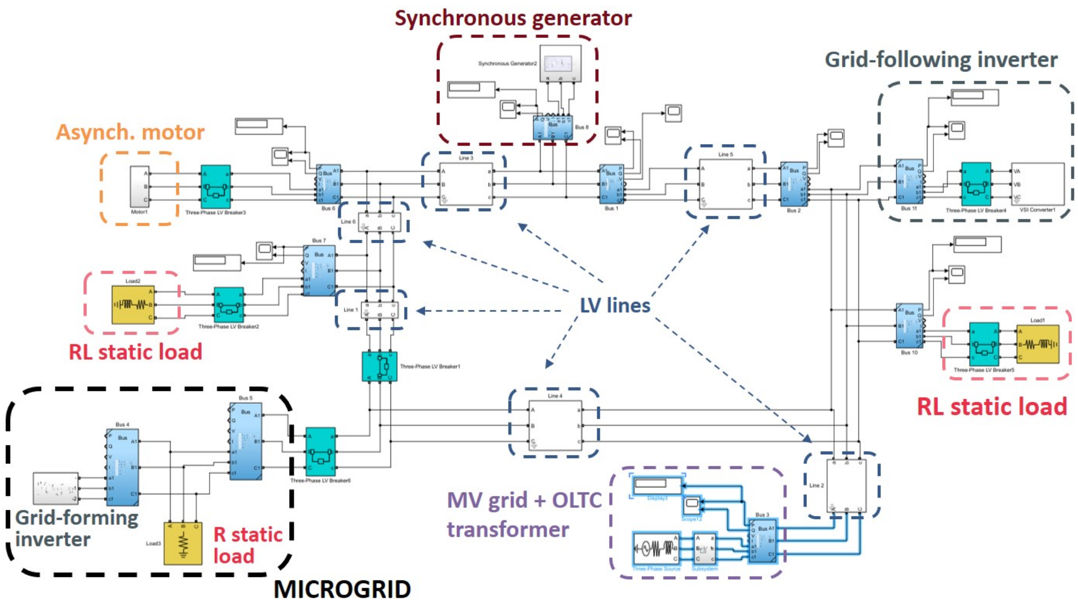

Fig. 1. Simulink diagram of the benchmark model (dynamic version).

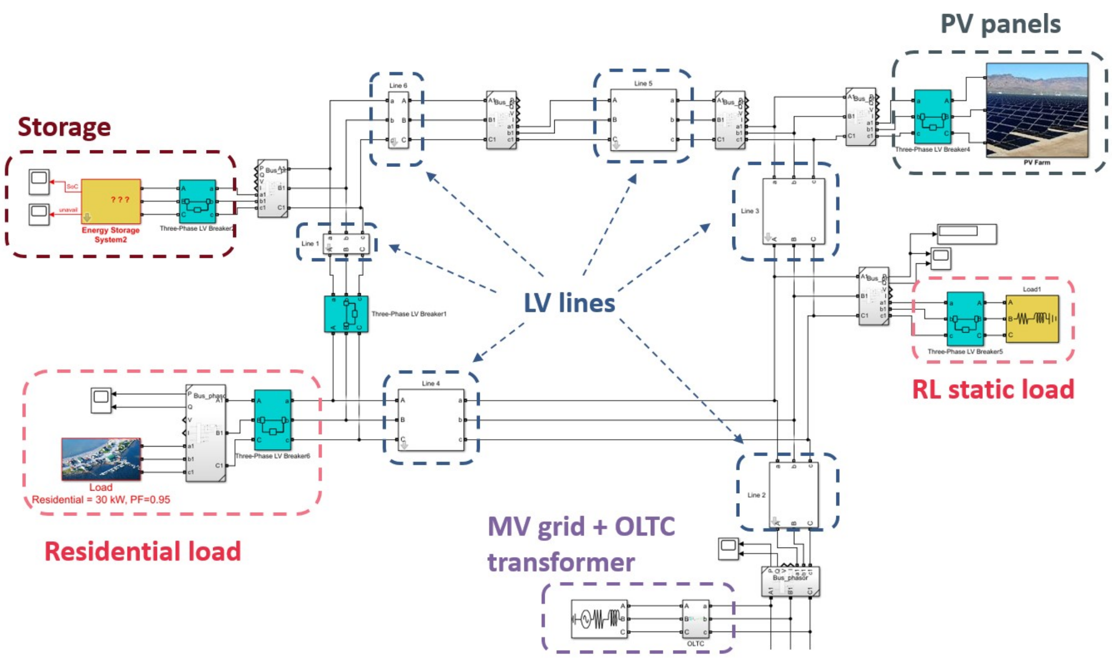

Fig. 2. Simulink diagram of the benchmark model (phasor version).

referred to [17]. In the sequel, all the developed documentation will be introduced and discussed:

- Power system description: the network part of the benchmark power systems was developed while investigating existing approaches and also taking into consideration all the modern components that may exist in power systems. The documentation of the benchmark networks, which uses the "System configuration template" of the PreCISE approach, is available on the ERIGRID 2.0 project Zenodo account [18]. All static information of the benchmark power system, i.e. lines impedance, topology, etc. can be found by the interested reader, thus facilitating its replication in various software environments. The power system description provides also a system breakdown of the network, with a classification and indexing of its different components (an example is provided in Fig. 3 for the dynamic version).
- Components description: as it was discussed in the pre-

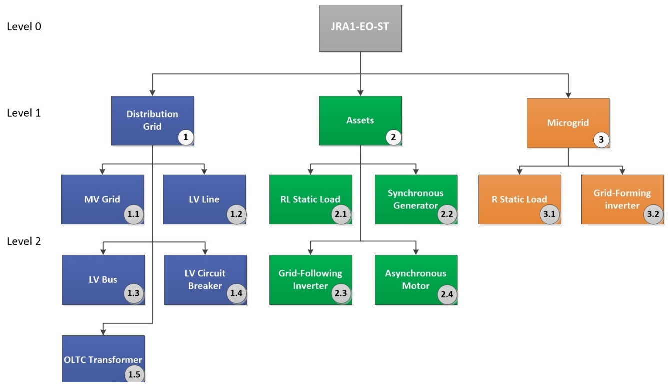

Fig. 3. System breakdown of the benchmark model (dynamic version).

vious sections, the benchmark power system described in this paper not only consists of the network itself but it also contains the most common components of modern power systems, together with their basic associated control and automation components. More specifically, synchronous machines, motor loads, residential loads, grid-following inverters, grid-forming inverters and others are contained in the proposed benchmark electrical networks. Since the above components are very diverse, in order to achieve a straight-forward replication of the benchmark models, the PreCISE approach was selected for the open-source documentation of each component description, using its ad hoc "Component model template". Through that template, for each of the components classified and indexed in the System Breakdown (see Fig. 3), the interested reader can identify its dynamic behaviour, locate its governing equations as well as familiarize with the procedure for its model validation. Again, all components' documentation is available at the ERIGRID 2.0 Zenodo account [18].

- Simulation files: a core attribute of the benchmark models proposed in this paper is that their simulation files are also available with an open-access license. Due to its wide use in studies of power systems with high penetration-level of DERs and of smart grids, the Matlab/Simulink environment was selected for the creation of the publicly available simulation files. Nevertheless, the benchmark networks and their components can be easily replicated with the main software packages for power system simulation (including open-source software environments), based on the provided PreCISE descriptions of the overall network and of the single components. The Matlab/Simulink files of the benchmark electrical networks are also available at the ERIGRID 2.0 Zenodo account [18].

IV. Simulation Results

In order to validate the applicability of the proposed electrical network benchmark in various setups, the two versions of the benchmark model have been simulated in distinct case studies. For this purpose, test cases #1 and #10 were selected from the ERIGRID 2.0 test cases library, available at ERIGRID 2.0 Zenodo channel [19]. This library was developed as a reference framework for the validation and testing of different power and energy systems throughout the ERIGRID 2.0 project, while ensuring its potential application in external projects as well. For the library development, the "ERIGRID Holistic Test Description" (HTD) [20] methodology was employed. In particular, based on the HTD methodology, every test case documentation contains its basic description, intended setup, test and experiment specifications, thus providing a complete definition of its intended use. Noteworthy, the ERIGRID 2.0 Test cases library has been also reported in an open-source fashion, thanks to ERIGRID 2.0 and H2020 open-access policies. Even if the ERIGRID 2.0 Test cases library was not developed as part of the benchmark electrical networks activity discussed in this paper, it fits well with the overall aim of the networks to act as a basis for the investigation of various test cases, without starting the modeling procedure from scratch.

A. Islanding Operation of the Microgrid

In the first considered example (a simplified version of TC #10 in [19]), the dynamic version of the grid was used to test the capability by the grid-forming inverter to restore and maintain the MG frequency at its nominal value after the MG has disconnected from the network and has started to operate in islanded mode. To achieve in simulation the critical frequency conditions envisioned for the test, the Medium Voltage (MV) source and OLTC transformer of the original benchmark model were replaced by a programmable LV source which could arbitrarily set the network frequency. The relevant simulation events are the following:

- Time $= 0.2$ s: connection of the synchronous generator in the LV grid.
- Time $= 1.0$ s: the LV grid frequency starts ramping up, at a rate of 0.5 Hz/s.
- Time $= 2.0$ s: as the frequency reaches the limit threshold of 50.5 Hz, the MG is disconnected from the grid and begins to operate in islanded mode.
- Time $= 5.0$ s: end of simulation.

Given the absence of an ad-hoc frequency measurement block in the Simulink environment chosen for the simulation, the frequency of the MG and of the LV network in the simulation were estimated ex-post. The frequency values were determined as the inverse of the time interval between two negative-to-positive zero crossings of the voltage signal. A moving average low-pass filter was applied to smooth out oscillations. The resulting frequency values for the LV network (measured at the transformer bus) and for the microgrid (measured at the grid-forming inverter) are shown in Fig. 4. After the initial oscillations between 0.2 and 0.8 s (due to the connection of the synchronous generator), the frequency values at the two measurement points remain equal until the MG disconnection occurs at 2.0 s. The grid-forming inverter of the MG is able to restore the frequency in less than one second: after some oscillations and an undershoot at about 2.4 s, the MG frequency quickly reaches its nominal value and does not

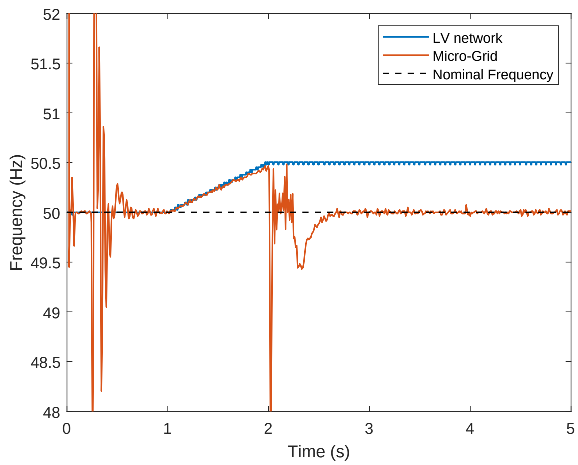

Fig. 4. Frequency profile in the LV network (blue) and estimated frequency in the microgrid (red).

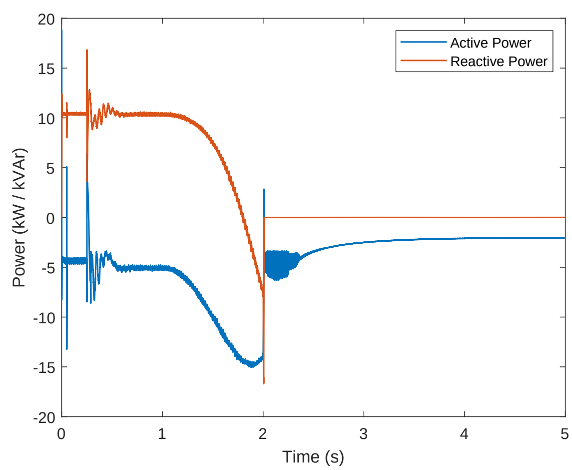

Fig. 5. Active and reactive power exchanged by the microgrid inverter.

exhibit further variations. The power exchanged by the grid-former inverter in the microgrid during the simulation has also been analysed and it is shown in Fig. 5. When connected to the grid, the MG inverter injects about 5 kW of active power (indicated by convention with a negative sign) and absorbs around 10 kVAr of reactive power. As the frequency increases (starting from 1.0 s), the direction of the reactive power exchange is gradually reverted and more active power is injected into the grid (up to 15 kW). At the time of disconnection (2.0 s), no reactive power is exchanged. As the microgrid begins to operate in islanded mode, the controller of the grid-forming inverter ensures that the injected active power (after brief oscillations between 2.0 and 2.3 s) corresponds to the quantity requested by the resistive load of the MG.

B. Testing of OLTC Controller

The second test case (a simplified version of TC #1 in [19]) was performed on the phasor version of the model, with the purpose of assessing the capability by the OLTC transformer

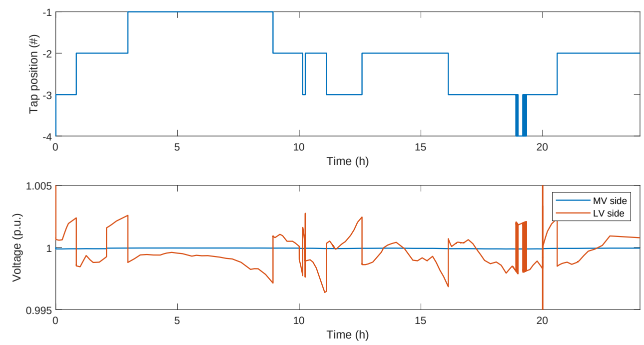

Fig. 6. Tap position (top) and voltage on primary/secondary side (bottom) of the OLTC transformer.

to regulate the voltage in the LV network in response to faults or disconnections of the grid components. To this end, the following simulation events were considered:

- Time $\in [0, 2]$ h: the storage device performs a constant 15 kW charge, bringing its State of Charge (SoC) from 0.5 to 0.9.
- Time $= 10$ h: fault on the line connecting the residential load and the storage device (see Fig. 2 for reference), which is cleared after 15 minutes.
- Time $= 20$ h: disconnection of the RL static load from the grid, with no reconnection within the considered simulation time interval.
- Time $= 24$ h: end of simulation.

Within the described simulation setup, the operation of the OLTC transformer (represented by the tap position over time) and the resulting voltage values (measured at the primary and secondary side of the transformer) are represented in Fig. 6. To emphasise the activity of the transformer, a low value was set for the voltage-step-per-tap and for the deadband considered in the voltage regulation (both equal to 0.00375 p.u.). In general, it can be seen that the transformer is able to maintain the LV voltage within the specified deadband (centred around the 1 p.u. nominal value) throughout the whole considered time interval. For example, note how the gradual voltage reduction on the LV side between $t = 5$ h and $t = 8$ h is interrupted by the transformer tap switching from position -1 to position -2, thus avoiding a violation by the LV voltage of the imposed regulation boundaries. A similar action is performed in the opposite sense at around $t = 21$ h, when the tap position switches from -3 to -2 following the voltage increase in the previous hour. The OLTC is also able to react to network events such as the line tripping at $t = 10$ h: the tap position switches from -2 to -3 right after the event and then returns to its original value once the fault is cleared, after 15 minutes.

In terms of transformer currents, displayed for a single phase on the LV side in Fig. 7, it can be seen that the impact of the tap switching is negligible (given the chosen low value of voltage-step-per-tap) and the current evolution over time is mostly dictated by the network dynamics and events. In this regard, note for example the significant current

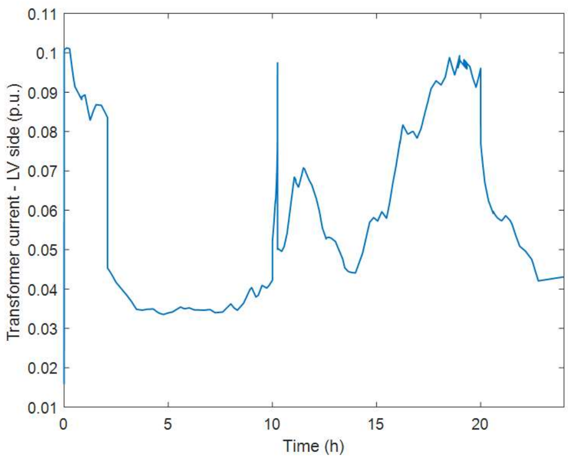

Fig. 7. Current profile on the secondary side of the OLTC transformer.

drop at $t = 2$h, in correspondence of the storage terminating its charging process.

V. Conclusions

The paper presents a novel open-source benchmark model of low-voltage grids with high penetration of power electronics and renewable energy sources. Two different model versions have been designed and implemented in a Matlab environment, allowing to perform dynamical studies over short time intervals and to run power flow studies on longer time horizons. The documentation of the models has followed an open-source approach aimed at facilitating their utilization, tuning and expansion by external users. The Matlab implementation of the models is made available online, together with a comprehensive and detailed open-source documentation within the PreCISE framework which presents the network topology, its connections and the modelling of the individual components. Future work will focus on improving the level of detail and modularity in the models, with the inclusion of additional components (e.g. heat pumps) and the possibility of selecting modeling blocks of varying complexity for the same component, so that the user can achieve the desired trade-off between accuracy and simulation time.

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