Microgrid Modeling for Stability Analysis

IEEE-PES Task Force on Microgrid Dynamic Modeling

Chairman: Claudio A. Cañizares Secretary: Rodrigo Palma-Behnke

Contributors: Danny Espín-Sarzosa, *Member IEEE,* Rodrigo Palma-Behnke, *Senior Member IEEE*, Claudio A. Cañizares, *Fellow IEEE*, Udaya Annakkage, *Senior Member IEEE*, Marcelo Elizondo, *Member IEEE*, Wei Du, *Member IEEE*, Lasantha Meegahapola, *Member IEEE*, Patricio A. Mendoza-Araya, *Member IEEE*, Ehsan Nasr, *Senior Member IEEE*, Rodrigo Ramos, *Senior Member IEEE*, Michael Ropp, *Senior Member IEEE*, John W. Simpson-Porco, *Senior Member IEEE*, Kai Strunz, *Senior Member IEEE*, and James T. Reilly*, Senior Member IEEE*

***Abstract*—This document is a summary of a report prepared by the IEEE PES Task Force (TF) on Microgrid (MG) Dynamic Modeling, IEEE Power and Energy Society, Tech. Rep. PES-TR106, 2023. In this paper, the major issues and challenges in microgrid modeling for stability analysis are discussed, and a review of state-of-the-art modeling approaches and trends is presented. In the context of the IEEE 1547 standard, the document covers issues associated with component models for MG dynamic studies and simulations, including generator and grid modeling, full and average converter models, unbalanced and balanced system conditions, dynamic and static loads, protection requirements, and detailed and simplified controls considering communications delays, packet losses, and security issues. Considering the future integration of grids and MGs to form broad integrated networks, a discussion is presented of the use of phasor vis-à-vis electromagnetic transient simulation tools for MG dynamic stability studies, as well as modeling scale-up issues and MG equivalent models. Specifically white-, grey-, and black-box models, are presented. This TF paper and companion report constitute a modeling guide for R&D groups working on developments and standards of MGs with a focus on stability issues.**

***Index Terms*—Computational burden, control, dynamics, electromagnetic transient simulation, microgrid, modeling, protection, simulation tools, stability.**

List of Acronyms

ANN	Artificial Neural Network
AVM	Average-Value Model
BESS	Battery Energy Storage System
BPS	Bulk Power System
CHIL	Control Hardware in the Loop
CPL	Constant Power Load
DEM	Detailed Equivalent Model
DER	Distributed Energy Resource
DFIG	Doubly-Fed Induction Generator
DG	Distributed Generation
DOL	Direct On-Line
EMS	Energy Management System
EMT	Electromagnetic Transients
ESS	Energy Storage System
EV	Electric Vehicle
FAST	Frequency-adaptive Simulation of Transients
GFL	Grid-Following
GFM	Grid-Forming
GSC	Grid Side Converter
HELICS	Hierarchical Engine for Large-scale Infrastructure Co-Simulation
IBR	Inverter-Based Resources
IM	Induction Motor
INR/I	Incremental Negative Resistance or Impedance
MG	Microgrid
MOR	Model Order Reduction
PCC	Point of Common Coupling
PEC	Power Electronic Converter
PLL	Phase-Locked Loop
PV	Photovoltaic
RNNs	Recurrent Neural Networks

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D. Espín-Sarzosa is with the Escuela de Ingeniería Eléctrica, Pontificia Universidad Católica de Valparaíso (e-mail: danny.espin@pucv.cl).

R. Palma-Behnke and P. A. Mendoza-Araya are with the Department of Electrical Engineering, Energy Center, University of Chile, Santiago, Chile (e-mail: rodpalma@cec.uchile.cl; pmendoza@ing.uchile.cl).

C. A. Cañizares is with the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, Ontario, Canada (e-mail: ccanizares@uwaterloo.ca).

U. Annakkage is with the Department of Electrical and Computer Engineering, University of Manitoba, Winnipeg, Canada (e-mail: udaya.annakkage@umanitoba.ca).

M. Elizondo and W. Du are with the Pacific Northwest National Laboratory (PNNL), Richland, Washington, USA (e-mail: marcelo.elizondo@pnnl.gov; wei.du@pnnl.gov).

L. Meegahapola is with the Electrical and Biomedical Engineering Department, RMIT University, Melbourne, Victoria, Australia (e-mail: Lasantha@ieee.org).

E. Nasr is with Microsoft, Redmond, Washington, USA (e-mail: ehsan.nasr@microsoft.com).

R. Ramos is with the Department of Electrical Engineering, University of Sao Paulo, Sao Paulo, Brazil (e-mail: rodrigo.ramos@ieee.org).

M. Ropp is with Sandia National Laboratories, Albuquerque, New Mexico, USA (e-mail: meropp@sandia.gov).

J. W. Simpson-Porco is with the Department of Electrical and Computer Engineering, University of Toronto, Toronto, O, Canada (e-mail: jwsimpson@ece.utoronto.ca).

K. Strunz is with the Department of Electrical Engineering and Computer Sciences, Technical University of Berlin, Berlin, Germany (e-mail: kai.strunz@tu-berlin.de).

J. T. Reilly is with Reilly Associates, New Jersey, USA (e-mail: j_reilly@verizon.net)

RSC	Rotor Side Converter
SG	Synchronous Generator
SMPS	Switch-Mode Power Supplies
SoS	Systems of Systems
TF	Task Force
UTP/STP	Unshielded/shielded copper Twisted Pairs
VFD	Variable Frequency Drive
VSCs	Voltage Source Converters
VSG	Virtual Synchronous Generator
VSIs	Voltage Source Inverters
WECC	Western Electricity Coordinating Council

I. Introduction

THE modeling and computational requirements to represent in detail various system elements and conditions to properly study stability in Microgrids (MGs) could be very onerous, requiring certain computational tools that restrict the types of studies that can be performed, thus limiting dynamic simulations to a few seconds for a reduced number of MG components. Moreover, model approximations that reduce the computational burden and may be able to efficiently represent certain dynamic phenomena in MGs might not be sufficient to fully analyze the stability of these systems. In this context, this document summarizes the detailed IEEE PES Task Force (TF) report [1], which focuses on studying and determining the validity and types of applications of detailed and approximate component models for MG dynamic studies and simulations for stability analysis, in the context of the IEEE 1547 standard.

The structure of modern power systems is transitioning from a centralized one, where bulk generation supplies loads through transmission and distribution system infrastructure, to a more complex grid, which incorporates decentralized self-sufficient low-voltage grids with Distributed Energy Resources (DERs) that can form MGs. These DERs, which include diesel generators as well as Inverter-Based Resources (IBRs), such as Photovoltaic (PV) generation, small natural-gas-based generators, controllable loads, Energy Storage Systems (ESSs), and Electric Vehicles (EVs), not only have the capability of exchanging power with the grid, but can also provide grid services, such as voltage and frequency regulation, and improve system stability, which are essential when MGs operate in islanded mode. Furthermore, concerns about the security of supply, power quality issues, and grid resilience, accompanied by dropping prices of PV systems and Battery ESSs (BESSs), are resulting in new MGs being formed and embedded in distribution grids, which have the potential to impact the grids where they are connected. For example, the direction and magnitude of the power exchange at the Point of Common Coupling (PCC) with the grid can rapidly change depending on the MG's own requirements. Finally, IBRs embedded in MGs do not contribute inertial response to the MG and main grid, affecting the stability of these systems. Hence, understanding the dynamic behavior of MGs, which act as single controllable entities at their respective PCC, and their impact and interaction with the grid, is becoming essential for grid operators and planners, requiring appropriate modeling approaches.

The final report and associated paper of the IEE PES TF entitled "MG Stability Definitions, Analysis, and Modeling" define concepts and identify relevant issues related to stability in MGs [2], [3]. These documents propose definitions and a classification of MG stability, considering pertinent system features such as voltage-frequency dependency, unbalancing, low inertia, and generation variability. They also conclude that the models of the different components of a MG have a significant impact on the simulation and associated results of dynamic events in these systems. Hence, to address these challenges, a TF on MG Modeling for Stability Analysis was created, focusing on various relevant aspects of ac MG dynamic studies and simulations for stability studies, in the context of the IEEE Std. 1547 series [4].

Based on the aforementioned modeling aspects, this document comprises multiple sections that discuss MG equipment and system dynamic models, including controls and communications, and modeling techniques and analysis tools, starting with a historical perspective in Section II, providing a comprehensive overview of the existing technical literature on the topic. Section III presents generator and grid models for MG stability studies, while Section IV reviews relevant converter modeling aspects, and Section V discusses load modeling approaches. In Section VI, control and communication modeling and associated issues relevant to MG stability are reviewed, and Section VII describes relevant modeling tools for MG stability analysis. Section VIII presents different modeling scale-up approaches that may be used for MG stability analysis, especially in the context of large interconnected MG systems, Section IX reviews and describes the system equivalent models of MGs for their stability analysis from a system interconnection perspective, and Section X outlines the challenges associated with MG modeling for protection design and lays out a set of requirements for associated design tools. Finally, Section XI highlights the main contributions and conclusions of the TF work.

II. Historical Perspective

The technical challenges of operating more than one DER in an islanded mode have been evident since the early years of MG stability research [5]. Thus, small-perturbation models were developed to study the dynamic behavior of these systems based on eigenvalue analyses, and guidelines were provided in 2008 for the design of controllers that met the IEEE P1547 performance specifications [4].

Control strategies were one of the main issues discussed in the technical literature in 2009. Supervisory and control systems were classified into centralized and decentralized in [6], and unbalanced operation, harmonic distortion, and computational burden were identified as aspects that should be considered for stability and control studies in [7].

With the developments in MGs, published work moved beyond optimizing the dispatch of a number of generators and loads toward the optimization of numerous micro sources/storage, as well as the coupling with heat and gas. Thus, in [8], issues associated with grid-connected and islanded operation were analyzed, as these are likely to produce large power balance mismatches, causing severe frequency and voltage control problems in MGs. Furthermore, "plug-and-play" capabilities were also identified as a source for serious stability issues with the possible and concurrent connection/disconnection of a large number of micro sources.

With the consideration of the unique characteristics of solar PV sources and wind turbines, the validity of conventional

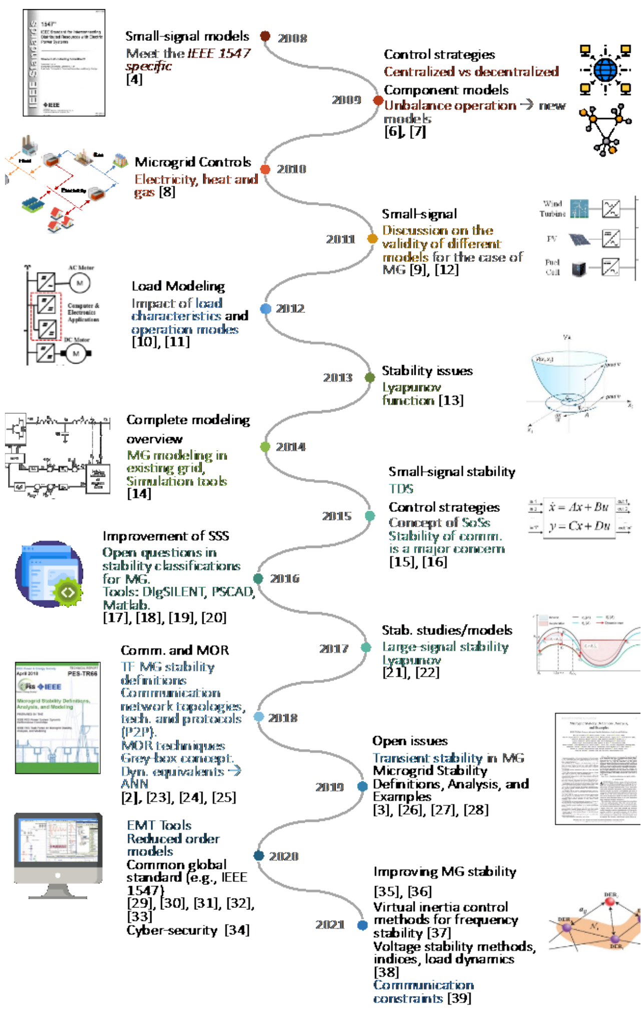

Fig. 1. Evolution of MG modeling topics for stability analysis. Different colors are used to identify the year the highlighted topic first appeared.

small-perturbation stability models based on local linearization was questioned in [9]. Moreover, as discussed in [10], while the impact of load characteristics on MG stability is quite evident, it was not until 2012 that concerns were reported regarding load modeling. Also, in [11], stability analyses were carried out for the four modes of MG operation, identified in the IEEE Std. 1547.4-2011 [12], i.e., connected mode, transition-to-island mode, island mode, and reconnection mode.

Reference [13] investigated in 2013 different stability issues with MGs depending on the application. Thus, it was noted that the MG structure and the control topology vary depending on the application, hence affecting system stability. Stability studies of various types of MGs were presented for different controls using eigenvalue analyses and time domain simulations. A state-space model was used for modeling DERs and loads, primarily using Lyapunov function techniques for stability studies, and discussing modeling alternatives to improve system stability.

In [14], a summary of MG modeling and control, as well as the relevance of incorporating MGs into the existing grid were discussed in 2014. The need for full dynamic modeling of the complete network was examined, comprising inverters, network, and loads, and considering various options for modeling DERs and converter interfaces. Matlab and ATPDraw simulation tools were used for the presented dynamic studies.

In 2015, [15] presented a summary of four different methods used/proposed for stability analysis of power converters, and the increasing complexity of converter topologies was highlighted as a challenge that required attention. In [16], several MG architectures, models, and control schemes were summarized, applying the concept of System of Systems (SoS) to MGs, as these are integrated systems with heterogeneous and independently operable systems, networked together for cost effectiveness, robustness, and better performance. Moreover, the stability of the communication network connecting the Distributed Generation (DG) units and inverters was also discussed.

In 2016, [17] reviewed state-of-the-art analytical methods used for stability analysis of MGs, including eigenvalue analyses based on state-space models, impedance-based approaches, and other nonlinear system analysis techniques, discussing their respective advantages and disadvantages. In [18], an extensive literature survey on several stability issues in MGs was presented, and in [19], a classification of MG stability, which considers the MG operating mode, types of disturbances, and time frames, was proposed. The latter also presented a comprehensive review of the literature on MG stability, mentioning that stability studies have been primarily based on simulation tools (e.g., DIgSILENT, PSCAD, and Matlab), but that further research on theoretical approaches was needed. Finally, the authors in [20] reviewed the key characteristics and main components of a MG, such as standard operating modes and control schemes of IBRs.

In 2017, [21] presented a survey of Lyapunov-based large-perturbation stability studies of MGs, discussing also large-perturbation analyses of individual generator and load types in the context of MGs, as well as stability studies of dc/ac droop-controlled inverters, ac/dc and dc/dc converters, and motor drives. Reference [22] provided a comprehensive review of load dynamic models in MGs, such as Constant Power Load (CPL) and Incremental-Negative Resistance or Impedance (INR/I) models, and their dynamic behavior, as well as an analysis of compensation methods to stabilize MGs with CPLs.

Based on the existing literature and the state-of-the-art on MG stability in 2018, the IEEE PES Task Force on MG Stability, Definitions, Analysis, and Modeling defined and classified MG stability in [2], summarizing later the report in [3]. Besides the definitions and classification for MG stability, the report presented a general discussion of models of MG components in the context of stability studies, as well as an overview of analysis techniques and tools. The same year, a comprehensive review of research work on stabilization of ac MGs with CPLs was presented in [23], which also reviewed several tools for stability analysis, such as Matlab/Simulink, PSCAD/EMTDC, and others. Reference [24] presented a comprehensive survey for existing MG models and their principles and applicability, together with stochastic and predictive modeling, and a classification of various modeling techniques under four categories: component-wise, single entity/lumped, stochastic/predictive, and dynamic equivalency. Lower-order models obtained from Model Order Reduction (MOR) techniques and dynamic equivalent models such as black-box, grey-box, and Artificial Neural Networks (ANNs) were also discussed. Lastly, [25] provided a systematic review of the most suitable communication network topologies, technologies, and protocols for MGs, concluding that a new generation of Peer-to-Peer communication systems would be required in smart MGs; potential research on communications for the next generation of MGs was also discussed.

In 2019, [26] summarized the definitions, classifications, and characteristics of MGs for researchers working on MGs, and highlighted the fact that although large-disturbance issues have been extensively studied in large power systems, these types of studies for MGs were limited. Furthermore, the need for additional research in MG stability analysis considering characteristics such as mesh networks, nonlinear loads such as induction motors (IMs), CPLs, EVs, and others, and various controls for power converters was discussed. In the same year, a comprehensive review of the control methods used in transient stability of MGs and their advantages and disadvantages was presented in [27]. Finally, an overview of small-perturbation modeling challenges was presented in [28], summarizing, and analyzing the most challenging topics in MG modeling, and explaining and providing a timeline of small-perturbation modeling methods for MGs.

During 2020, various publications discussed current topics and challenges in MG stability. Thus, in [29], an overview of different approaches for the provision of virtual inertia was presented, along with a detailed description of Virtual Synchronous Generators (VSGs), discussing methods for its stability analysis such as small-perturbation and transient stability techniques. The authors in [30] presented a comprehensive literature review of the main design features of existing MGs, as well as the main control functions that are required to ensure their economic, reliable, and secure operation in different operating modes. Several other topics were also identified, particularly the use of time domain simulators for MG dynamic security assessment, the need for accurate and computationally efficient dynamic models, and the upgrade of existing protection schemes to adaptive protection schemes. A comprehensive review and assessment of reduced-order models for small-perturbation stability studies of MGs was presented in [31], and in [32], an overview was provided for large-disturbance stability analysis of MGs dominated by power converters, discussing their characteristics and the technical challenges associated with using conventional and Lyapunov-based methods for stability studies. Additionally, in [33], the authors identified the need to define a common global regulatory framework and standards for DERs and MGs, since the current available standards have significant differences among them. Finally, in [34], cyber-attacks were identified as a relevant issue as they can negatively affect MG stability and operation, providing a review of cyber-attacks in the MG context, and standards and protocols associated with MG cyber-security.

In 2021, [35] and [36] summarized methods, techniques, and strategies to improve stability in MGs. In [36] in particular, the need for future research focused on the effects on MG stability due to the presence of different types of loads and uncertain conditions was mentioned. Reference [37] presented a summary of the MG control methods suitable for different scenarios from the perspective of frequency stability, the associated open theoretical and numerical challenges, and the predominant control strategies, reviewing studies related to inertia control methods in islanded MGs. The authors in [38] provided a comprehensive review on voltage stability of MGs considering topics such as voltage stability of autonomous MGs, impact of interlinking converters, coordination of voltage control loops, load dynamics on voltage stability, methods of static and dynamic analysis for determining voltage stability, and voltage stability indices for MGs. Finally, the influence of communication constraints on the stability of MGs was discussed in [39], providing a survey of cyber-enabled distributed control techniques for MG secondary control; the need for considering multiple communication constraints on MG stability is also highlighted in this work.

Fig. 1 summarizes the evolution of MG modeling topics for stability analysis, based on the aforementioned review of the existing literature on the topic. The diagram illustrates the chronological perspective of the main trends in MG modeling for stability analysis, summarizing specific topics in the existing literature relevant to the TF scope.

III. Generator and Grid Modeling

In this section, the modeling of the MG's underlaying grid is first presented, based on a three-phase power flow representation of the system. Then, relevant dynamic and static models of Synchronous Generators (SGs) and their voltage controllers, governors, and limiters are described. Finally, the dynamic models of various DERs' primer movers are briefly reviewed.

A. MG Power Flow Modeling

There are several differences in MG power flow modeling compared to traditional Bulk Power Systems (BPSs). Unlike BPSs, MGs usually operate at low/medium voltage levels in radial network topologies, as their grid backbone is basically structured as a distribution system. Thus, MGs typically have unbalanced loads and hence three-phase power flow models are necessary to analyze these systems. Moreover, conventional power flow modeling assumptions for some buses may not be valid for MGs, as IBRs at such buses may operate in different control modes, such as Grid-Following (GFL) mode or Grid-Forming (GFM) mode. Thus, while a GFL IBR can be treated as a PV or PQ bus, for a GFM IBR, droop control should be considered [40]–[42].

In [43], a three-phase power flow algorithm for islanded MGs is proposed. The proposed method considers the three main operation modes of DER units, i.e., PV, PQ, and droop modes. For a droop bus, besides the active and reactive power balance equations, relations determined by the droop control are modeled with 12 equations for each droop bus. To achieve a robust solution and global convergence, the authors implemented a Newton-trust region approach for the power flow problem. Similarly, [44] and [45] consider droop control and treat the system frequency as a state variable. In [46], a generalized MG power flow is proposed to incorporate hierarchical control schemes into MG power flows. The proposed approach is based on the direct backward/forward sweep algorithm and no slack bus is assumed, with the power loss being shared among all DERs. In [47], besides the traditional PV and PQ buses, a new bus type referred to as DER bus is introduced for DERs equipped with droop and/or secondary control. A modified Jacobian matrix is then derived to incorporate droop control and various secondary control modes, and since the

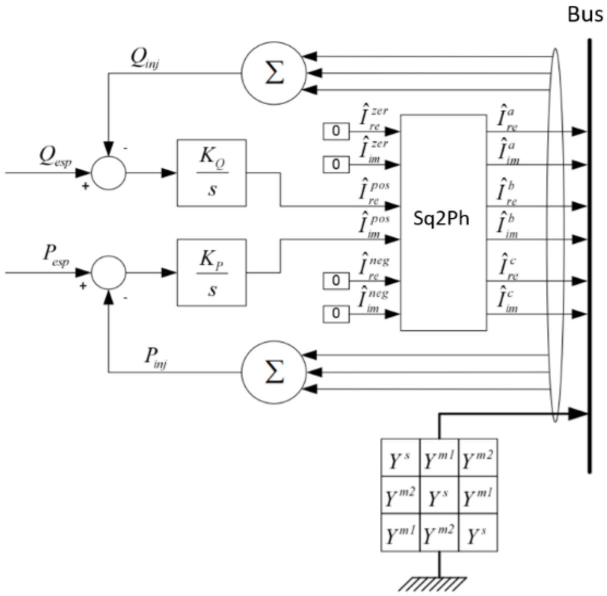

Fig. 2. Three-phase PQ bus.

Newton-type power flows are sensitive to starting points, power flows are first run with droop controls only.

Generally, three-phase representation of MGs can be performed using either sequence or phase components [48], [49]. The models to represent MG branches (π-model), three-phase loads, and three-phase transformers (Y and Δ connections) are basically the same as those used in a BPS [50]; however, for underground cables, shunt admittances must be considered. The buses for three-phase load flow can be represented as Norton equivalents, and zero and negative-sequence quantities must be appropriately incorporated. Thus, specific models can be applied for PQ, PV, and Vθ (Slack) bus representation. Fig. 2 shows a schematic representation of a PQ bus, where P_{esp} and Q_{esp} are the specified active power and reactive power setpoints, respectively, and P_{inj} is calculated using the injected currents in phase components, the phase voltages at the terminal bus, and the active power through the Norton admittance matrix. Thus, P_{inj} is compared to P_{esp} and the error is "integrated" by K_P/s, which yields the imaginary part of the positive-sequence current. The treatment of the reactive powers is analogous. A detailed representation of limits is provided in [51], [52].

B. MG RMS Dynamic Modeling

For MG RMS dynamic simulations, branches, transformers, loads (except IM), reactor and capacitor banks, and switches are modeled as described in the in previous section. The components that must be changed for dynamic studies are the SG, the IM, and DERs, which may be connected with or without power electronic interfaces.

The general scheme of DER models is shown in Fig. 3, where based on different DER technologies, the interface grid can be classified into two categories:

- Direct grid-connected DER without converters.
- Indirect grid-connected DER through converters.

This section focuses on SGs and various DER prime movers, with the modeling of the power electronic interfaces being discussed in Section IV.

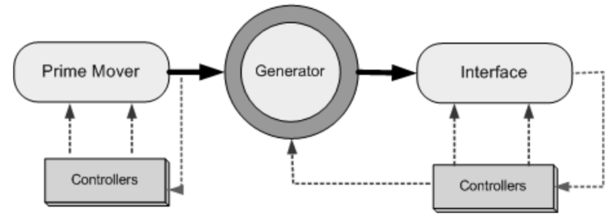

Fig. 3. General scheme of DG models.

1) Synchronous Machine

Dynamic models of three-phase synchronous machines and IMs for stability studies presented, for example, in [53]–[55], have gained new impetus with the increased penetration of DGs connected at distribution networks and forming MGs [56]–[58], where imbalances are not negligible. Focusing on stability issues, [59] shows how to account for the negative-sequence braking torque in the three-phase SG based on a Park model.

2) Exciter, Voltage Regulator

MGs typically include significant levels of variable renewable energy and are characterized by faster dynamics than conventional grid-connected distribution systems, mainly due to the lack of inertia of inverter-interfaced DERs. As a result, SG may operate close to their limits and their excitation systems should be modeled with enough detail to evaluate the possible impact of excitation control limits.

The automatic voltage regulator dynamic model may be based on the IEEE Standard 421.5 [60]. However, the specification of the voltage transducer has considerable relevance in unbalanced networks. Thus, references [61]–[63] mention that the limiters of synchronous machines may not operate properly under unbalanced load conditions, with the main cause being the terminal voltage transducer. To overcome this difficulty in operation under unbalanced load conditions, a low-pass filter can be inserted in the loop for the measured field current signal. When a MG is more heavily loaded, this approach can become unstable as unbalancing increases [57]. There are several methods such as active or reactive power compensators to mitigate the resulting oscillations; for example, in [57], unbalanced voltage stabilizer are used to mitigate these oscillations.

3) Dynamic Models of DER Prime Movers

The machine of a DER based on diesel generators and a microturbines (small gas turbines) is commonly modeled using standard synchronous machine models with a six order state-space model, accounting for the stator, field, and damper winding dynamics [64]. Additionally, numerous dynamic simulations of diesel generators have used simplified diesel genset models, often containing only one or two first order transfer functions to simulate the full diesel generator system [65], [66]. In [66] and [67], a suitable model of an emergency diesel generator is presented.

IV. Converter Modeling

The dominance of ac grids along with the fact that many loads at the consumer level (consumer electronics, for example)

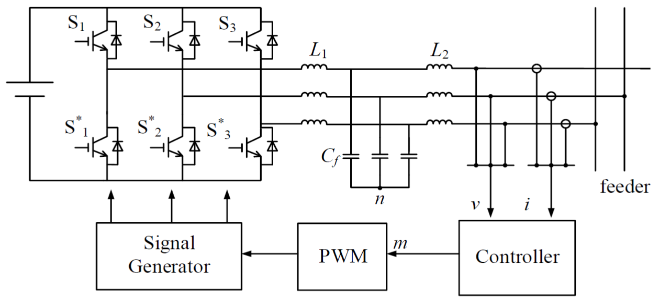

Fig. 5. A two-level, three-phase voltage-sourced inverter [77].

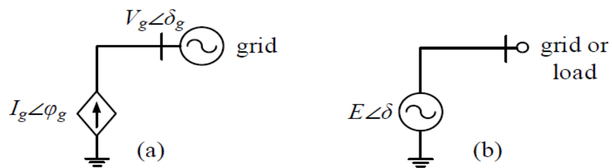

Fig. 6. Concepts of inverter controls: (a) GFL and (b) GFM.

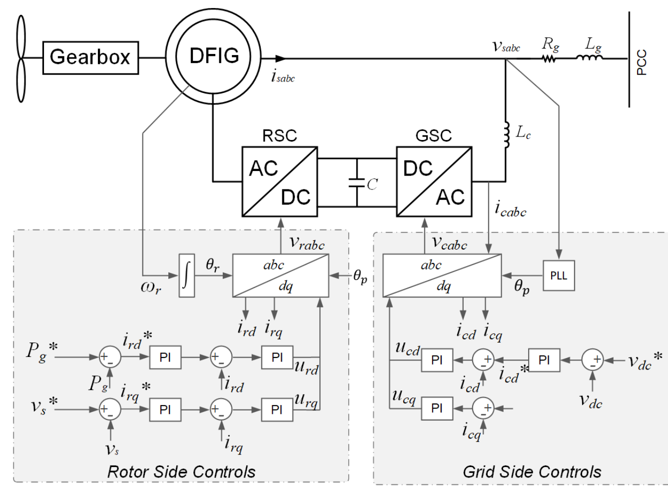

Fig. 4. Modeling of control loops in DFIG wind generator (adapted from [96]).

are designed to operate on an ac grid, has naturally led to the dominance of ac MGs. However, many DERs share a key characteristic of producing electricity in dc form (e.g., solar panels, batteries, fuel cells). Therefore, the power conversion between dc and ac in MGs in the form of inverters is required [32]. Power converters, which are the main components of IBRs, are widely used in MGs for generators, storage, and loads. Research in power converter modeling and control has been prolific, with a focus ranging from modulation techniques to primary control of MGs with multiple converters [24].

From the perspective of physical realization, Voltage Source Inverters (VSIs), sometimes called Voltage Source Converters (VSCs), are the most popular (e.g., [24], [69]–[73]). These converters are usually connected to the MG through a coupling inductor, transformer, and/or LC filter. This coupling/filtering stage is instrumental to both filter the waveforms of both voltages and currents displayed by the inverter, and measure the grid-side quantities, thus correctly implementing the control. VSIs are traditionally controlled either in current control mode or voltage control mode, and internal control loops include modulation (e.g., space vector modulation or sinusoidal PWM), current control and voltage control in the form of PI control [74], proportional-resonant control [75], and VSG control [70], among others.

A common converter topology is the two-level, three-phase, three-leg VSI, as shown in Fig. 5. From the modeling perspective, the VSI is usually modeled as an ideal controlled voltage source [74], [76], neglecting the switching phenomena of the converters. Inner control loops are modeled in general, although some exceptions are seen in the literature, where the converter and internal control loops are simplified into an ideal voltage source or an ideal current source behind an impedance [77]. Additional outer control loops are found along with converter models, including those that enable a standalone operation, usually known as GFM controls (Fig. 6(b)), and those that enable operation in parallel with a strong grid or infinite busbar, usually known as GFL controls (Fig. 6(a)).

A. Inverter Controls

GFL control makes VSIs behave like a current source operating at constant power on steady-state and as constant current during transients [77]. GFL inverters do not control the voltage and frequency of MGs, instead the voltage and frequency references are obtained from an external voltage measurement. Advanced Phase-Locked Loops (PLLs), which perform better under unbalanced conditions and/or phase jumps, are used in MG modeling. An overview of various types of PLLs is provided in [78]–[80]. Accurate models of the dynamics of these control loops are required for proper dynamic simulations and studies [3].

The GFM approach controls the voltage and frequency of the inverter [81], [82], making the voltage-sourced inverter behave approximately like a voltage source [83]. Because the voltage and frequency approximately remain constant, the GFM inverters can work in the standalone mode and track the loads [82]. GFM control is considered as an emerging technology for improving the stability of highly-inverter-penetrated power systems [72], [82]. However, there are still many important research topics for GFM inverters that need to be further studied, such as: dynamics of the dc bus voltage, over-currents of inverters during faults, and interaction between different inverters and SGs [77], [84].

Imbalances can propagate through the control loops of both GFM and GFL converters, negatively impacting the performance of such converters. For example, in GFL inverters, voltage imbalance may propagate through PLLs and reach inner control loops, where PI regulators would not see dc values at steady-state [75].

Although not as prolific as with their three-phase counterparts, single-phase inverters are covered in the existing literature (e.g., [85], [86]). The modeling of single-phase inverters does not differ much from the three-phase inverters.

In practical manufacturers' implementations, proprietary controls are, in general, not freely available to the public. This fact has motivated a Western Electricity Coordinating Council (WECC) Task Force to produce generic solar and wind (type IV) positive-sequence RMS models [87]. To account for studies in unbalanced MGs or feeders, these models have been extended to a three-phase model [61], considering a generalized Norton equivalent.

As an alternative to the traditional state-space models used in converters, an impedance-based model (also called admittance-based or terminal-behavioral model) uses a transfer function representation for small-signal analysis [88], [89]. This technique has been explored before by the power electronics community in dc systems (e.g. [90]), and it has been extended to ac systems, with applications in multilevel converters [91], droop-controlled inverters [92], and full ac MGs [89], [93], [94].

B. Applications to Generation & Energy Storage

Wind generation [95]–[104], photovoltaic plants [105]–[108], ESSs [109]–[113], and fuel cells [114]–[120] are interfaced with the grid using various converter topologies. For these systems, the aforementioned converter control options are integrated together with the specific energy conversion technology. Each interface is discussed in some detail in [1], using generic models for MG stability analysis. For example, a Type-3 wind turbine, referred to as Doubly-Fed Induction Generators (DFIGs), consisted of a Rotor-Side Converter (RSC) and a Grid-Side Converter (GSC), as depicted in Fig. 4, where the associated controls are shown. The control loops for both GSC and RSC are based on a cascaded PI structure.

ESSs can be treated as dispatchable power supplies in MGs. Hence, they are typically modeled using the previously described grid forming controls; however, GFL/grid-supporting models can also be used, depending on the ESS application.

V. MICROGRID LOAD MODELING

A. Overview

This section discusses load modeling issues in MGs, covering both traditional and other types of loads found nowadays in MGs. Loads play a critical role in the stability and dynamics of the MG, as they could affect the transient, frequency and voltage stability of the MG [13]. MG stability issues associated with constant power and induction machine loads have been investigated in, for example, [121], [122], and [123], with their impact on MG dynamics and stability being well understood. In these studies, accurate representation of MG loads is shown to be of paramount importance for the accurate characterization and analysis of MG dynamics and stability.

A range of different types of loads are connected to MGs, and their composition in MGs depends on the application area [124]. New load types are also being connected to MG to enhanced demand flexibility and energy efficiency, such as flexible smart-loads [125]. These loads are mainly composed of a Power Electronic Converter (PEC) interface at the front-end that has the capability to respond to external signals [125], and hence their dynamics are different from conventional load types. Furthermore, it is common practice to aggregate similar load types and represent them as aggregated loads in stability and dynamic studies [126]. Therefore, there are depth and breadth aspects to consider when representing loads in MG dynamic and stability studies.

MG applications include residential distribution feeders, commercial buildings, industrial facilities, institutions (e.g., research centers and universities), and transportation systems (e.g., ships). Therefore, the composition of each load type depends on the MG application area. For example, in commercial building MGs, lighting loads, Switch-Mode Power Supplies (SMPS), and motor loads are dominant [127]. Table I lists the dominant loads for different MG applications.

TABLE I
LOAD TYPES IN DIFFERENT MG APPLICATIONS

Load Types	**MG Application Area**			
	Residential distribution feeders, and remote area MGs	Commercial Building & Institutional MGs	Industrial MGs	Trans-portation MGs
Resistive loads	√	–	√	√
Lighting loads	√	√	√	√
Thermostatically controlled loads	√	√	–	√
SMPS	–	√	–	–
Direct-online start motors (1-Φ)	√	√	–	√
Direct-online start motors (3-Φ)	–	√	√	√
VFD motor loads	–	√	√	√

In addition to the load types listed in Table I, the following load types are also emerging in MGs:

- *Smart loads* are flexible loads that can vary their power consumption based on an external signal [125]. Usually, these loads have a power electronic interface, and they are used for providing demand response and other services to MGs.
- Many commercial building MG installations are now being built with plug-in EV bays and thus these are becoming an important load segment in modern building MGs. Therefore, EVs should be modeled with special emphasis on the charging dynamics associated with the charger [128].

B. Models for Dynamic and Stability Studies

The load models available for dynamic and stability studies can be fundamentally categorized into four types [129], [130]: (1) Static load models in which the active and reactive power of the load are determined by the terminal voltage and frequency characteristics; (2) dynamic load models in which the load active and reactive power vary with time in addition to voltage and frequency variations at their terminals; (3) composite load models in which static load models and reduced-order dynamic induction machine loads are combined; and (4) PEC-interfaced load models that have a front-end PEC interface showing constant power behavior within a specified voltage and frequency range, with dynamic nonlinear characteristics outside that range. The general classification of the load models is shown in Fig. 7.

Static load models are the most commonly used models in MG dynamic studies [130]. These models can be mainly divided into five types: (1) Simple impedance load model; (2) ZIP load model; (3) extended multi-zone ZIP load model; (4)

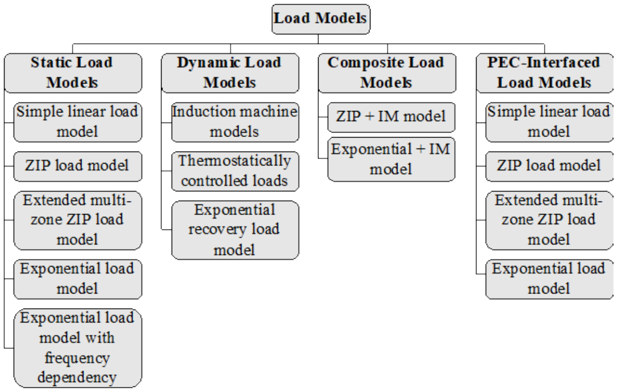

Fig. 7. Classification of load models.

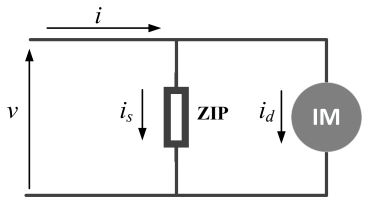

Fig. 8. ZIP+IM composite load model.

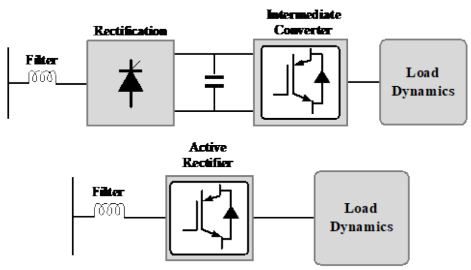

Fig. 9. General structure of a PEC-interfaced load.

exponential voltage load model; and (5) exponential load model with both voltage and frequency dependency/sensitivity.

Dynamic load models can be mainly divided into three types: (1) Direct On-line (DOL) start induction machine models; (2) thermostatically controlled models; and (3) exponential recovery models. Among the dynamic load models, the DOL start IMs (both three-phase and single-phase) are the most significant load types found in MGs, due to their sensitivity to terminal voltage and frequency. It has been determined that IM characteristics have a significant impact on the dynamics and stability of MGs [131]. Since Variable Frequency Drives (VFDs) have a power electronic interface, they have been categorized under PEC-interfaced loads in Fig. 7. Thermostatically controlled loads (e.g., air conditioners and heaters) are also considered dynamic loads, due to their time-dependent response.

Composite load models represent both static and dynamic loads as a lumped model. Common composite load models are composed of a ZIP load in parallel with a simplified IM load, as shown in Fig. 8 [132].

Different types of PEC-interfaced loads are connected to MGs and include SMPS, light-emitting-diode loads, VFDs, smart loads, and EVs. A generic structure of a PEC-interfaced load is shown in Fig. 9, where a passive filter is connected at the front-end of the PEC-interfaced load to eliminate harmonics, which can be either a simple inductive (L) filter or an LC or LCL type filter. The ac voltage is converted to dc using a simple rectifier, a controlled rectifier, or an active rectifier.

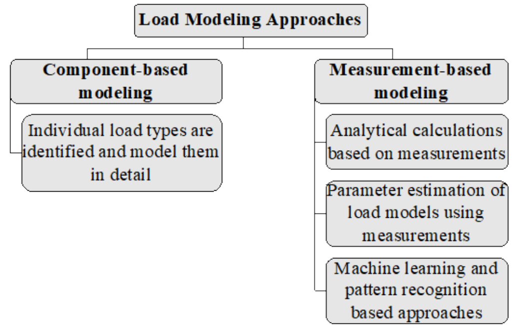

Fig. 10. Classification of load modeling approaches.

C. Loads Representation in Stability and Dynamic Studies

The load modeling approaches used for representing loads in stability and dynamic MG studies can be broadly classified into two categories: (1) Component-based and (2) measurement-based modeling [132], as illustrated in Fig. 10. In component-based load modeling, each load type in the MG is identified and then modeled in detail. In measurement-based load modeling, measurements are obtained via data recorders (e.g., event recorders) and then various techniques are applied to derive the load model.

Measurement-based load modeling techniques can be classified into three types: (1) Analytical-calculations-based on measurements, (2) parameter estimation of load models using measurements, and (3) machine learning and pattern recognition- based approaches [123], [127]. Analytical-calculation-based approaches are rarely used in the MG context since specific tests should be conducted to capture the necessary measurements from the load to calculate the load model parameters (e.g., induction machine parameter estimation).

The selection of the appropriate load modeling approach depends on the following factors: (1) nature of the dynamic stability investigation (e.g., voltage stability, frequency stability); (2) number of loads in the MG and size of the MG; (3) relative size of each load (e.g., if the size of a particular load is significant, then it must be represented in detail), and (4) availability of data for modeling.

VI. Impact of Coordinated Control and Communications on Microgrid Stability

One of the most challenging aspects in the control of MGs is that heterogeneous resources within the MG must be coordinated to achieve the desired performance objectives. Such coordinated control can be achieved via the implementation of an appropriately designed digital control system, with measurements and commands being transmitted throughout the MG via some available communication infrastructure. These control and communication systems are the main subject of this section, with a focus on when and how they impact the overall MG dynamic stability.

The conventional three-layer hierarchical control architecture of MGs is depicted in Fig. 11, which shows the decomposition into distinct primary, secondary, and tertiary control layers [133]. This three-level hierarchical architecture has largely been inherited from the control of BPS and attempts to strike a balance between the respective weaknesses and advantages of decentralized and centralized control. Each layer in the control

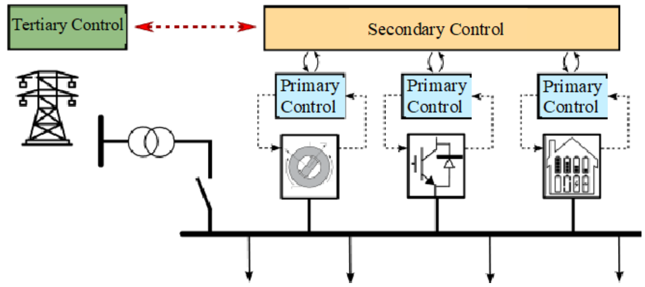

Fig. 11. Illustration of traditional hierarchical MG control.

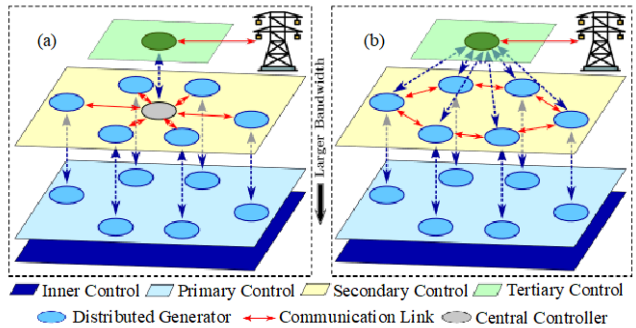

Fig. 12. Architectures for secondary control: (a) centralized and (b) distributed.

hierarchy has a specific role, spatial scale, and timescale; we describe each layer next. Other overviews of MG architectures and controls can be found in [124], [133], [142], [134]–[141].

Tertiary control refers to the coordination between the MG and an external entity, such as the host grid, a market operator, or even to a collection of other MGs in a multi-MG configuration [124], [136]. The role of the primary control layer is to continuously stabilize the frequency and voltage of the MG in the presence of unmeasured load and generation disturbances, to which controls respond quickly, with time constants in the order of seconds or less. The secondary control layer is the global control layer within the MG, which is responsible for all functionality that requires coordination between MG components. The most common objective of the secondary control layer is that of ensuring restoration of frequency and voltage to their nominal values. Various other objectives are sometimes also seen as being responsibilities of the secondary control layer, including improvement of power quality, balancing of load across phases, shedding of noncritical loads, coordination of black start, and security monitoring [133], [134]. In this document, the architecture of a secondary control system refers to the spatial organization of where measurements are taken, and how they are processed to determine secondary control actions. The possible architectures are classified as centralized and distributed, as depicted in Fig. 12.

Depending on the control problem and control timescale under consideration, it may be the case that little dynamic interaction occurs between system-level coordinating MG controllers and the lower level dynamics of the MG. An example of this would occur when a MG operates in grid-connected mode, where the frequency and voltage of the MG are largely imposed by the interconnection to the host grid. In such a scenario, the use of resources within the MG is typically managed via an Energy Management System (EMS), which optimizes the setpoints of devices based on market prices and on forecasts of generation and load [143]. Such a high-level control scheme

TABLE II
COMMUNICATION TECHNOLOGIES APPLICABLE TO MGS

Type	*Technology*	*Cost*	*Complexity of expansion*	*Distance coverage*	*Latency*	*Control level*		
						P	*S*	*T*
Wired	Optical fiber	×××	×××	×××	×	✓	✓	
	Twisted pairs	××	×××	×	×	✓	✓	
	Power line	×	×××	×	××			✓
Wireless	Wi-Fi	×	×	×	×		✓	✓
	ZigBee	×	×	×	××			✓
	Bluetooth	××	×	×	××			✓
	Cellular 3G	×××	×	××	××			✓
	Cellular 4G	×××	×	××	××			✓
	Cellular 5G	×××	×	××	×			✓
	LoRa	××	×	××	×××			✓

can be designed confidently without consideration of the MG dynamics.

A more complex scenario can occur in the case of an isolated or islanded MG, which is disconnected from the main grid. In this case, DERs must be quickly and reliably coordinated to maintain the MG frequency and voltage near nominal levels, leading to the potential of dynamic interaction between system-level MG controllers and the underlying MG dynamics. The dynamic performance of such a coordinated control system depends on several factors, including (1) the chosen control architecture, (2) the dynamic controller design and tuning, (3) the manner in which the controller is digitally implemented, and (4) the capabilities and performance of the communication infrastructure.

Both wired and wireless communication technologies can be deployed for use in MGs. Typically, the signals within an individual device in the MG (e.g., a converter-based DER), such as measurements and control signals, are carried via wired connection like optical fiber or Unshielded/Shielded copper Twisted Pairs (UTP/STP). On the other hand, information communicated between different devices within the MG (e.g., between different DERs, or between a DER and the MG central controller) travels through wired or wireless technologies depending on the specific characteristics of the system. Characteristics that influence the choice of wireless versus wired communication include distance, implementation and maintenance costs, and security. The main advantages/disadvantages of wired and wireless communications are summarized in Table II, based on [144].

The key messages are that several key digital control and communication system effects should be considered when testing proposed secondary control implementations, particularly the effects of controller sampling rates and communication delays. Distributed control implementations can have significant benefits over centralized implementations, as they remove a single point of failure from the MG and rely more on localized measurements for control purposes. The development of distributed and multi-agent secondary control techniques for MGs has received substantial attention, but further work is required to understand whether distributed solutions are feasible and appropriate for secondary control objectives beyond frequency and voltage regulation.

VII. MODELING TOOLS

A variety of diverse modeling tools is available for simulating MGs. Thus, it is useful to categorize the used techniques according to the approaches to model network elements and

TABLE III
MODELING CATEGORIES

Modeling category	Different representations
Power electronic conversion	Detailed vs. averaged switching
AC waveforms	Instantaneous (waveform) vs. envelope
AC lines	Three individual phases vs. single-phase equivalent

representing waveforms, as illustrated in Table III. The left column lists the categories, while the right column gives the different modeling approaches. For the modeling of power electronic converters, one can distinguish between detailed and averaged representations of switching processes. AC waveforms may be simulated according to their instantaneous waveshapes or just as envelopes, and ac lines may be represented individually for each of the three phases, while a single-phase equivalent can be an alternative. The first two categories are elaborated upon immediately hereafter, while the third category is discussed in the context of unbalances in Sections VIII.A and VIII.B.

A. Modeling of Detailed vs. Averaged Switching of Power Electronic Converters

Power electronic converters often pose challenges to the modeling and simulation of the systems in which they are embedded. This is due to the fact that power electronic converters operate based upon high-frequency switching, which requires the use of small simulation time-steps for the numerical integration of system equations.

To address the computational burden of simulating power electronic systems, several solution techniques have been developed. Detailed Equivalent Models (DEMs) use specialized techniques such as Thevenin-based equivalents to create numerical models that retain accuracy while reducing computational complexity. These methods are widely used for simulating converters of various forms, increasing computational efficiency by reducing the number of switching nodes that the converter model adds to the circuit model [145], [146].

Another category of models for reducing the computational burden of converter simulations are Average-Value Models (AVMs) [147], [148]. AVMs are based on the observation that the response of a well-designed power electronic converter is primarily dominated by frequency ranges well below the switching frequency, with negligible harmonic content that can be ignored without much practical implication. Thus, AVMs capture those frequency ranges relevant to intended dynamic converter functions, while ignoring the high-frequency switching transients, thus allowing the use of much larger simulation time-steps, as this is computationally advantageous. Whiles DEMs and AVMs are applicable in numerical simulation tools, most AVMs support the formulation of explicit dynamic equations or equivalent circuits that can be readily linearized and used in conjunction with established control system and stability analysis methods.

The concept of averaging a quantity can be extended to what is known as generalized multi-frequency averaging that also includes higher-order Fourier components of ac or dc quantities. In the context of converters with ac variables, such as inverters, the averaging process yields a time-varying complex number that describes the amplitude and phase angle of the respective harmonics, usually referred to as dynamic phasor. This is a powerful technique, as it allows applying the concept of averaging to dynamic phasor analysis methods common in power systems.

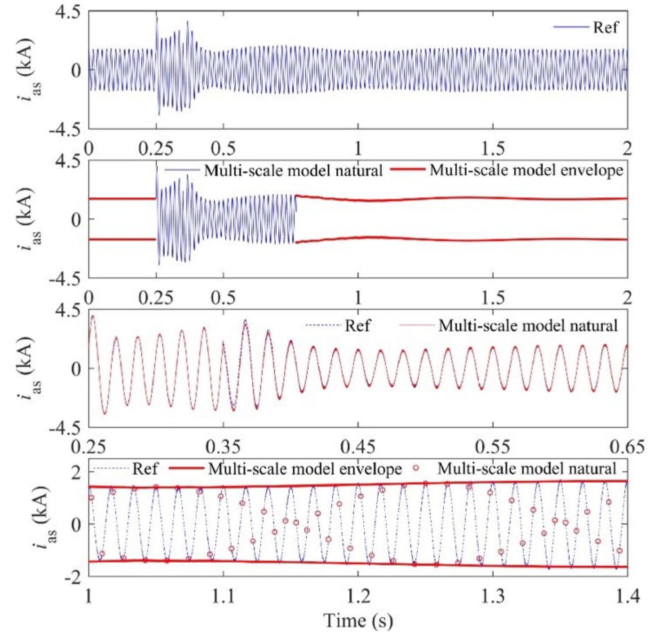

Fig. 13. Phase-a stator current $\boldsymbol{i_{as}}$ of DFIG; (a) natural waveform of the reference solution in PSCAD; (b) natural and envelope waveforms in the multi-scale simulation; solid light: natural waveform; solid bold: envelope; (c) zoomed-in view of $\boldsymbol{i_{as}}$ during electromagnetic transients, dashed: natural waveform of the reference solution in PSCAD/EMTDC; solid: natural waveforms in the multi-scale simulation; (d) zoomed-in view of $\boldsymbol{i_{as}}$ during electromechanical transients, solid light: natural waveform of the reference solution; solid bold: envelope waveforms in the multi-scale simulation; circle: natural waveforms in the multi-scale simulation.

B. Modeling of Natural vs. Envelope Waveforms

While some studies call for an accurate tracking of ac waveform details, for other studies envelopes are sufficient. Electromagnetic Transient (EMT) simulators support the accurate natural waveform tracking at small time-step sizes. Larger time-steps are possible when just tracking the envelopes in ac power systems thanks to dynamic phasor techniques [149]–[152]. The less accurate quasi-static phasor calculus is obtained as a simplified version when the transient behavior due to the network inductances and capacitances is neglected.

In practical simulation tools, the time-step size is treated as a simulation parameter. The introduction of the shift frequency as an additional adaptive simulation parameter allows for multi-scale simulation. For a frequency-shift of zero, EMT modeling is emulated, while an actual shifting of the Fourier spectra enables dynamic phasor calculus. This method is also referred to as Frequency-Adaptive Simulation of Transients (FAST) [151], [153]. A case study of multi-scale modeling of a DFIG wind energy conversion system and comparison with an EMT solution based on PSCAD is illustrated in Fig. 13, as detailed in [154]. The stator current of the DFIG in phase a is shown, and it can be observed that there are no visible differences between the multi-scale simulation and the corresponding PSCAD simulation. Whenever the envelopes are shown, the shift frequency is set to f_s = Hz.

Co-simulation combines two or more solvers by performing a simulation of a system based on a segmentation into several subsystems and assigning distinct solvers or tools based on the properties of each subsystem, with the subsystems being coupled through interfaces [155]. For example, a multi-rate co-simulator could simulate an area of main interest through an EMT-based method, while modeling the remainder of the system using dynamic phasors with a larger time-step.

C. Main Trends

In the context of MGs, tools relying on quasi-static phasor calculus, which are typically referred to as transient stability programs or RMS models, are not suitable for accurately analyzing such systems, especially where there is a significant share of converter-interfaced generation [156]. On the other hand, simulators based on dynamic phasors combined with average-value modeling are very well suited for small-disturbance analysis as well as larger disturbances concerning load changes, fluctuation of generation, phase imbalances, and corresponding control design. EMT-type models combined with the modeling of power electronic switches can be used for large-disturbance analysis concerned with significant faults such as short-circuit fault transients and harmonics. EMT tools may also be used for small-disturbance analysis; however, compared with envelope tracking in dynamic phasor calculus, a much smaller time-step size is required in that case.

The FAST multi-scale modeling approach integrates the virtues of dynamic phasor calculus and EMT-based techniques within one unified framework. This approach is of particular interest when broad time scales are considered, for example, when a fault and small disturbances are considered within one study. Finally, co-simulation may be applied when the techniques of dynamic phasors, EMT-based, or multi-scale modeling are to be allocated to different subsystems. Possible applications are the study of multi-MG systems or MGs coupled with large-scale power systems.

For dc MGs, EMT-based approaches are suitable and can be combined with average models or more detailed switching models. The latter being recommended for fault analysis and consideration of harmonics.

VIII. Modeling Scale-Up

MG stability models can become very large for three main reasons:

1. Large MGs containing hundreds of nodes.
2. MGs may be interconnected with other MGs, also known as networked MGs, to leverage their resources.
3. High modeling detail sometimes needed to model some loads, such as in the case of loads containing many motor loads.

Many simplifications normally used to deal with these system-scale issues do not typically apply to MGs. For example, capturing unbalanced loads and lines is critical for MG modeling; therefore, RMS models traditionally used in transmission are generally not enough for analyzing a large-scale MG. The following ways of dealing with the scaling problem can be considered:

- Use of modeling assumptions like those used in RMS models (also known as electromechanical or transient stability modeling or quasi-static phasor calculus as mentioned in Section VII) but capturing unbalances and the fact that MGs do not generally have a strong substation or generator.
- Dynamic phasor approximation can capture additional dynamics including effects such as inrush currents, while maintaining lower computational cost than EMT models with microsecond time-steps.
- Adaptive simulation or FAST that switches between steady-state and dynamics when needed.
- Co-simulation where different models are interfaced for information exchange at each simulation time step for two or more models.
- Equivalencing or MOR.

The first four approaches in the bullet list above are discussed in this section, while the last item. i.e., equivalencing, is covered in Section IX. Table IV illustrates examples of test systems and associated simulation approaches.

TABLE IV
EXAMPLES OF LARGE-SCALE EXAMPLE SYSTEMS MODELED BY USING SCALE UP MODELING APPROACHES

Test system	Number of nodes/generators	Simulation approach
IEEE 8500-node distribution system	8500/1	Unbalanced transient stability with single phase motor loads [162]. Electromagnetic transients with power flow initialization [183]
MG based on prototypical distribution feeder, R3-12.47-3	5,252/13 (3 synchronous machines and 10 inverters) [77]	Unbalanced RMS model (transient stability), 5,252 node MG model with 3 diesel generation and 10 inverter models (GFM and GFL) [77]
IEEE 342-node low voltage network test system	342/various primary feeders [161]	Dynamic phasors
IEEE 123-node test system	123/4 [58]; 123/7 (partitioned into 3) [158], [159]; 123/4 (with 500 motor loads) [157]	Unbalanced transient stability
IEEE 34-node test system	34/7 [184]	34 node MG in RMS (transient stability) and electromagnetic simulations [184]
IEEE 13-node test system	13/2 [58]	Unbalanced transient stability
IEEE-39-bus transmission system model with 6 MG models	39/16 [166]	Balanced transient stability at transmission level with multiple grid-connected MGs

A. Unbalanced RMS Models

Traditional RMS models have been applied at the transmission system level, which is mostly balanced, allowing the representation of the network using the positive sequence only. In the case of MGs, it is important to capture full imbalances, considering the fact that typically there is no strong substation voltage source, especially for islanded MGs. RMS MG models that capture full imbalances with an initialization equilibrium for synchronous machines have been developed [58].

Large MG systems have been tested in RMS models, taking advantage of the scalability of the approach in terms of computational efficiency. Large test feeders have been tested configured as MGs [77], [157]–[159], and utility MGs have also been tested with these models to study distribution resilience, such as in [160]. Computational efficiency for this approach associated with the ability of using larger time steps has been reported to be of a speed 7x or greater with respect to EMT-based models [58]; however, it is important to highlight that, even though unbalanced conditions are captured, accuracy is reduced due to the simplifications of the RMS models vis-à-vis the use of full EMT-based models.

B. Unbalanced Dynamic Phasor Models

Dynamic phasor modeling is discussed in some detail in Section VII. Large MGs systems have been tested using the dynamic phasor approach. Scalability has been tested on the IEEE 342-node low voltage network test system [161], which represents an urban core system with meshed topology fed from various sources that are feeders in normal conditions but could be thought of as emergency generation in a MG configuration. The phasor dynamic approach has also been applied to the modeling of single-phase IM loads as part of a multi-state load model in [157], where a MG is constructed from the IEEE 123-node system with 500 motors.

C. Adaptive Simulation and Co-Simulation

As the MG stability models increase in size and complexity, two popular methods to keep the simulations tractable are to utilize adaptive simulation capabilities and to leverage co-simulation platforms. For adaptive simulation scenarios, two primary approaches have emerged. The first is to select between different model types or representations of the system, as necessary [162], such as utilizing traditional multi-state ZIP models and power flow for periods of no change in the system. However, when an event occurs, the simulator changes to differential-equation-based models and smaller time-steps for more detailed analysis. Multi-scale modeling as discussed in Section VII may also be considered in this context. The second approach is to adjust the time-step of the simulation, as in the case of [163], where state-driven models are used, advancing the simulation to the next predicted state change.

Co-simulation platforms serve to coordinate multiple different simulators into a common simulation scenario. In simple words, this method breaks the simulation down into smaller portions in identical software that are solved individually, and then coordinated into a larger, aggregate MG model, effectively parallelizing the simulation. Other co-simulation approaches leverage different simulators for specific domains of analysis, and coordinate and combine the results for greater detail in the full simulation. Both approaches have since evolved into commercial software platforms [164], as well as more generalized co-simulation platforms.

D. Control and Communications in Networked MGs

As the complexity and scale of MG analysis increases, methods to operate and optimize the economics of the resources are increasingly of interest. There are numerous articles on improved control or optimization strategies for MGs and networked MGs. Properly deploying and evaluating these techniques requires increasing levels of detail in both the control systems themselves, but also the communication network between devices. Co-simulation platforms, such as Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS) [165], are obvious platform choices to perform these evaluations.

E. Coordination of MGs Connected Through the Transmission System

Networked MGs could also be connected through a transmission system, further scaling up the modeling problem. This configuration could lead to thousands of MGs connected through a transmission system, in which case the problem of coordinating among these many MGs becomes relevant. An analysis of the dynamic stability impact due to the penetration of multiple MGs through a transmission system is presented in [166], where the MG aggregated model consists of a power balance between load, storage, and other distributed energy resources controlled centrally using an electricity market pricing mechanism. In the simulation example discussed in this reference, aggregated MGs models are connected through the IEEE-39-bus transmission system.

IX. Equivalent Models of Microgrids

In the context of electrical grid studies, most loads, including some complex ones, such as buildings, small factories, etc., are usually modeled as lumped elements, representing the behind-the-meter aggregated loads. However, MGs, which are characterized by more complex components (particularly DERs) and responses due to control actions, entail more detailed modeling. This is particularly relevant in the context of active distribution networks and BPSs with embedded MGs, in which MG equivalent models allow accurate and computationally feasible simulations.

This section is intended as a survey of available techniques to produce equivalent aggregated models for MGs. The main idea is that, for dynamic simulation purposes, there is an area or component of interest in the MG that does not need to be represented in detail, highlighting the principle that there is no "general-purpose" method for producing a dynamic equivalent of a MG. This requires that at least some information about the phenomenon to be studied must be available, which is crucial for determining the most adequate equivalent model structure and parameters. Based on the level of available information, the most suitable approaches to build the desired equivalent can be divided into three categories: white-box, gray-box, and black-box approaches.

A. White-Box Equivalents

One approach consists of detailed modeling of the MG using "white-box" techniques. For a method to be classified as a white-box one, full knowledge about the system structure is required, and, in some cases, about the operating conditions as well (e.g., linear analysis techniques). This knowledge is used to build an equivalent that can reproduce the dynamic behavior of the portion of the system to which the equivalent is referred. These types of equivalents are usually reduced-order models with physical meaning, albeit this is not a strict requirement.

The selection of the model reduction technique depends on the types of studies that need to be performed. Thus, there are generally two equivalent types suited for the following studies:

(1) transient stability studies and (2) small-signal or -disturbance stability studies. However, this may not be practical, as it can significantly increase the computational burden of simulations (especially for large MGs) and requires knowledge of all MG components and their parameters, which may not be available. Hence, equivalent aggregated MG models can be found proposed in the literature instead, with gray-box and black-box models being among the most common modeling approaches. In these approaches, parameters are typically obtained using system identification and measurement-based techniques or data from simulations and/or laboratory experiments [167].

B. Gray-Box Equivalents

Gray-box approaches have been used to obtain equivalent models of MGs applied to dynamic studies of distribution or BPSs. In a gray-box approach, a suitable model structure based on prior knowledge or physical insight about the system is used to represent the real system with unknown parameters. The model structure is not the exact composition of the system, but it should be capable of representing its main characteristics with components that have a physical meaning or interpretation [168], [169].

Gray-box approaches are based on measurements, since they do not require detailed knowledge of the architecture and composition of the system, so measurements are used to identify the model parameters. These techniques require field measurements, which is challenging, given the difficulty in obtaining parameters from actual MG equipment and associated control systems. However, as distribution grids evolve in the context of smart grids, actual measurements are becoming more widely available, which can be used as input data to these types of approaches.

Equivalent models of MGs can be represented either by equations used to represent nonlinear state-space models of the MG components, or standard models available in various existing simulation tools. To tune the required equivalent model parameters, field measurements or sampled data taken from the simulation of the full model can be used. Therefore, as opposed to white-box approaches, gray-box techniques rely heavily on sampled information collected at specific points of the MG to build the corresponding equivalent model.

C. Black-Box Equivalents

Black-box models of MGs have been proposed for evaluating the impact and interaction of MGs with the grids to which these are connected. The main advantage of black-box models over other MG equivalent models is that these do not require knowledge of the MG topology, nor the individual components [170]. Most works on black-box modeling are based on representing the MG as active P and reactive Q power injections at the PCC [171], or as a current source which, along with the voltage at the PCC, yields P and Q injections at the PCC [172], [173]. In [171], two methods are proposed to develop a small-signal dynamic black-box model of a MG, based on actual measurements obtained in a laboratory setup. In [174], parameter identification using a Prony nonlinear least-square optimization method proposed in [171] is further explored and enhanced, introducing the concept of model correction factors. Other works based on polytopic models, such as [175]–[179], overcome some limitations of Prony-analysis and linear-state space black-box models to accurately reproduce the behavior of detailed models for a wide range of operating points. In [180] and [181], a recursive damped least square method is used as the system identification technique to develop a black-box model of a MG. Black-box models based on ANNs have also been proposed in the literature to represent equivalent MGs. For example, in [172], Recurrent NNs (RNNs) are used to represent a MG connected to a distribution network, where the MG corresponds to part of a low voltage distribution grid that includes multiple loads, three small PV units, and a single-shaft microturbine.

X. Modeling Needs in Microgrid Protection

Traditional distribution system protection design is assisted by software tools that automate the necessary calculations of source impedance as seen from various points along the circuit. These tools, which are commercially available, are designed to automate the calculations associated with the most commonly used protection methods in distribution systems such as coordinated time-overcurrent. However, these tools may not always be applicable to the protection design for MGs. There are several challenges specific to the design of protection systems for MGs [182]. This section describes some of them.

A. Requirements for Protection Modeling Tools for MGs

Ideally, a protection design tool for MGs would have the following properties:

- The tool should be able to reliably initialize and provide fault current calculations for systems that do not have an infinite bus. It should also initialize and provide realistic fault current calculations for systems with multiple IBRs.
- While preserving the capability to simulate on-grid fault currents, the tool should be able to reasonably represent the dynamics of MG sources during fault events, such as the time-varying fault current from SGs, the limited current from IBRs, the variations in negative-sequence current magnitudes and phase angles between various sources, and any dc-side limitations of IBRs.
- The tool should possess some forms of multiple-run capability that would allow the tool to assist in the design of a protection system that works under all expected MG conditions (e.g., different source combinations or different tie-line states).
- The tool should be able to simulate the expected response of a specific device under the dynamic conditions expected in the faulted MG. This includes but is not limited to the responses of current transformers, potential transformers, symmetrical component and RMS calculations, and other algorithmic elements in the presence of rapidly-varying frequency or voltage.
- The tool should evolve over time as MG protection methods are developed and come into use. For example, adaptive protection, fault location, isolation, and service restoration systems may be near-term candidates for protection of MGs with non-oversized IBR sources; thus, MG protection design tools should be developed to support the deployment of these systems.
- The tool should have all the above properties and capabilities for both ac and dc systems.

Accumulated experience and R&D efforts will lead to the development and standardization of effective microgrid protection techniques, with standardized protection approaches being sufficient for most microgrid protection designs. Commercial distribution protection modeling tools will eventually include many useful capabilities for setting the parameters of standardized microgrid protection in "typical" cases. In the near term, and into the future for "nontypical" cases, EMT simulations are necessary for protection design; in this context, faster, easier-to-use EMT tools are necessary. Furthermore, relay control hardware in the loop will become increasingly common for testing implementations of novel microgrid protection functions in relays.

XI. Conclusions

The document covered major issues associated with component models for MG stability studies and dynamic simulations, including generator and grid modeling, full and average converter models, unbalanced and balanced system conditions, dynamic and static loads, protection requirements, and detailed and simplified controls considering communications delays, packet losses, and security issues. Considering the future integration of grids and MGs to form broad integrated networks, a discussion was presented of the use of phasor vis-à-vis EMT simulation tools for MG dynamic stability studies, as well as modeling scale-up issues and MG equivalent models, specifically white-, grey-, and black-box models, were discussed. A review of state-of-the-art modeling approaches and trends has been presented for each topic.

This TF paper and companion report constitute a modeling guide for R&D groups working on current MG development and standards with a focus on stability and associated control issues. It also addresses various modeling issues being faced as MGs evolve, such as cyber-physical modeling and multi-MG issues. Hence, it should be helpful for studies investigating the future of MGs, while identifying challenges in MG network, DER, control, and communication and protection systems dynamic modeling, especially in the context of the wide integration of MGs in ADNs and bulk power systems.

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