Read-Me File for the Harmonic Power-Flow

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Contents

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1 Introduction

This repository comprehends a Matlab project for the *Harmonic Power-Flow* (HPF) calculus in power systems with a high share of *Converter-Interfaced Distributed Energy Resources* (CIDERs). The project consists of the Matlab Code performing the HPF study proposed in [1], [2] and its extensions as in [3], [4], along with the Simulink models for its validation. This HPF framework is capable of analyzing systems in periodic steady-state. It considers the propagation of the fundamental and harmonic frequencies and, specifically, includes the coupling between them. The Simulink models are used to perform *Time-Domain Simulations* (TDS), that are transformed to frequency domain spectra by means of the Fourier analysis. Multiple examples are provided, including the validation of the individual resource models of different types of CIDERs as well as entire distribution grids based on benchmark systems from CIGRÉ. The code and framework are designed in a generic way, such that the inclusion and analysis of additional types of CIDERs and/or other configurations of power systems is straightforward.

2 HPF Framework

2.1 Version Overview

The first version of the HPF framework proposed in [1], [2] is used for the analysis of harmonics in AC grids with CIDER models that represent the AC dynamics. The second version of the HPF framework proposed in [3] extends the CIDER model to include the DC-link capacitor and the corresponding AC/DC interactions. To this end, the HPF algorithm is updated in order to include necessary linearizations, that, in this case, are introduced by the nonlinearity of the PWM actuator. The third version of the HPF framework proposed in [4] further allows the analysis of entire hybrid AC/DC system interconnected through *Network-Interfacing Converters* (NICs). To this end, the Jacobian matrix of the Newton-Raphson algorithm is updated to additionally account for the DC grid.

2.2 Problem Formulation

The HPF is formulated by combining the hybrid nodal equations of the grid with the closed-loop transfer functions of the CIDERs, which are derived from their *Linear Time-Periodic* (LTP) state-space models. The mismatch between these two sets of equations must be zero in equilibrium. This problem is solved via a Newton-Raphson algorithm.

2.3 Grid Model

In all versions of the HPF framework, the grid components are characterized by compound electrical parameters, which accurately represent both AC and DC grids. In both cases, lines are modeled as π-section equivalents (single- or three-wire). The grid is described by hybrid parameters w.r.t. the nodes where grid-forming and grid-following CIDERs are connected, respectively.

2.4 CIDER Models

In all version of the HPF framework, CIDERs are represented by modular LTP systems that are transformed into harmonic domain by means of the Fourier Transform and Toeplitz matrices. Different levels of abstraction for the CIDER models are available. The first category used in [2] models only the AC components of the CIDER. Advantages are the reduced complexity and model order. The second category of CIDERs additionally models the PWM actuator and the DC-link capacitor. This version was used in [3] and allows to analyse AC/DC interactions of the CIDERs. For the analysis of hybrid AC/DC grids, the so-called NICs that interconnect the AC and DC subsystems are introduced in [4]. The main difference of a NIC compared to a CIDER is the additional input/output pair on its DC side.

3 Code Structure

3.1 Software

The code of this repository was implemented in Matlab/Simulink R2021b.

3.2 Matlab Code

The project follows the philosophy of Object-Oriented Programming (OOP). The corresponding UML diagram is shown in fig. 2.

The provided resources models contain CIDERs and NICs as well as passive impedance loads. Any resource class possesses the function `calculateGridResponse()`, which calculates the nodal voltage based on the injected current or vice versa, depending of the type of resource (i.e., grid-forming or grid-following). A CIDER or NIC comprises the `power_hardware` and `control_software`, and the `internal_transform` and `external_transform`. From these modules the harmonic-domain transfer function and, ultimately, the grid response can be calculated via the process shown in fig. 1a. More details on the CIDER structure can be found in [1]–[4].

The HPF can be performed on an object of the class `System` (i.e., for hybrid AC/DC grids) or on an object of the class `AC_Subsystem`. Any `Subsystem` (i.e., AC or DC) consists of one grid and several resources, while a `System` consists of several such subsystems, which are interconnected through NICs. The flow graph of a single Newton-Raphson iteration is shown in fig. 1b. Additionally, the link to the equations in the corresponding references is provided.

3.3 Simulink Models

The Simulink library in fig. 3 includes all available models of CIDERs and NICs, along with the most commonly used elements of power systems (e.g., lines, measurement blocks, other types of resources, etc.). In the provided Simulink models, the parameters of all components are automatically initialized through the functions `intializeTimeDomainSimulation()` from the objects created for the HPF study. Some models require the user to provide variant controls in the Matlab workspace to choose between variant subsystems [1]. This allows the user for example to change the PWM actuator model from average to switching function.

[1] www.mathworks.com/help/simulink/ug/variant-control-modes-in-variant-blocks.html

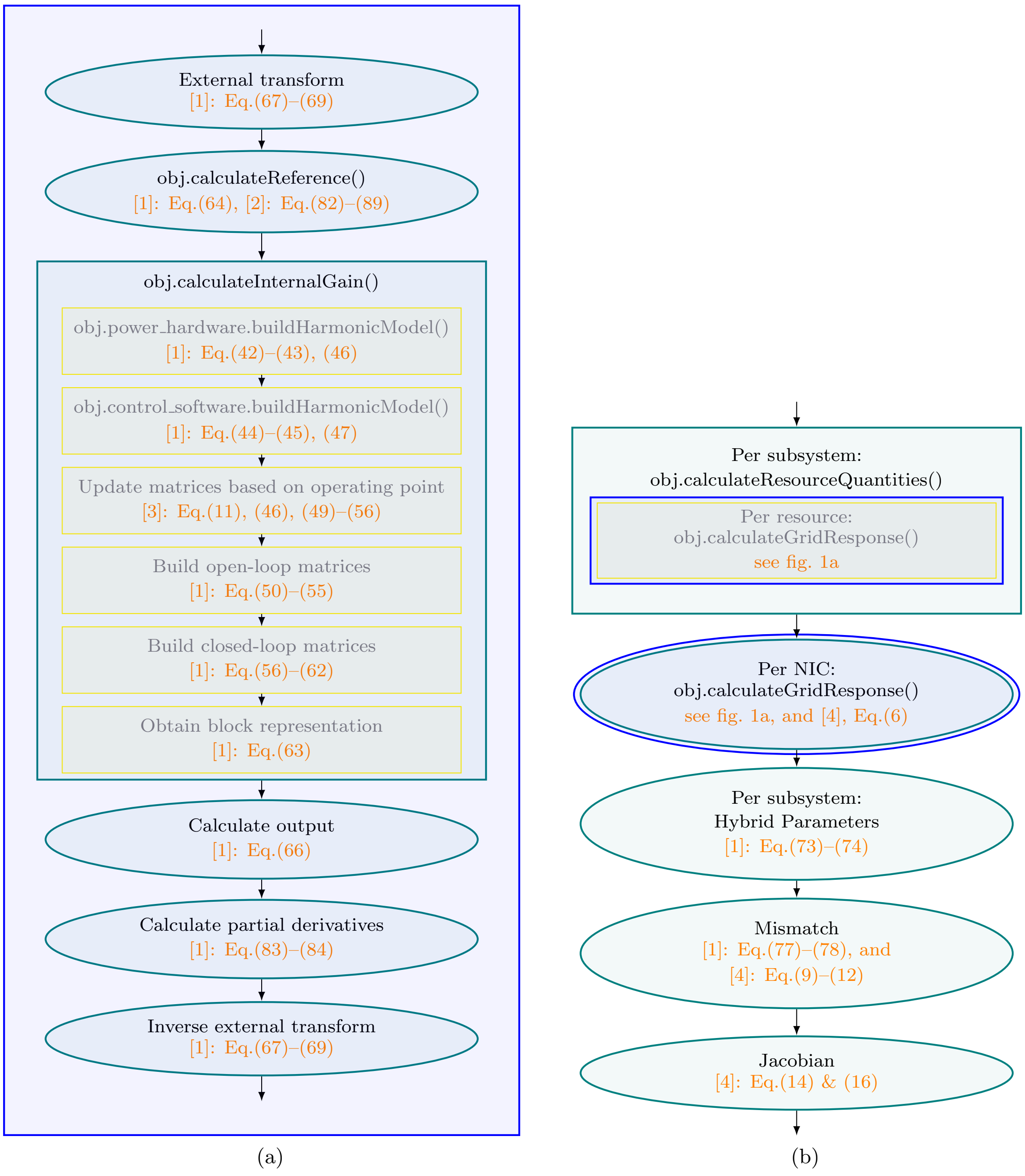

Figure 1: Link of the Matlab code to the theory developped in the papers [1]–[4]. (fig. 1a) `calculateGridResponse()` of a CIDER or NIC, (fig. 1b) a single Newton-Raphson iteration of the HPF.

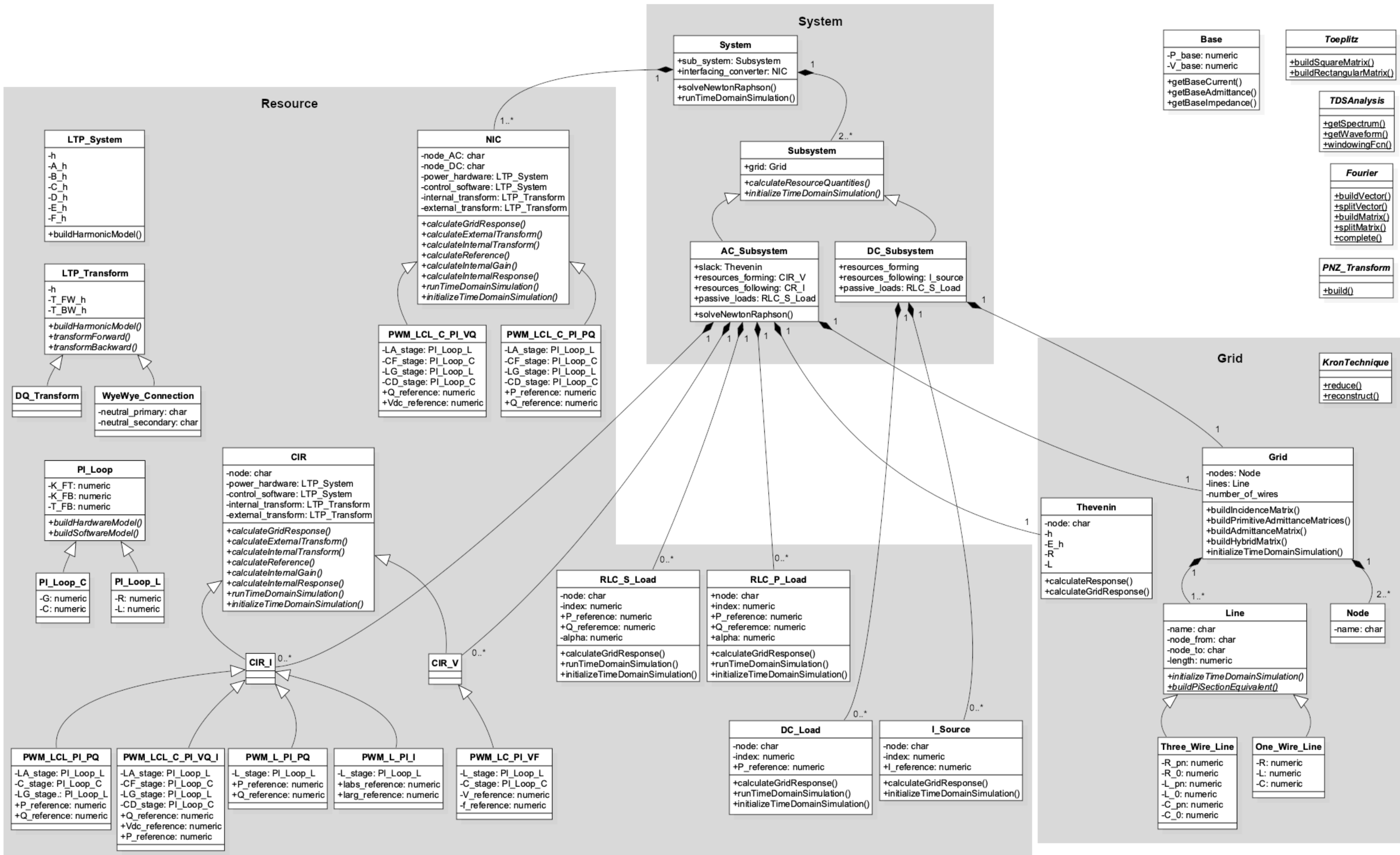

Figure 2: UML diagram of the Code performing the HPF study.

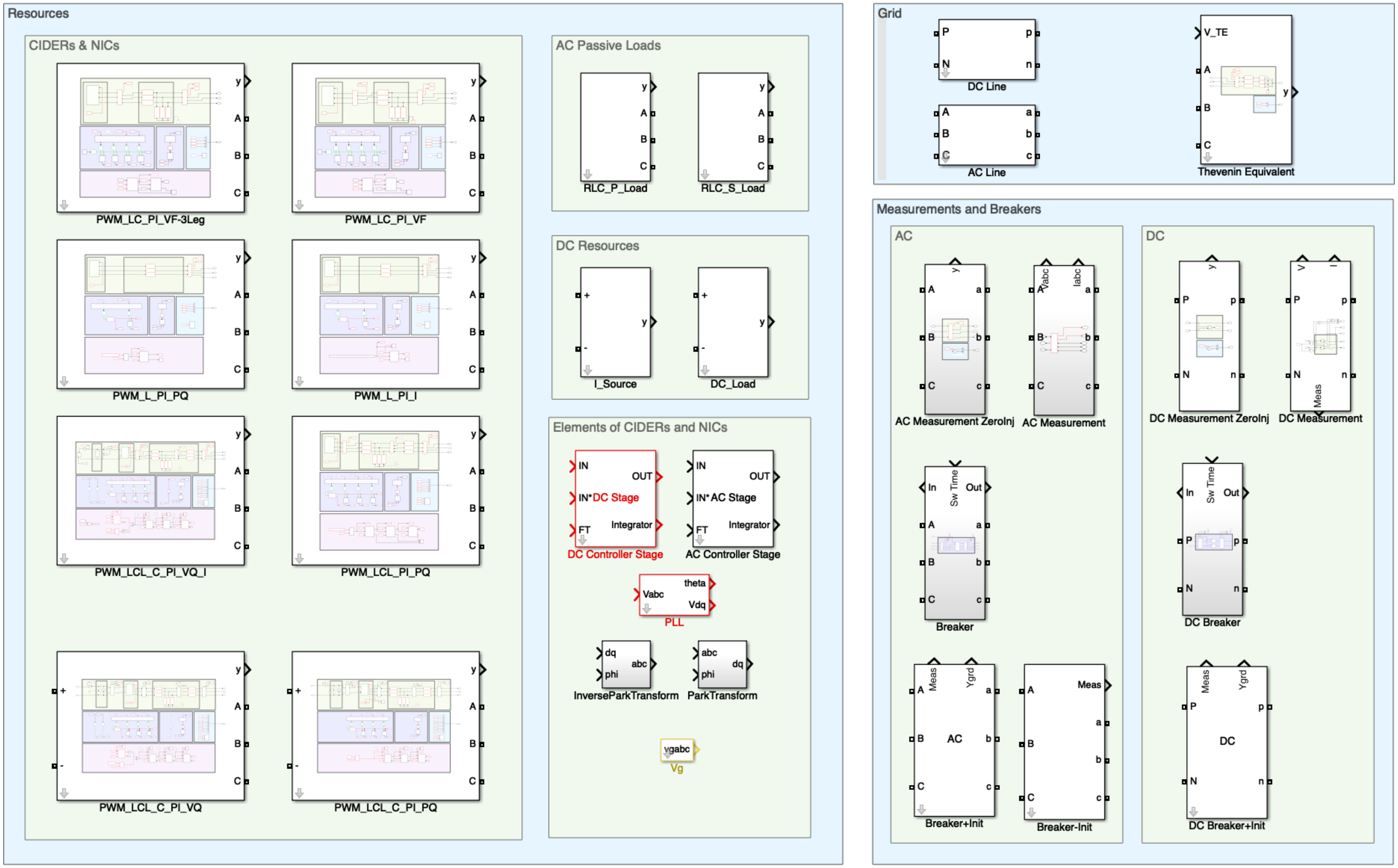

Figure 3: Screenshot of the Simulink Library.

4 Examples

4.1 Individual Resource Validation

1. For each provided CIDER or NIC model, there exists a file `main_xxx.m`, which performs the validation of the harmonic transfer function of the corresponding resource.

2. Based on an Excel file, which includes all necessary parameters, an object of the class of the resource is created.

3. For the TDS, the resource's Simulink model is connected to a *Thévenin Equivalent* (TE), which injects a specified level of harmonics.

4. The TDS are run by calling the function `obj.runTimeDomainSimulation(...)` until they reach steady state. From the last 5 periods of the resulting waveforms, spectra are calculated using the DFT.

5. The function `obj.calculateInternalResponse()` is executed to calculate the resource's harmonic-domain response. To this end, the TDS solution (voltage or current an the point of connection) is used as the input. In case the resource requires an operating point, this quantity is also taken from the TDS.

6. The results of the resource's transfer function are compared to the spectra obtained from the TDS.

7. These scripts allow to do a preliminary check on the accuracy of the internal response of the individual resources.

4.2 System Validation

1. For each provided example system, there exist a file `main_xxx.m`, which performs the validation of the HPF w.r.t. the Simulink model.

2. First, an object of the system is created, which includes all individual components (i.e., the configurations of grid and resources).

3. The TDS is run on the system in order to obtain the spectra required for the validation of the HPF. As an example, the screenshot of the Simulink model of the 22-Bus system used in [2] is shown in fig. 4.

4. The nodal voltages and currents, as well as the operating points of the CIDERs and NICs, are initialized (e.g., setting voltages to 1p.u. and/or from reference values).

5. The parameters of the Newton-Raphson algorithm are set, such as the maximum iterations, the convergence tolerance, etc. Finally, the HPF is run by calling the function `solveNewtonRaphson()`.

6. The results of the HPF are compared to those of the TDS.

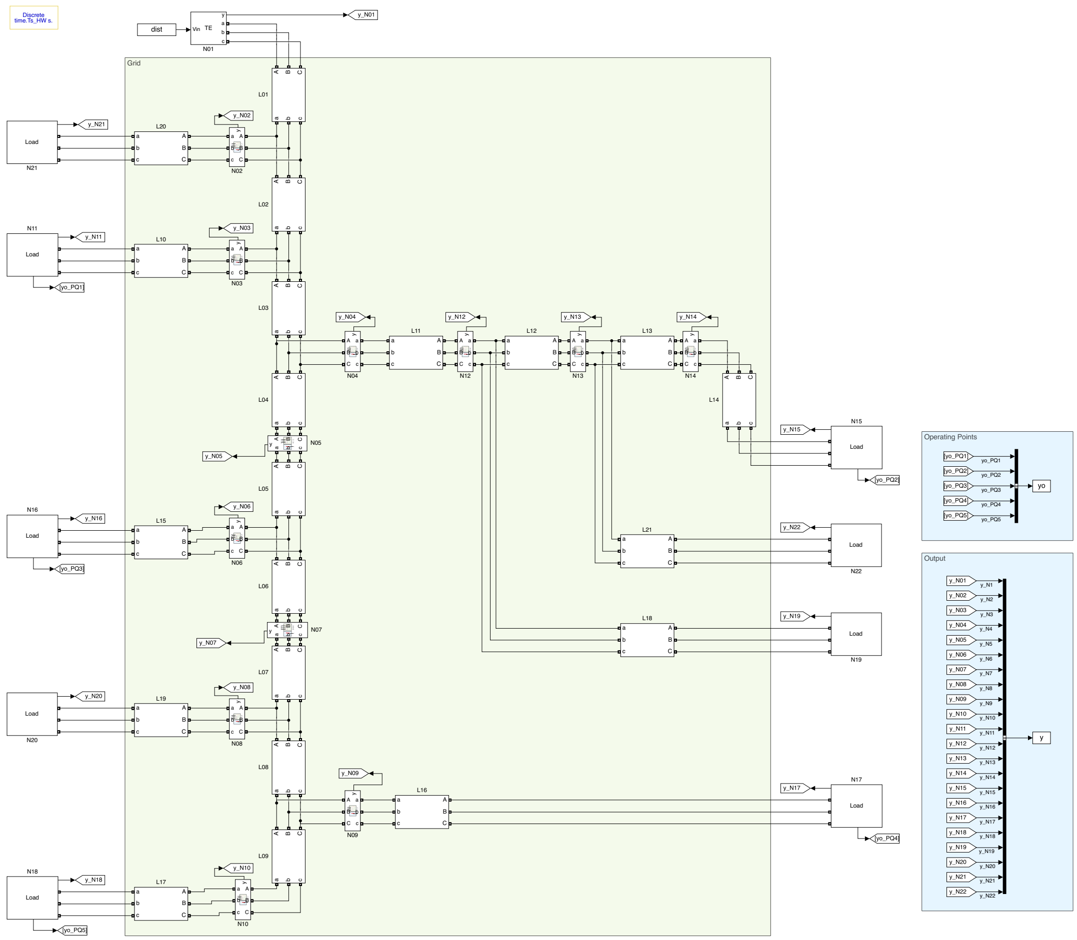

Figure 4: Screenshot of the 22-bus test system.

5 How to use - Guidelines

1. Create Excel files containing all parameters of the system:

   - One file for the grid configuration. A line is described by the two nodes which it connects plus the line parameters (i.e., line length plus per-unit-length series resistance, series inductance, and shunt capacitance).
   - One file per resource. Depending on the resource, the parameters of the power hardware and control software have to be provided. Furthermore, the reference values for the controller are requried.

2. Create individual objects (i.e., grid and resources) and combine them to create the subsystem objects. Ultimately, the system object is obtained as combination of subsystems and NICs.

3. Specify all other parameters, such as the maximum harmonic order, the base values, and all options for the Newton-Raphson algorithm.

4. Initialize the nodal quantities and operating points of the Newton-Raphson algorithm (e.g., setting voltages to 1p.u. and/or from reference values).

5. Run the function `solveNewtonRaphson()` on the object.

6. For further details, please refer to the files `main_xxx.m`, which are provided in the repository.

6 Bibliography

[1] A. M. Kettner, L. Reyes-Chamorro, J. K. M. Becker, Z. Zou, M. Liserre, and M. Paolone, "Harmonic power-flow study of polyphase grids with converter-interfaced distributed energy resources—part i: Modeling framework and algorithm," *IEEE Trans. Smart Grid*, vol. 13, no. 1, pp. 458–469, 2021.

[2] J. K. M. Becker, A. M. Kettner, L. Reyes-Chamorro, Z. Zou, M. Liserre, and M. Paolone, "Harmonic power-flow study of polyphase grids with converter-interfaced distributed energy resources—part ii: Model library and validation," *IEEE Trans. Smart Grid*, vol. 13, no. 1, pp. 470–481, 2021.

[3] J. K. M. Becker, A. M. Kettner, Y. Zuo, *et al.*, "Modelling of ac/dc interactions of converter-interfaced resources for harmonic power-flow studies in microgrids," *IEEE Trans. Smart Grid*, 2022.

[4] J. K. M. Becker, A. M. Kettner, Y. Zuo, and M. Paolone, "Harmonic power-flow study of hybrid ac/dc grids with converter-interfaced distributed energy resources," arXiv, 2023. DOI: `10.48550/ARXIV.2302.02864`. [Online]. Available: `https://arxiv.org/abs/2302.02864`.