A Micro-Grid Simulator Tool (SGridSim) using Effective Node-to-Node Complex Impedance (EN2NCI) Models

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Abstract—**This paper presents a micro-grid simulator tool useful for implementing and testing multi-agent controllers (SGridSim). As a common engineering practice it is important to have a tool that simplifies the modeling of the salient features of a desired system. In electric micro-grids, these salient features are the voltage and power distributions within the micro-grid. Current simplified electric power grid simulator tools such as PowerWorld, PowerSim, Gridlab, etc, model only the power distribution features of a desired micro-grid. Other power grid simulators such as Simulink, Modelica, etc, use detailed Ordinary Differential Equation (ODE) modeling to accommodate the voltage distribution features. This paper presents a SGridSim micro-grid simulator tool that simplifies the modeling of both the voltage and power distribution features in a desired micro-grid. The SGridSim tool accomplishes this simplified modeling by using Effective Node-to-Node Complex Impedance (EN2NCI) models of components that typically make-up a micro-grid. The term EN2NCI models means that the impedance based components of a micro-grid are modeled as single impedances tied between their respective voltage nodes on the micro-grid. The benefit of the presented SGridSim tool are 1) simulation of a micro-grid is performed strictly in the complex-domain; 2) faster simulation of a micro-grid by avoiding ODE solving. An example micro-grid model was built using the SGridSim tool and tested to simulate both the voltage and power distribution features with a total absolute relative error of less than 6%.**

Keywords—Computer aided modeling, Simulation, Electric power grids.

I. INTRODUCTION

Multi-Agent control design has been a topic of research for over a decade [1].The ideas that lead to the development of multi-agent control began around three decades ago when decentralization of control of large systems was a major topic of research. In the paper [2], Sandell et al. connote that when considering large systems the presupposition of centralized control fails either due to the lack of centralized information or the lack of centralized computing capabilities. The lack arises due to the geographical separation of the system [2]. Examples of such systems are 1) power networks; 2) urban traffic networks; 3) digital communication networks; 4) flexible manufacturing networks; etc. Ever since, the decentralization of control has been maturing towards distributed control and multi-agent control [3] – [6].

Several work have been published in the field of Smart Grid research that were directed towards improving the communication and control of power grids [7] – [11]. Recent papers have also been addressing the development of multi-agent and hierarchical control in Smart Grids [12] – [20].

As common engineering practice, it is desirable to have a tool that models a system in a simplistic way and yet maintain the salient features of that system. In a micro-grid, these salient features are the power and voltage distributions. Current simplified power grid simulator tools such as PowerWorld, PowerSim, Gridlab, etc, model only the power distribution features of a micro-grid while tools such as Simulink, Modelica, etc, use detailed Ordinary Differential Equation (ODE) modeling to accommodate the voltage distribution features.

The presented SGridSim tool simplifies the modeling of both the power and voltage distribution features of a desired micro-grid using Effective Node-to-Node Complex Impedance (EN2NCI) models of the components that typically make-up a micro-grid. The EN2NCI models model the load sectors, transmission lines and transformers as single complex impedances tied between their respective voltage nodes on the micro-grid. Unlike Simulink, Modelica, etc, the presented SGridSim tool does not solve ODEs of the micro-grid model. The tool instead simulates the point value characteristics in the complex-domain that arise due the assigned electric frequency.

The rest of this paper proceeds as follows: Section II discusses the development of the EN2NCI models. Section III then describes the design of the presented micro-grid simulator tool (SGridSim). Section IV shows the test results of simulation for an example micro-grid constructed using the SGridSim tool. The paper finally concludes with future work in Section V.

II. EN2NCI MODELING AN ELECTRIC MICROGRID

This section develops the EN2NCI models that simplify the modeling of a desired micro-grid in terms of the salient

features of a micro-grid, i.e. the power and voltage distributions.

An electric micro-grid is primarily composed of 1) Load Sectors; 2) Generators; 3) Transmission Lines; 4) Transformers. A substation in a micro-grid consists of 1) breakers that connect the micro-grid to an adjacent micro-grid; 2) voltage regulating transformers that regulate the load sector voltages. No matter how complex the architectures of each of these components are today, they are either impedances or voltage sources.

The following subsections develop the EN2NCI models for each of the primary components in a micro-grid. The EN2NCI modeling method models the impedance based components of a micro-grid, i.e. transmission lines and transformers, as single complex impedances tied between their respective voltage nodes in the micro-grid. Note that while real electric micro-grid components are three-phase, this paper considers only the per-phase impedance models for simplicity.

A. Load Sectors

Load sectors are typically defined by rated root-mean-square (r.m.s.) voltages and frequency. These are, for example, the power outlets in buildings that are commonly rated at 110V/120V 60 Hz in the US. In other parts of the world they are rated at 230V/240V 50 Hz. Industrial sectors have higher voltage ratings at the orders of 10kV to 100kV depending upon the type. These higher voltages are required to make large furnaces and machines to function.

Also associated with load sectors are their respective power-factors (PF) that provide information about the amount of active and reactive load powers drawn. Hence for a given measured active load power, known PF and known r.m.s. voltage rating, the EN2NCI model of a load sector can be described by the following equation:

$$Z = \frac{V_{rate}^2}{S_{rms}}\left(\cos\phi + j\sin\phi\right)$$

$$(1)$$

$$where \quad \begin{aligned}&\phi = \cos^{-1}(PF)\\&S_{rms} = \frac{P}{PF}\end{aligned}$$

with φ as the angle of the load, S_{rms} as the r.m.s apparent load power, P as the measured active load power, PF as the known power-factor, V_{rate} as the known r.m.s voltage rating.

B. Generators

In this paper generators are modeled as complex voltage sources rather than the elaborate Automatic Generation Control (AGC) and Automatic Voltage Regulation (AVR) schemes typically found in the literature. This complex voltage modeling method is particularly useful for the EN2NCI models developed for the transmission lines and transformers. The powers generated by the generator voltage sources are calculated based on the grid connecting impedances which are typically transformers.

C. Transmission Lines

Transmission lines can be modeled as impedances that are a function of their lengths in km. Hence the EN2NCI model of a transmission line can be described by the following equation:

$$Z = (r + j\omega l)\cdot length\,(km)$$

$$(2)$$

$$where \quad \begin{aligned}&r = 0.01273\Omega\,/\,km\\&l = 0.9337mH\,/\,km\end{aligned}$$

D. Transformers

Transformers are typically modeled as devices with a primary-side impedance, a secondary-side impedance and turns-ratio. These models are typically in the form of *t*-circuit models which need to be transformed into EN2NCI models.

The transformation of the original *t*-circuit models into EN2NCI models technically does not require elaborate derivations. Since the EN2NCI model is in the form of a single complex impedance between the respective voltage nodes, the sign combinations for the real and imaginary parts of the complex impedance only need to change. Typically, transformers in electric power grids are either perform of step-down or step-up voltage transformations and therefore the sign combinations in the EN2NCI model of a transformer must emulate the same.

For a step-down transformer, the EN2NCI model is

$$Z = R + j\omega L$$

$$(3)$$

while for a step-up transformer, the EN2NCI model is

$$Z = -R - j\omega L$$

$$(4)$$

Although these models are too simplistic, they provide a milestone towards better simplification of real micro-grid components. The next section discusses the tool design for simulating a desired micro-grid using the EN2NCI models.

III.   THE SGRIDSIM MICRO-GRID SIMULATOR TOOL DESIGN

The previous section developed the EN2NCI models of the components that typically make-up a micro-grid. In this section the development of the presented SGridSim micro-grid simulator tool that uses the EN2NCI models is discussed.

The SGridSim tool was developed in C++ along with OpenGL for creating a user interface. The tool was designed in the form of a CAD tool so that any desired micro-grid can be constructed and simulated. The simulation of the desired micro-grid model, like currently available tools such as PowerWorld, PowerSim, Gridlab, Simulink, Modelica, PSPICE, LTSPICE, etc, is performed by the tool engine that works based on Kirchoff's Current Law. The only difference the presented SGridSim tool has from the currently available tools is that the presented SGridSim tool performs all computations strictly in the complex-domain. Hence the SGridSim tool does not simulate the detailed transients occurring in a micro-grid. The complex-domain method of simulation is sufficient for implementing and testing future design of multi-agent controllers.
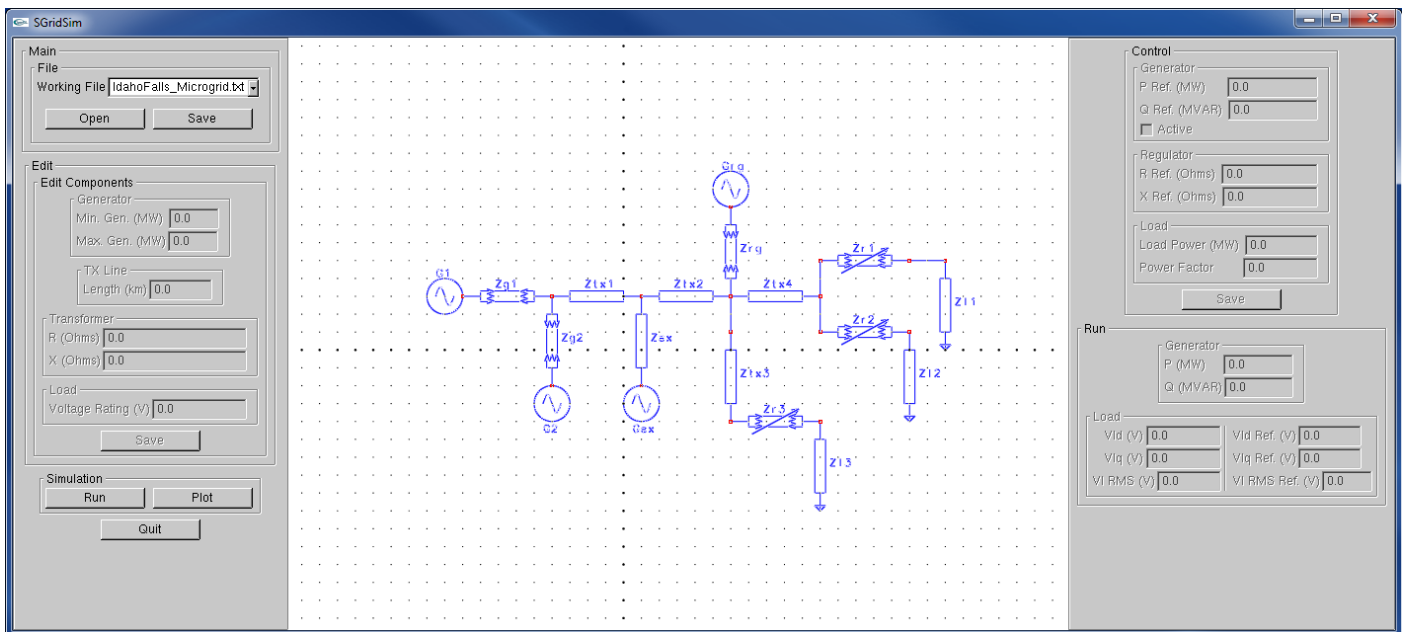
Fig. 1. The micro-grid simulator tool.

Fig. 1 shows the presented SGridSim tool. The tool consists of two user interfaces and one CAD window. The leftmost user interface consists of a main panel, an edit panel and a simulation panel while the rightmost user interface consists of a control panel and a run panel.

In the leftmost panel, the main panel provides the user the means to load the desired micro-grid file for display on the CAD window. The edit panel provides the user the means to edit and save the component parameters. The simulation panel provides the user the means to run the micro-grid model.

In the rightmost panel, the control panel provides the user the means to 1) set the load at the available load sectors; 2) set the desired power generation supplied by the available generators; 3) set the voltage regulating transformer impedances. The run panel provides the user feedback about status of the micro-grid in terms of the actual generation supplied to the micro-grid and the load voltage demands met based on control settings provided by the user in the control panel.

The control panel is designed as such in order to enable future design work of multi-agent controllers to control the power inputs to the micro-grid and manage stability.

The desired micro-grid is constructed using a configuration file that specifies the components present on the micro-grid along with their positions on the CAD window and related parameters. The general format for specifying a component on the micro-grid is

<Type> <Label> <X position> <Y position> <orientation> <parameter1> <parameter2> … <parameterN>

There are a total of six types of components that can be drawn on the micro-grid simulator CAD window. These types of components are 1) Generators; 2) Connectors; 3) Transmission Lines; 4) Transformers; 5) Voltage Regulating Transformers; 6) Load Sectors. The following subsections elaborate the required configuration file descriptions to draw and simulate the six types of components.

A. Generators

Fig. 2. Generator symbol.

Fig. 2 shows the symbol of a generator drawn on the micro-grid simulator CAD window. The configuration file description that draws a generator is

<Type> = G
<orientation> : 0 = Voltage source node on East corner of symbol
                1 = Voltage source node on North corner of symbol
                2 = Voltage source node on West corner of symbol
                3 = Voltage source node on South corner of symbol
<parameter1> = min. generation capacity
<parameter2> = max. generation capacity

B. Connectors

Connectors are just simple lines drawn between components to ensure connectivity between the components that are placed in the CAD window in positions that do not overlap other components.

C. Transmission Lines

Fig. 3. Transmission line symbol.

Fig. 3 shows the symbol of a transmission line drawn on the micro-grid simulator CAD window. The configuration file description that draws a transmission line is

```
<Type> = Z
<orientation> : 0 = Symbol is horizontally oriented
               1 = Symbol is vertically oriented
<parameter1> = length of transmission line in km
```

D. Transformers

Fig. 4. Transformer symbol.

Fig. 4 shows the symbol of a transformer drawn on the micro-grid simulator CAD window. The configuration file description that draws a transformer is

```
<Type> = T
<orientation> : 0 = Symbol is horizontally oriented
               1 = Symbol is vertically oriented
<parameter1> = real component of transformer impedance
<parameter2> = imaginary component of transformer impedance
```

E. Voltage Regulating Transformers

Fig. 5. Voltage regulating transformer symbol.

Fig. 5 shows the symbol of a voltage regulating transformer drawn on the micro-grid simulator CAD window. The configuration file description that draws a voltage regulating transformer is

```
<Type> = R
<orientation> : 0 = Symbol is horizontally oriented
               1 = Symbol is vertically oriented
```

F. Load Sectors

Fig. 6 shows the symbol of a load sector drawn on the micro-grid simulator CAD window. The configuration file description that draws a load sector is

```
<Type> = L
<orientation> : Not Applicable. Vertical orientation by default.
<parameter1> = Voltage rating of load sector
```


Fig. 6. Load sector symbol.

IV. TEST RESULTS

The previous section discussed the development of the presented SGridSim tool that simulates the voltage and power distribution features of a constructed micro-grid model. This section presents the test results of the SGridSim tool on an example micro-grid model constructed on the tool.

Fig. 7 shows the example micro-grid model constructed with the components discussed in Section IV. The micro-grid model of Fig. 7 consists of three load sectors Zl1, Zl2 and Zl3, one renewable generator Grg that can be either solar or wind, one external micro-grid generator Gex emulating power bought from the adjacent micro-grid, two local generators G1 and G2. Among the three load sectors, Zl1 is rated at 13kV while Zl2 and Zl3 are rated at 120V. All components in the micro-grid model assume 60Hz frequency.

The micro-grid model in Fig. 7 has a total of twelve voltage nodes of which three are load voltage nodes and four are source voltage nodes. In this micro-grid model, the total n number of unknown voltage nodes is equal to eight, i.e. excluding only the source voltage nodes. The unknown voltage nodes are V1, V3, V5, V7, V8, V9, V10 and V11 among which V8, V10 and V11 are the load voltage nodes.

Table I (see next page) shows the parameters and control values of the components on micro-grid model of Fig. 7. The parameters of the components were set in the configuration file while the control values were set on the control panel. Using the values shown in Table I, Fig. 8 shows the results obtained
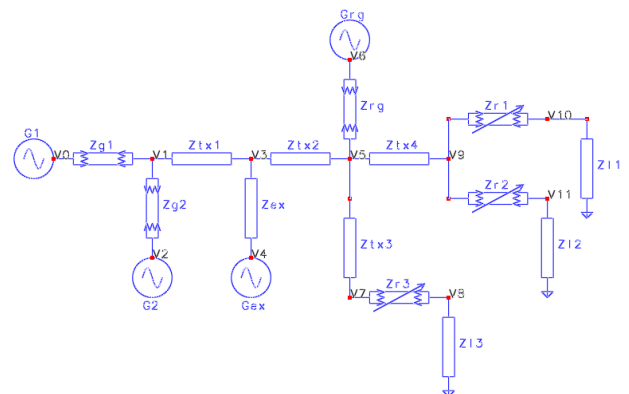

Fig. 7. The example micro-grid model.

TABLE I.   MICRO-GRID MODEL PARAMETERS AND CONTROL VALUES

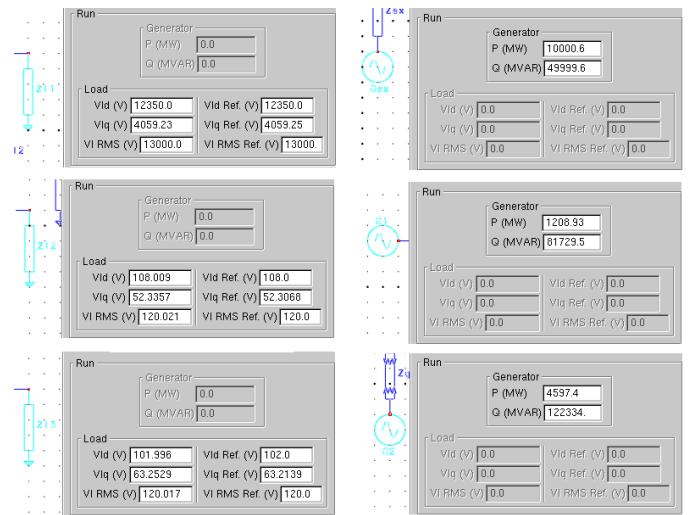| Component	Parameters and Control Values		
	Type	Variable Type	Value
Zg1	Parameter	Impedance (Ω)	-0.0002-j0.1131
Zg2	Parameter	Impedance (Ω)	-0.0001-j0.0754
Zrg	Parameter	Impedance (Ω)	-0.0001-j0.0377
Ztx1	Parameter	Length (km)	2.0
Ztx2	Parameter	Length (km)	3.0
Ztx3	Parameter	Length (km)	10.0
Ztx4	Parameter	Length (km)	5.0
Zex	Parameter	Length (km)	20.0
Zl1	Control	Active Power (MW)	36.0
		Power Factor	0.95
Zl2	Control	Active Power (MW)	7.0
		Power Factor	0.9
Zl3	Control	Active Power (MW)	29.0
		Power Factor	0.85
Zr1	Control	Impedance (Ω)	0.001+j0.005
Zr2	Control	Impedance (Ω)	0.1889+j0.062
Zr3	Control	Impedance (Ω)	-0.069-j3.0866
Grg	Control	Apparent Power (MW+jMVAR)	5.0+j0.0
Gex	Control	Apparent Power (GW+jGVAR)	10.0+j50.0
G1	Control	Apparent Power (GW+jGVAR)	1.2608+j81.7
G2	Control	Apparent Power (GW+jGVAR)	4.6752+j122.29

Fig. 8. Voltage and power distribution in the example micro-grid of Fig. 7. (Components shown: Zl1, Zl2, Zl3, Gex, G1, G2)

a desired micro-grid by using the Effective Node-to-Node Complex Impedance (EN2NCI) models. The SGridSim tool further expedites the simulation of a microgrid by calculating only the point value characteristics in complex-domain, i.e. avoiding the solving of detailed ODEs as done by Simulink, Modelica, etc. An example micro-grid model was constructed and tested using the presented tool. Test results showed that the SGridSim tool simulated the example micro-grid model with a total absolute relative error of less than 6%.

The future work for the presented SGridSim micro-grid simulator tool will improve modeling simplification to reflect real world parameters commonly known to power engineers.

by running the simulation engine.

In Fig. 8, the leftmost column shows voltage demands met for each of the available load sectors Zl1, Zl2 and Zl3. The rightmost column of Fig. 8 shows the measured power inputs to the micro-grid model from generators Gex, G1 and G2. Based on the result obtained in the simulation, the total absolute relative error obtained is less than 6%.

V.   CONCLUSION AND FUTURE WORK

This paper presented a SGridSim tool that simplifies the modeling of the salient features of a desired micro-grid thereby making the tool is useful for implementing and testing multi-agent control schemes. The salient features of a micro-grid are the power and voltage distributions in that micro-grid. Current simplified electric power grid simulator tools such as PowerWorld, PowerSim, Gridlab, etc, model only the power distribution in the desired micro-grid while other tools such as Simulink, Modelica, etc, use detailed Ordinary Differential Equation (ODE) modeling to accommodated the voltage distribution. The presented SGridSim tool simplifies the modeling of both the power and voltage distribution features of

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