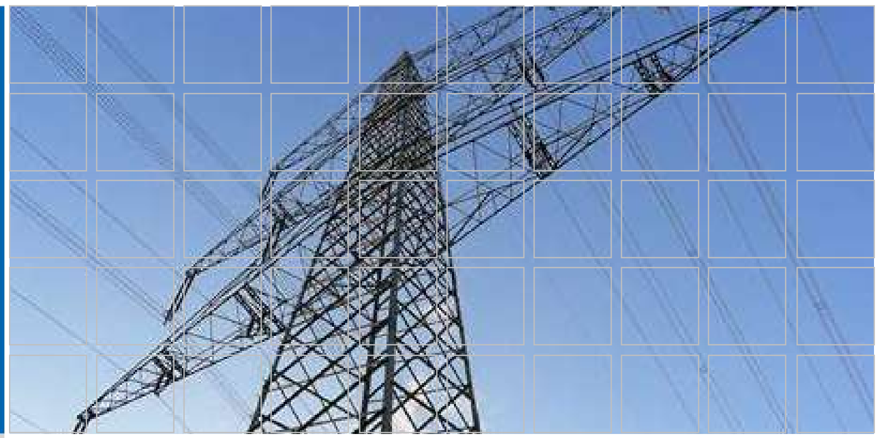
Institute of Electrical Power Systems



LFC Simulator V1.2
Documentation

July 2025

ELECTRICAL
POWER SYSTEMS
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CONTENTS

1 Introduction

This manual provides information about the low frequency current (LFC) simulation software, developed at the Institute of Electrical Power Systems of Graz University of Technology. The tool is a work in progress, therefore not all features are available yet, some options are still hard coded and bugs may occur.

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More information on the research project can be found at:

https://www.tugraz.at/en/institutes/iean/research/power-quality-supply-reliability/low-frequency-neutral-point-currents/

2 Installation

If version 9.6 (R2019a) of the MATLAB Runtime is installed on the computer, the application should start without any other installation steps and simulations are possible immediately. Simply start the application by running *GIC_Simulator.exe*.

If the requirements mentioned above are not fulfilled, the application can be installed by running *MyAppInstaller_web.exe*. Just follow the instructions to install the application on your computer. After the installation process finished successfully, the application *GIC_Simulator.exe* can be found in the previously selected directory, e.g. *C:\Program Files\Institute of Electrical Power Systems\GIC_Simulator\application.*

Note: Once the program was installed, it is not necessary to repeat the installation process of the MATLAB Runtime to run newer versions of the simulator. They should start immediately after running the executable file.

3 Methodology

Figure 1 depicts the basic method flow chart of the simulation. No further theoretical consideration is given at this point; for a complete description please refer to [1, 2]. The simulation results are currents in every transformer, line and substation grounding.

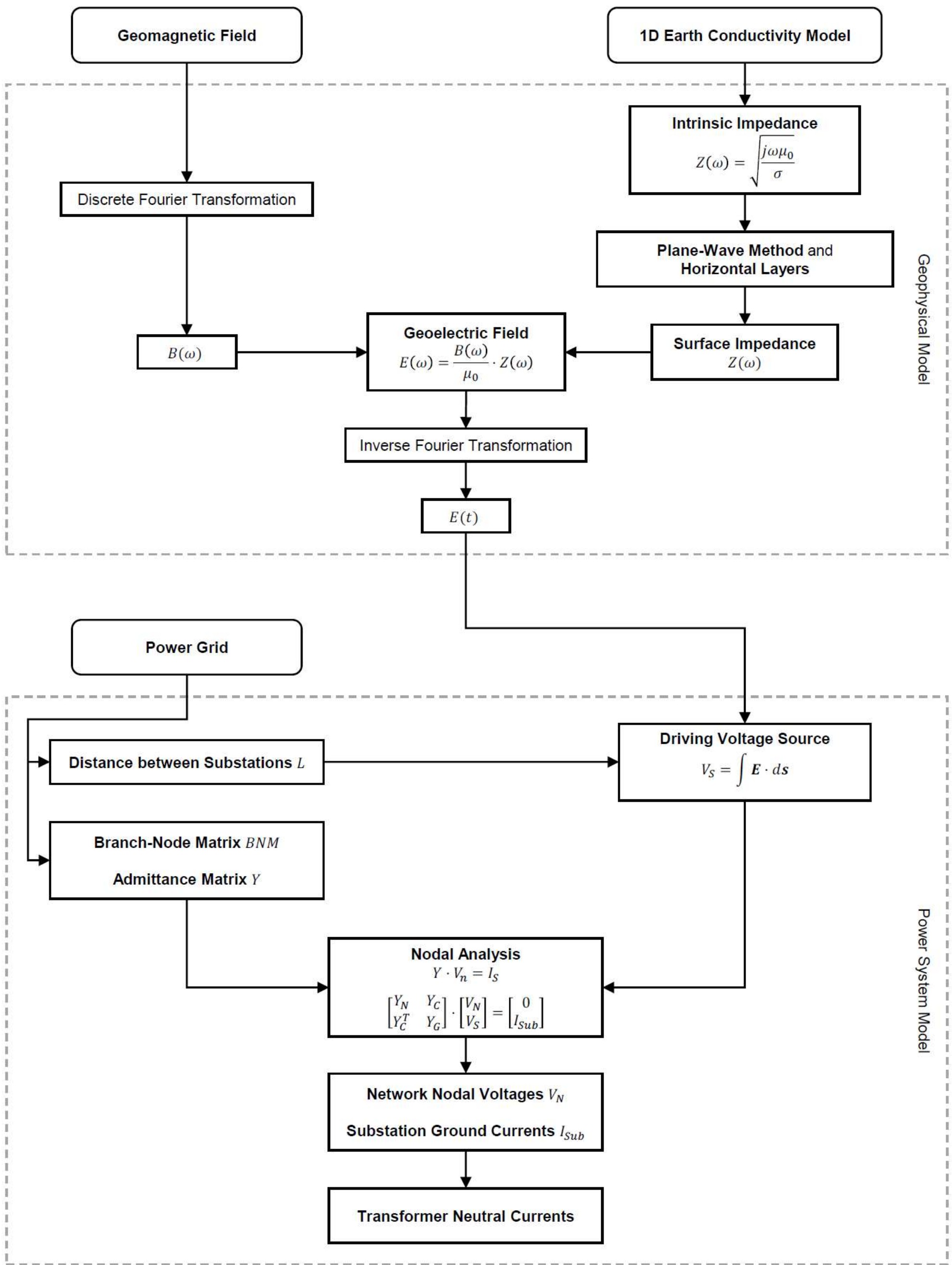


Figure 1: Method flow chart of the GIC simulation method [1]

3.1 Changelog

3.1.1 Version 1.1

A new feature in Version v1.1 is the calculation of additional reactive power of transformers. This is done in reference to [3] with a linear relationship between an effective transformer neutral current I_{eff} and the additional reactive power Q. However, as in European Transmission Grids most of the time only one neutral point per transformer is grounded, the I_{eff} calculation is changes to the sum of absolute currents of different windings. (Further description coming soon).

The linear relation between neutral point current and reactive power demand is split into to areas with two different slopes and a threshold current, as shown in Figure 2.

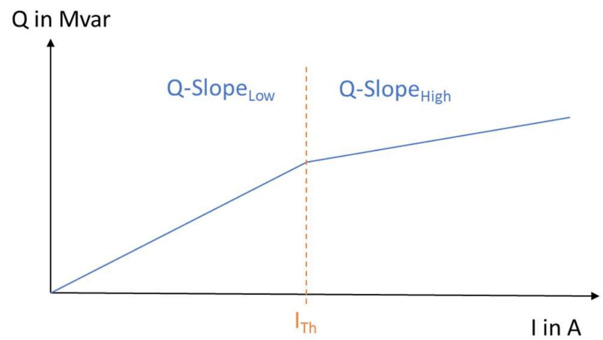


Figure 2: Graphical representation of reactive power calculation

$$Q(I_{eff}) = \begin{cases} k_1 \cdot I_{eff}\,, & I_{eff} \le I_{Th} \\ k_1 \cdot I_{Th} + k_2 \cdot (I_{eff} - I_{Th})\,, & I_{eff} > I_{Th} \end{cases}$$

k_1 … Q-Slope$_{Low}$

k_2 … Q-Slope$_{High}$

I_{Th} … Threshold for changing slope

I_{eff} … Effective current

3.1.2 Version 1.2

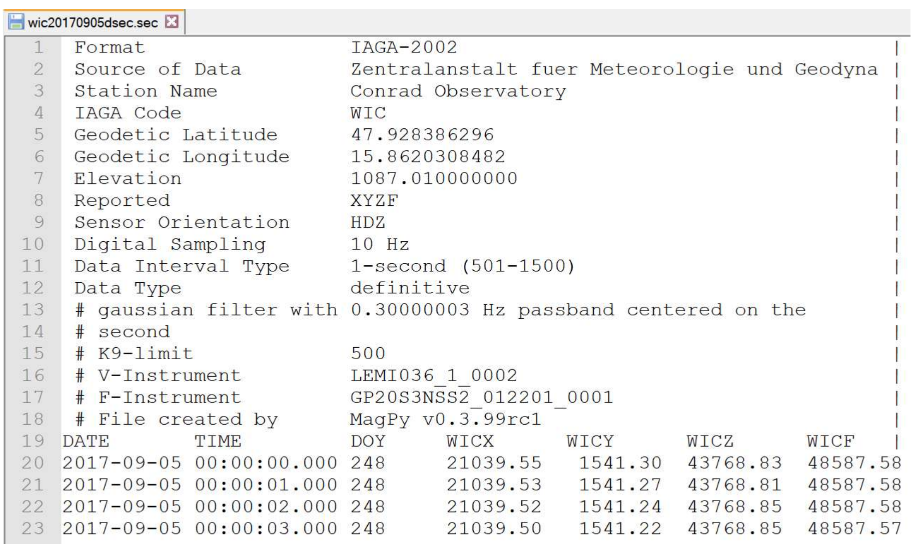
For Version 1.2 the Methedology for creating the BNI Matrix was adapted to enable a two-busbar configuration per substation and voltage level. This is done to better simulate dual circuit lines and different coupling scenarios in the substations which can impact the flow of GIC in the grid. The input method has changed for this version which is explained below in section 4.2

4 Input and sample data

The LFC Simulation tool needs three datasets for calculations: magnetic field data, earth resistivity layers and grid data. There are samples available, which show the needed data formats. All samples can be found in the *SampleData* folder. Please note that the structure of the files needs to be identical to the structure of the exemplary sample data shown in this section for the simulation to work properly.

4.1 Magnetic field data

Magnetic field data is available at https://www.intermagnet.org/. The software is built to use data sampled in seconds. An exemplary file is depicted in Figure 3. Please note that the first 18 header-lines will be ignored by the simulation tool, as they are not required to run a simulation.


wic20170905dsec.sec

```
 Format                 IAGA-2002                                     |
 Source of Data         Zentralanstalt fuer Meteorologie und Geodyna |
 Station Name           Conrad Observatory                            |
 IAGA Code              WIC                                           |
 Geodetic Latitude      47.928386296                                  |
 Geodetic Longitude     15.8620308482                                 |
 Elevation              1087.010000000                                |
 Reported               XYZF                                          |
 Sensor Orientation     HDZ                                           |
 Digital Sampling       10 Hz                                         |
 Data Interval Type     1-second (501-1500)                           |
 Data Type              definitive                                    |
 # gaussian filter with 0.30000003 Hz passband centered on the       |
 # second                                                             |
 # K9-limit             500                                           |
 # V-Instrument         LEMI036_1_0002                                |
 # F-Instrument         GP20S3NSS2_012201_0001                        |
 # File created by      MagPy v0.3.99rc1                              |
DATE       TIME         DOY     WICX      WICY      WICZ      WICF   |
2017-09-05 00:00:00.000 248     21039.55   1541.30  43768.83  48587.58
2017-09-05 00:00:01.000 248     21039.53   1541.27  43768.81  48587.58
2017-09-05 00:00:02.000 248     21039.52   1541.24  43768.85  48587.58
2017-09-05 00:00:03.000 248     21039.50   1541.22  43768.85  48587.57
```

Figure 3: Magnetic field data (example)

In this example, data of the Conrad Observatory is used. WIC is the IAGA Code of the observatory; *WICX/WICY/WICZ/WICF* are the magnetic field data vectors in x, y and z direction and corresponding F vector in nT. DOY is the day of the year. For the calculation only x- and y-components are used.

4.2 Network/Grid data

Network details are stored in an Excel-File containing three different sheets: Substations, Transformers, and Lines. The exact structure of those files is shown in **Error! Reference source not found.**. The example can be found in the sample directory and is called *LFC_Grid_Template_2Nodes.xlsx*. The Excel File itself contains 3 pages of input data. Every input will be explained.

4.2.1 Substations

Nr	Name	bbreviatic	Country Code	Latitude Degree	Longitude Degree	Groundi Ohm	Voltage Level V_1	V_2	V_3	V_4	N_1	N_2	N_3	N_4	N_5	Node N_6	N_7	N_8	Neutral	Ground	BB Breaker V_1	BB Breaker V_2	BB Breaker V_3	BB Breaker V_4
1	Sub 1	Sub1	US	33,6135	-87,3737	0,2	345	0	0	0	1	2	3	4	5	6	7	8	9	73	0	0	0	0
2	Sub 2	Sub2	US	34,3104	-86,3658	0,2	345	0	0	0	10	11	12	13	14	15	16	17	18	74	0	0	0	0
3	Sub 3	Sub3	US	33,9551	-84,6794	0,2	500	345	0	0	19	20	21	22	23	24	25	26	27	75	0	0	0	0
4	Sub 4	Sub4	US	33,5479	-86,0746	1	500	345	0	0	28	29	30	31	32	33	34	35	36	76	0	0	0	0
5	Sub 5	Sub5	US	32,7051	-84,6634	0,1	500	345	0	0	37	38	39	40	41	42	43	44	45	77	0	0	0	0
6	Sub 6	Sub6	US	33,3773	-82,6188	0,1	500	0	0	0	46	47	48	49	50	51	52	53	54	78	0	0	0	0
7	Sub 7	Sub7	US	34,2522	-82,8363	1E+08	500	0	0	0	55	56	57	58	59	60	61	62	63	79	0	0	0	0
8	Sub 8	Sub8	US	34,1956	-81,098	0,1	500	0	0	0	64	65	66	67	68	69	70	71	72	80	1	0	0	0

Figure 4: Substation Input

- Nr: For Numbering the different substations
- Name: Name of substation
- Abbreviation: Short name of the substation (ideally no spaces for this name)
- Country Code: Country in which the substation is based in
- Latitude and Longitude: for exactly specifing the location of the substations
- Grounding Ohm: Grounding resistance of Substation in Ohm
- Voltage Level: Voltage levels in substations with direct connection to ground (up to 4 possible)
- Nodes: Every substation has up to 4 voltage levels, for each voltage leven there are up to two busbars. This means that there are 8 Nodes per Substation. The 9th Node is the neutral Node of the substation and the 10th node represents the node after the grounding resistance is taken into account. As can be seen in Figure 4 the Nodes have to be numbered in asscending order up to the neutral node and the Ground node in asscending order from the last neutral node.
- BB Breaker: These columns represent the state of the busbar breaker or coupling bay circuit breaker for the two busbars.
    - If the entry is 0 the busbar breaker is opened
    - If the entry is 1 the busbar breaker is closed
        - Example: In Figure 4 the coupling bay circuit breaker of substation 8 and voltage level 1 (in this case 500 kV) is closed. All other coupling bay circuit breaker are openned.
        - NOTE: Certain configurations can lead to multiple „island" grids which will result in an error during simulation, because the matrix will get singular.

4.2.2 Transformers

Nr	Substation	Type	Resistance HV (Ohms/phase)	Resistance LV (Ohms/phase)	GroundingHV nan	GroundingLV nan	Voltage Level V_HV	V_LV	Q Slope Low Mvar/A	Threshold Mvar/A	Q Slope High Mvar/A	Connected to BB HV nan	Connected to BB LV nan
1	Sub1	GSU	99999	0	1	0	345	0	0,15	20	0,2	1	1
2	Sub4	GY-GY	0	0	1	0	500	345	0,15	20	0,2	2	1
3	Sub2	GSU	0	0	1	0	345	0	0,15	20	0,2	1	1
4	Sub2	GSU	0,1	0	1	0	345	0	0,15	20	0,2	2	2
5	Sub3	Auto	0,04	0,06	1	0	500	345	0,15	20	0,2	2	2
6	Sub6	GSU	0	0	1	0	500	0	0,15	20	0,2	1	1
7	Sub6	GSU	0,15	0	1	0	500	0	0,15	20	0,2	2	2
8	Sub5	GY-GY	0	0	1	0	500	345	0,15	20	0,2	1	1
9	Sub5	GY-GY	0,04	0,06	1	0	500	345	0,15	20	0,2	2	2
10	Sub8	GSU	0	0	1	0	500	0	0,15	20	0,2	2	2
11	Sub8	GSU	0,1	0	1	0	500	0	0,15	20	0,2	1	1
12	Sub4	Auto	0,04	0,06	1	0	500	345	0,15	20	0,2	1	1
13	Sub4	GY-GY	0	0	1	0	500	345	0,15	20	0,2	2	2
14	Sub4	Auto	0,04	0,06	1	0	500	345	0,15	20	0,2	1	1
15	Sub3	Auto	0,04	0,06	1	0	500	345	0,15	20	0,2	1	1

Figure 5: Transformer Input

- Nr: Numbering the Transformers in ascending order
- Substation: Specifies in which substations the transformer is located
- Type:
  - GY-GY: Transformer which connects to parts of the grid which are directly grouned
  - GSU: Generator step up transformer, can also be used to connect parts of the grid which are not directly grounded
  - Auto: Autotransformer, same as GY-GY but resistances are defined differentl
- Resistance HV:
  - GY-GY and GSU: resistance of the high voltage winding in ohm
  - Auto: resistance of the series winding in ohm
- Resistance LV:
  - GY-GY: resistance of the low voltage winding in ohm
  - Auto: resistance of the common winding in ohm
- Grounding HV and LV: is not used anymore. The definition which of the transformer sides are grounded is done via the resistances: If the resistance is zero the transformer is not grounded on this voltage level. If the value is anything else it is grounded.
- Voltage Level HV and LV: Defines which voltage levels the transformer is connected to. For GSU type transformers the LV side is usually zero. However a GY-GY Transformer can also be defined as zero on one voltage level. This essentially sets the boundarys of the grid.
- Q Slope Low, Threshold and Q Slope High: see 3.1.1 and Figure 2. The values of Q_{Slope} and Threshold correspond to neutral point currents. If there is no data available for the Transformers Q-Slopes or the threshold, it must be replaced by ‘x’.
- Connected to BB HV and LV: This specifies to which busbar (either 1 or 2) the transformer is connected to for both voltage levels. If there is only one busbar in a certain substation and voltage level “1” has to be the input.

4.2.3 Lines

Nr	Sub from	Sub to	Length km	Resistance per km Ohm/km	Single Line Resistance Ohm	Voltage kV	Systems #	Multiple Conductor #	Connected to BB From nan	Connected to BB To nan
1	Sub1	Sub4	124,2091699	0,091008033	7,024	345	1	1	1	1
2	Sub1	Sub4	124,2091699	0,091008033	7,024	345	1	1	2	2
3	Sub1	Sub2	124,6758797	0,091002969	7,05	345	1	1	1	1
4	Sub1	Sub2	124,6758797	0,091002969	7,05	345	1	1	2	2
5	Sub3	Sub4	140,8336934	0,045389098	3,972	500	1	1	1	1
6	Sub3	Sub4	140,8336934	0,045389098	3,972	500	1	1	2	2
7	Sub2	Sub3	165,0221338	0,090988882	9,33	345	1	1	1	1
8	Sub2	Sub3	165,0221338	0,090988882	9,33	345	1	1	2	2
9	Sub4	Sub5	166,2613286	0,045397348	2,345	500	1	1	1	1
10	Sub4	Sub5	166,2613286	0,045397348	2,345	500	1	1	2	2
11	Sub5	Sub6	210,9045312	0,045402518	5,95	500	1	1	1	1
12	Sub5	Sub6	210,9045312	0,045402518	5,95	500	1	1	2	2
13	Sub5	Sub7	248,7563021	3,42886718	530	500	1	1	1	1
14	Sub5	Sub7	248,7563021	3,42886718	530	500	1	1	2	2
15	Sub6	Sub7	102,338185	0,045415946	2,888	500	1	1	1	1
16	Sub6	Sub7	102,338185	0,045415946	2,888	500	1	1	2	2
17	Sub4	Sub6	330,8328461	0,045395729	9,332	500	1	1	1	1
18	Sub4	Sub6	330,8328461	0,045395729	9,332	500	1	1	2	2
19	Sub3	Sub6	207,2996006	0,045400202	2,924	500	1	1	1	1
20	Sub3	Sub6	207,2996006	0,045400202	2,924	500	1	1	2	2
21	Sub7	Sub8	164,7807322	0,045395058	4,648	500	1	1	1	1
22	Sub7	Sub8	164,7807322	0,045395058	4,648	500	1	1	2	2
23	Sub3	Sub5	143,1994291	0,091009216	8,098	345	1	1	1	1
24	Sub3	Sub5	143,1994291	0,091009216	8,098	345	1	1	2	2
25	Sub2	Sub5	245,4732403	0,090998492	13,88	345	1	1	1	1
26	Sub2	Sub5	245,4732403	0,090998492	13,88	345	1	1	2	2

Figure 6: Lines Input

- Nr: Number of the Lines (can also be a specific identifier of the line: for example 225A)
- Sub From: Origin of the Line
- Sub To: Destination of the Line
- Length in km: Length of the line in km
- Resistance per km of the line: Resistance/km of the line in Ohm/km

- Single Line Resistance: Resistance of the entire lenght of the line
    - NOTE: Only this value is used in calculation, length and resistance per km can be left empty. They are only used to calculate the single line resistance
- Voltage: Voltage level of the line in kV
- Systems: Number of systems on the line (single line resistance gets divided by this value)
- Multiple conductor: If there are multiple conductors for higher transfer capacity or other reasons (This value is not used in calculation)
- Connected to BB From: Specifies to which busbar the line is connected in the origin substation
- Connected to BB To: Specifies to which busbar the line is connected in the destination substation

The example is based in the GIC model grid from [4].

4.3 Earth resistivity data

Earth resistivity data is stored in an Excel-File. Multiple conduction models can be stored in a single Excel-File. The File contains two sheets, one contains resistivity values (*R*) in Ωm, the other one the corresponding depth values (h) in meter. The last value in the R vector is then realised as half space. The exact structure of those files is shown in Figure 7. The example can be found in the sample directory and is called *LFC_Earth_conductivity_Template.xlsx*.

	A	B	C	D	E
1	M01	400	1300	140000	170000
2	M39	55000	45000		
3					

h | R

	A	B	C	D	E	F
1	M01	40	3	2000	115	15
2	M39	1000	300	1000		
3						

h | R

Figure 7: Earth resistivity data (example)

5 Usage

Using the simulator is easy, due to the available graphical user interface (GUI). The usage example given in this section can be used as a quick start guide for using the simulator.

5.1 GUI Overview

Figure 8: Graphical user interface

- **Switch between sections (A)**
    - Simulation
    - Beta-Functions *(not yet implemented)*
    - Sensitivity Analysis
    - Import & Preferences

- **Configuration of simulation (B)**
  This section is used to load input data and edit simulation parameters before conducting a simulation as described in section 5.2.

- **Graphical simulation results (C)**
  In this section, plots of simulation results are available. On the lower right corner, it is possible to switch between substations and voltage levels. In the middle bottom section, the feature to plot the results in a map can be started.

- **Status window (D)**
  The status window displays important information about active or completed processes as well as error messages if an error occurs.

5.2 Usage Example

The following example explains how to use the LFC simulator in a step-by-step way. All used data files (magnetic field data, grid data and earth layer data) can be found in the *SampleData* directory.

5.2.1 Data Import

As described in section 4, data needs to be organised in a particular way to be used for simulating. These files then need to be imported once in the simulators software environment to make them readable. This can be done in tab 4 (Import & Preferences) as shown below. All relevant sections are marked in Figure 9.

1. Go to tab 4 (Import & Preferences).
2. Import magnetic field measurement data:
    a. Enter the number of header-lines which are present in the data files. These lines contain no information which is relevant for simulating and therefore are ignored. In this example the data file contains 18 header-lines, as shown in Figure 3.
    b. Press *Import* and select data files (e.g. *wic20170905dsec.sec*). If multiple files are present in the directory, several files can be selected at once.
    c. After selecting all relevant files, the import process starts automatically.
    d. If the import process finished successfully, the resulting files (e.g. *wic20170905.mat*) can be found in the data file directory.
3. Import grid data:
    a. Enter the number of substations, transformers, and lines of the grid.
    b. Press *Import* and select the grid file (e.g. *LFC_Grid_Template_2Nodes.xlsx*).
    c. After selecting the file, the import process starts automatically.
    d. If the import process finished successfully, the resulting file (e.g. *LFC_Grid_Template_2Nodes.mat*) can be found in the grid file directory.
4. Import Earth layer data:
    a. Press *Import* and select the Earth layer data file (e.g. *LFC_Earth_conductivity_Template.xlsx*).
    b. After selecting the file, the import process starts automatically.
    c. If the import process finished successfully, the resulting file (e.g. *LFC_Earth_conductivity_Template.mat*) can be found in the grid file directory.

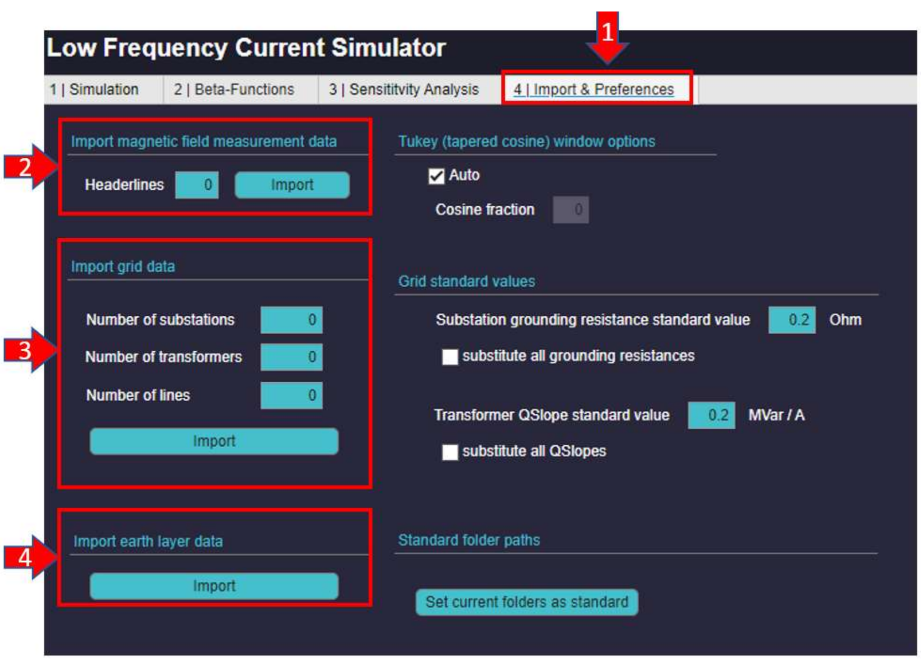


Figure 9: Data import process

5.2.2 Conduct simulation

To conduct a simulation, the previously generated files need to be loaded into the simulation tool. The *Preprocessing status* window shows if a specific data file is already loaded or not. After loading all files, the simulation can be started. All necessary steps are described below, and all relevant sections are marked again in Figure 10.

1. Go to tab 1 (Simulation).
2. Load magnetic field data:
    a. Press *Select Path* and select the folder/directory which contains the desired magnetic field measurement data (e.g. *SampleData/wic201709XX.mat*)
    b. Fill in the file prefix (case sensitive!) of the data files, as well as desired start date and end date.
    c. Select a sample interval, for instance *60*, which means that every 60th value of the data file is used for calculations in the simulation (downsampling).
    d. Select optional functions if necessary (e.g. filters).
    e. Press *Load Magnetic Field Data* to load data.
        i. Simulations can be performed with a constant electric field. For this the checkbox has to be ticked. However, magnetic field data still needs to be imported. The Unit of the defined electric field is V/km.
3. Load conductivity data:
    a. Press *Open Earth Data File* and select the desired conductivity model (e.g. *LFC_Earth_conductivity_Template.xlsx*).
    b. Select desired conduction model using the drop-down menu (e.g. *M39*).
    c. Press *Load Earth Model*.
4. Load grid data:
    a. Press *Load Network Model*.
    b. Select desired grid model (e.g. *LFC_Grid_Template_2Nodes.mat*).
    c. Fill in the number of phases (e.g. *3*).
5. Configure settings for result saving:
    a. Select a path/folder to store results.
    b. Select which components of the result should be saved and choose a data format.
        i. IMPORTANT: The current which is calculated is not a phase current. It is the sum of all 3 phases.
    c. If reactive power calculation is active, these values will be saved if transformer currents are saved
6. Press *Start Simulation* to start the simulation process. After a successful simulation, the results are shown in the GUI as depicted in Figure 11 and the results are saved (e.g. *LFC_Grid_Template_2Nodes_LineCurrents.mat*). On the bottom right corner, it is possible to switch between substations and transformer voltage levels.

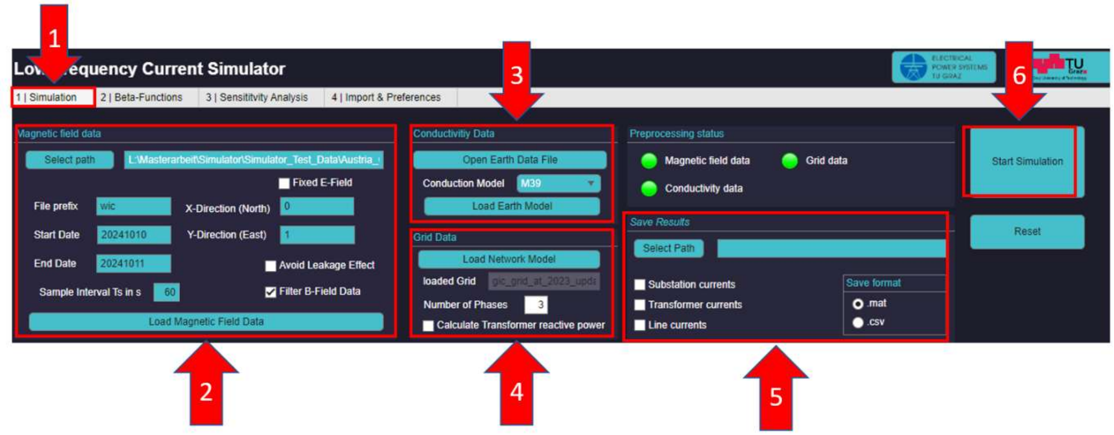


Figure 10: Simulation process

While performing a Fourier transform of the magnetic field data, leakage effects occur because of the discontinuous data. This can be prevented by adding additional data at the beginning and end of the magnetic field data. Therefore, if the checkbox “Avoid Leakage Effect” is selected, the two additional days need to be available for loading into the simulator. It is then tapered with a cosine bell window, options can be found in tab 4 | Import & Preferences.

Figure 11: Simulation results

5.2.3 Sensitivity Analysis

In tab 3 (Sensitivity Analysis), it is possible to calculate the maximum value of transformer neutral currents depending on arbitrary electric field values.

For the calculation, previously loaded grid data is used. After changing the input parameters and pressing *Start*

Simulation, results are shown on the right side of the simulator as shown in Figure 12. Substation and voltage level can be chosen arbitrarily. The results are saved at the path selected in tab 1.

It is also possible to import field data stored in a text-file. Therefore, check the "load data" option, push the "Load E-field" button and select the desired file. An exemplary file, called *E_field_100mV.txt* can be found in the sample data.

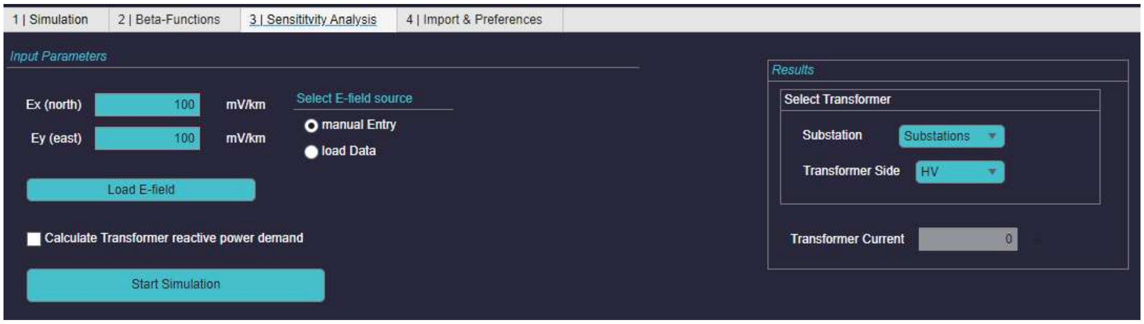


Figure 12: Sensitivity Analysis

5.2.4 Plotting results in a map

After a simulation has been successfully run, it is possible to plot the results in a map. A figure is created, which includes all substations of the grid plotted in the grid. For each timestep available, a separate figure will be created and, if the "save png" option is selected, every single figure will be saved as an image in a subfolder called *MapImages* in the current working folder.

To start the animation, just press the "show map" button in the bottom area of Tab 1 of the simulator. Depending on the size of the data, this may take some time. Please note, that a successful simulation must be conducted first, otherwise an error will occur. By modifying the "margin" value field right to the "show map" button, it is possible, to adjust the size of the animated map. To abort the process if necessary, close the figure window.

Figure 14 and Figure 13 show exemplary results of the "show map" feature, using the exemplary grid *LFC_Grid_Template_2Nodes.* In the top right corners, a reference circle is visible to indicate the size of a current of one ampere. Large currents are depicted as large circles, smaller values are drawn smaller.

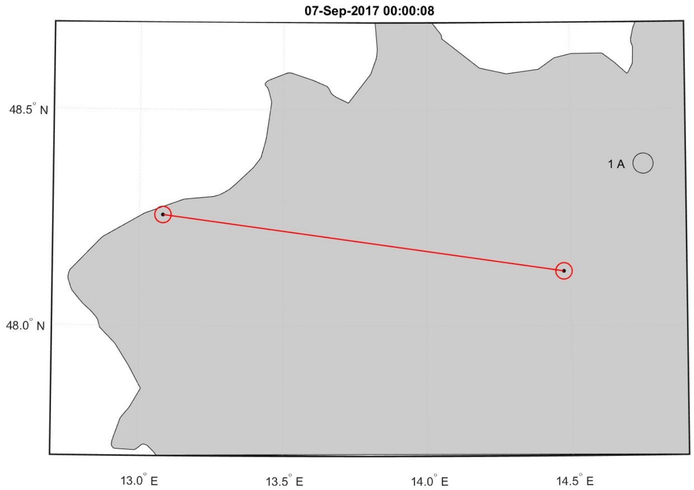


Figure 13: Representation of currents in a map (margin: 0.4 deg)

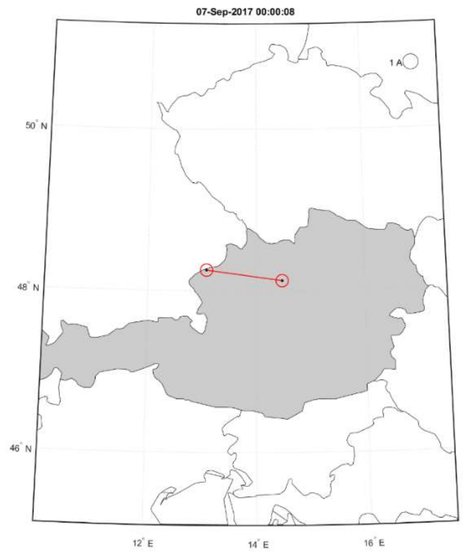


Figure 14: Representation of currents in a map (margin: 3 deg)

5.2.5 Displaying results as a slidable interactive figure

For a better overview, it is possible to display the calculation results in an interactive (slideable) figure as depicted in Figure 15. To open the figure window, press the *Slide* button next to the *Save png* button on the *Simulation* tab of the GIC Simulator. Then press the *Load Images* button in the newly opened figure to load a slideshow of the images stored in subfolder *MapImages* in the current project folder. In this figure window, it is possible to manually control the slideshow of the calculation results using the slider on the bottom of the figure.

Please note that this is only possible if a successful simulation has been done beforehand and the results have been stored as png-files as described in the previous section!

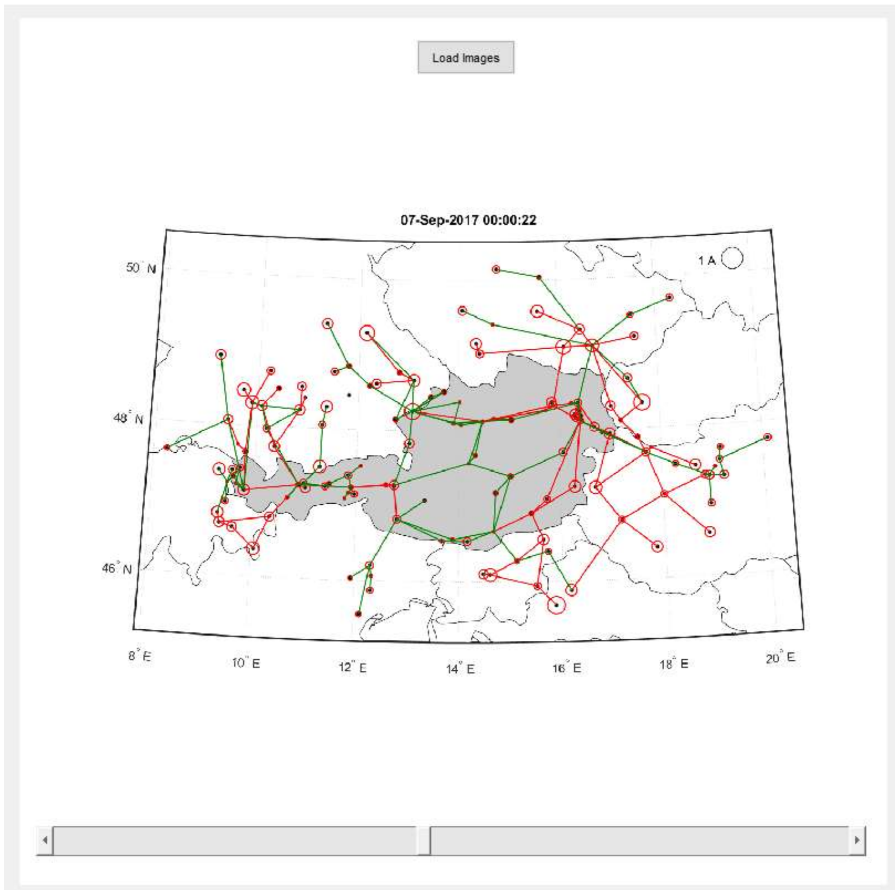


Figure 15: Interactive figure of calculation results

6 Planned / upcoming features

- Performance improvements
- Preference handling
- More Calculation options (e.g. leakage effect options)
- Neutral point switching optimizations

7 References

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