Unagi

Knowledge Base (Draft)

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Document history

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Unagi

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Executive Summary

Our key findings are:

- …

Amsterdam, June 2022.

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Part I

User Manual

1. How to use

Unagi is written by Python code. It can be used as a regular application via a graphical user interface (GUI) or as a backend application.

1.1. Use the GUI

Unagi implements two ways of use: Web GUI and Desktop GUI. When hosting the app on a cloud platform, the user can use it via the Web GUI. When hosting the app locally on the user's laptop, the user can use it via both GUIs.

The file index.py is the entrance for the Web GUI, while the file app_desktop.py is the entrance for the Desktop GUI.

1.2. Use the Web GUI

The Web GUI implements a navigation bar where the user can choose a study, access the database, or download help documents, see Fig. 1. Note that the URL in the address is from the local host. When you use the app on a cloud platform, you need to use a designated URL.

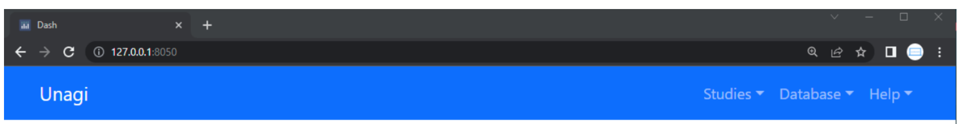

Figure 1: The navigation bar in the Web GUI.

1.2.1. Run A Study

You can select a study in the dropdown menu Studies on the navigation bar. A study page contains entries, buttons, tabs, and tables, which require the user to provide input, some studies even require user to upload CSV files.

Input Data Actions

At the top of each study page, user can choose three actions for input data: Load An Example, Export Input, and Import Input, see Fig. 2. Here, the page of Preliminary Study is used as an example.

For a quick start, the user can use the dropdown menu Load An Example. It will automatically fill all the relevant input data on that page, including CSV files (if needed).

To save a version of the input data for a specific study, the user can export the input data to a JSON file by the button Export Input. The JSON file, a plain-text file, will be saved to the user's local computer. And the user can import the JSON file to fill in all the saved data by the button Import Input. In addition, the user can send the JSON file to another colleague for collaboration. With these import and export features, everything is included in the JSON file. Even for those

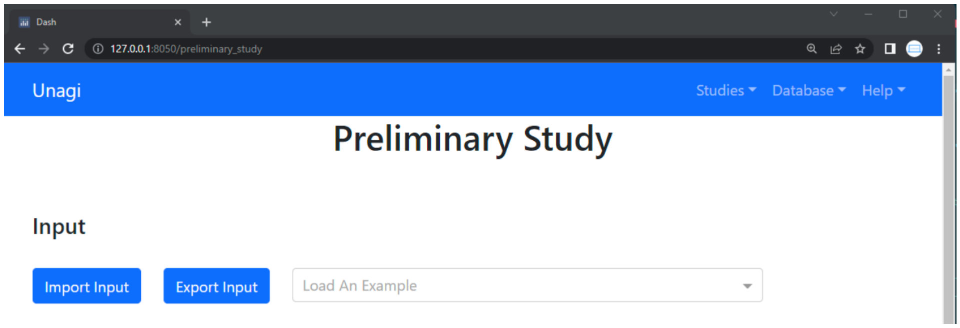

Figure 2: Input data actions in the `Web GUI`.

inputs that require the user to upload a CSV file, the content of the CSV file is also included in the JSON file.

Hint Message

Each input has a corresponding label. Placing the mouse on top of a label will pop up a hint message, see Fig. 3. It provides basic information to inform the user about the expected input data. The user can always check this `Knowledge Base` for detailed information.

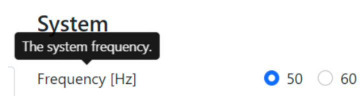

Figure 3: Hint message in the `Web GUI`.

Choose A Tab

In some studies, the user must select one from several tabs; only the selected tab is used for the study. Take the `Cable Loss Study` as an example, see Fig. 4. It implements two approaches: `IEC` and `Southampton`. If the user selects the `IEC` tab in the section `Cable Genre Table`, the study will use the `IEC` approach to calculate cable loss; likewise, if the `Southampton` tab is selected, the study will use the `Southampton` approach.

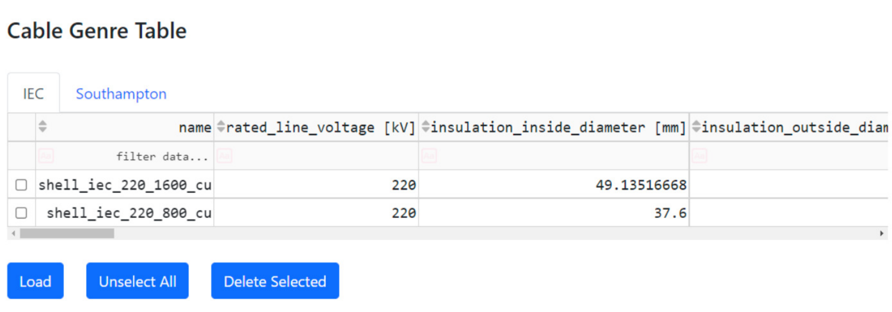

Figure 4: Tab selection in the `Web GUI`.

Cable Genre Table

In some studies, user can specify some cable genres in the `Cable Genre Table`, see Fig. 5 from the `Preliminary Study` as an example.

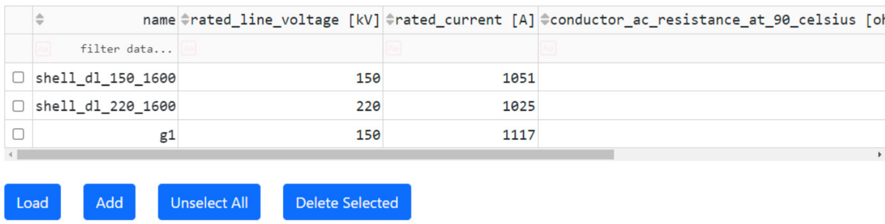

Figure 5: `Cable Genre Table` in the `Web GUI`.

The user can use the button `Load` to select one or more cable genres from the database. The selected ones will be shown in this table. The button `Add` allows the user to add some other cable genres that do not exist in the database for a quick check. To delete one or more cable genres from this table, the user can select them and click the button `Delete Selected`. Deleting from this table will not delete them from the database.

Note that the button `Add` is used only for power-flow related studies: `Preliminary Study` and `Transfer Capacity Study`. It is not available for studies about cable loss or cable thermal resistance calculation. Since the required cable genre's parameters are too many to let user add one by one. Instead, user can only load and select from the database.

Moreover, since different studies can require different parameters of a cable genre, and the cable genres stored in the database do not need to have values for all the parameters. This means, in the database, some cable genres may have values only for the parameters that needed by a power-flow calculation, and some cable genres may have values only for cable loss calculation, and some may have values for all the parameters. The button `Load` from a study page will only show the cable genres that have values for the parameters required by this specific study.

The Run Process

Each `Run` button has a companion `Stop` button. Before the `Run` button is clicked, the `Stop` button is disabled. After the `Run` button is clicked, the input data that filled on the study page will be collected and send to the backend, and the study starts to run. In the meanwhile, the `Run` button is disabled and the `Stop` button is enabled. The status of the on-going progress is regularly updated below the `Run` button. See Fig. 6 for the `Transfer Capacity Study` as an example.

If the study is finished successfully, a zip-file of study results can be downloaded to the user's local computer, and a success message is shown to inform the user, see Fig. 7. Then the `Run` button becomes enabled again, and the `Stop` button is disabled again. During the running process, the user can click the `Stop` button at any time to terminate the running process.

If there is any error, the running study is terminated and an error message is shown to the user. For example, the user forgets to provide an value to the entry of `U max [p.u.]` in the `Transfer Capacity Study` page. After the `Run` button is clicked, the error of missing value is detected by `Unagi` and an error message is shown to the user, and the study is terminated. See Fig. 8.

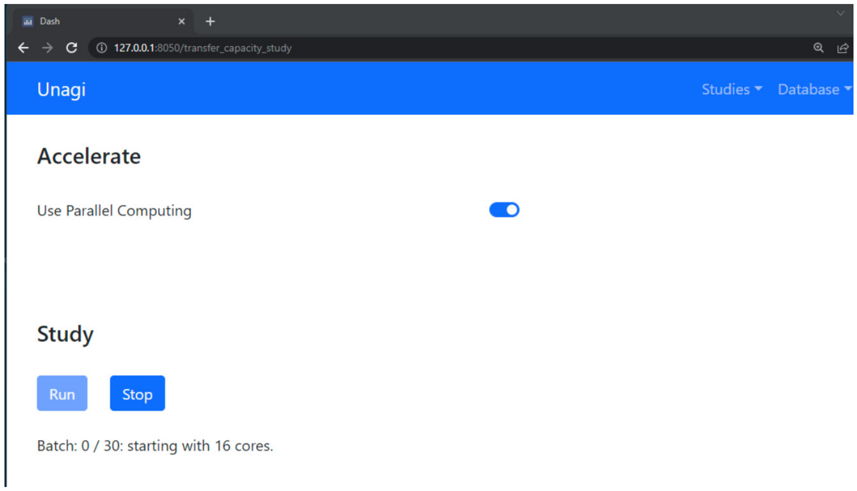

Figure 6: The progress status of an running study in the `Web GUI`.

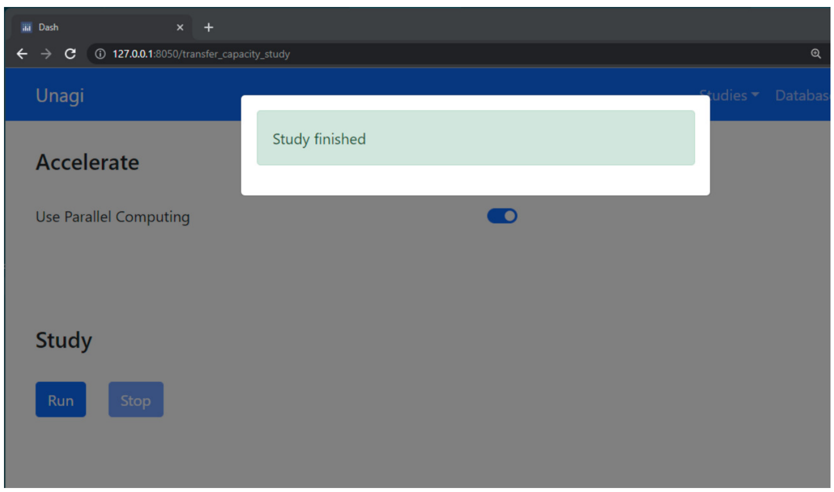

Figure 7: The pop-up message after a run is finished successfully in the `Web GUI`.

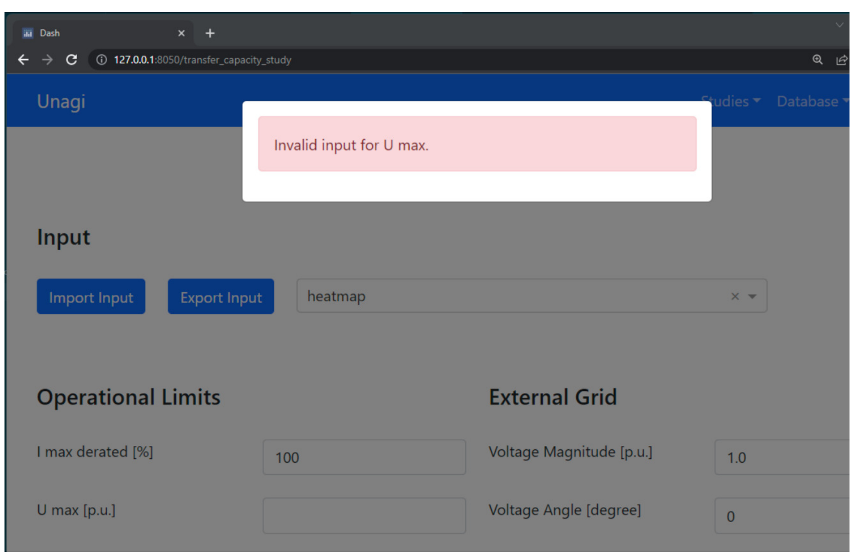

Figure 8: An example of the error message in the `Web GUI`.

Database Import Page

The user can import genres data from a CSV file to the database for `Cable Genre` (for 3-core cables), `Transformer2W` (for 2-winding transformer genres), and `Transformer3W` (for 3-winding transformer genres).

The user needs to upload a CSV file from a local computer, and must select the name of the corresponding content in the database: `Cable Genre`, `Transformer2W`, or `Transformer3W` from the dropdown menu. See Fig. 9.

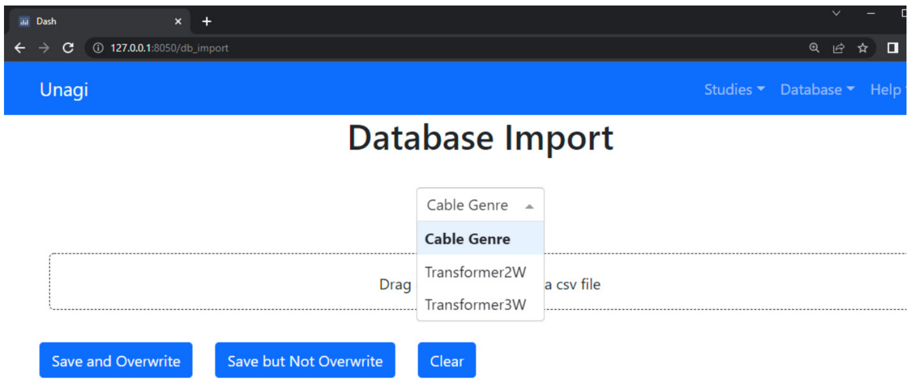

Figure 9: `Database Import Page` in the `Web GUI`.

The content of the uploaded file is displayed, allowing the user to have a final check before actually saving them into the database.

The uploaded file may contain genres' names that already exist in the database. However, the name of a genre must be unique. When this happens, the user has the following two options.

- If the user wants to use the version in the database and ignore the new version from the file, then click the button `Save but Not Overwrite`. And the duplicated genres from the uploaded file will be exported to a CSV file to the user's computer.
- If the user wants to replace the version in the database by the new version from the file, then click the button of `Save and Overwrite`.

Fig. 10 shows the help documents provided by `Unagi`. Note that the user can download an example CSV file for each table in the database. In addition, since the `Cable Genre` table contains many parameters for different calculations, a template XLSX file to identify the required parameters for different studies is available for the user to download. The example CSV files can be directly imported to the database for a quick start.

Database Management Page

In the page of `Database Management`, the user can view, export, and reset the existing database, see Fig. 11.

The user needs to select the table's name from the dropdown menu to view a specific table. They can export all or selected data from the table to a CSV file on the user's computer. The table allows user to define basic filters for querying and viewing the relevant data in the table. For example, if the user wants to know all the cable genres whose name contains the word `shell` and with rated voltage higher than 110 [kV], the user can enter the word `shell` in the column of `name`

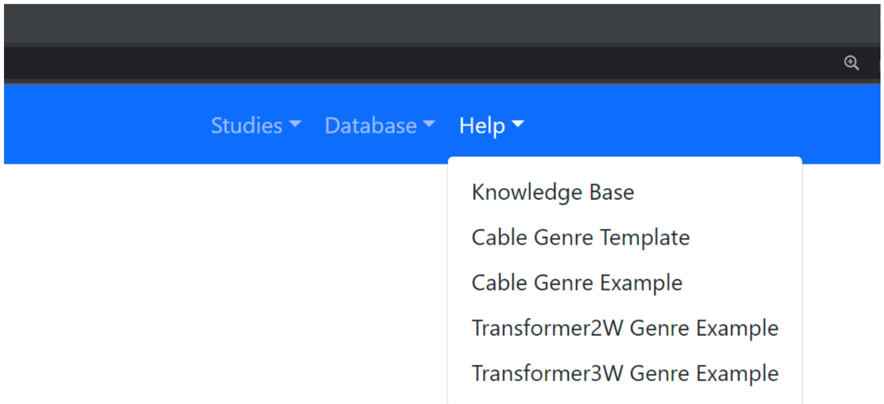

Figure 10: Help documents in the `Web GUI`.

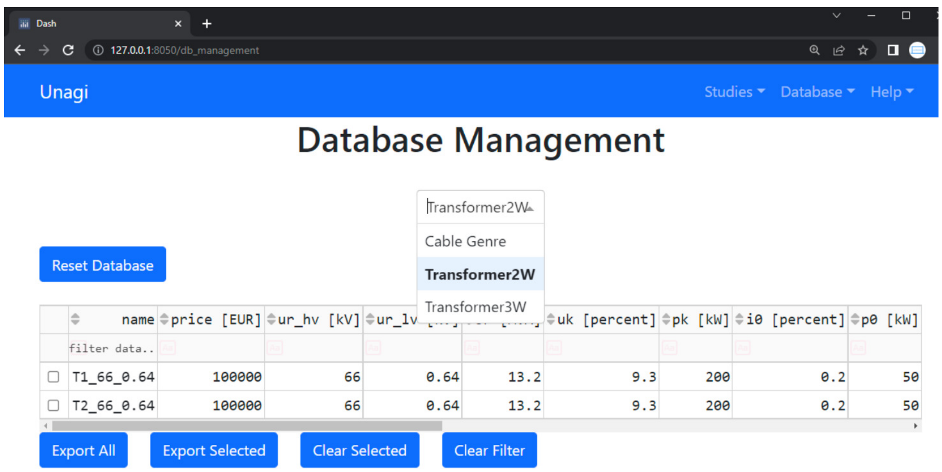

Figure 11: `Database Management Page` in the `Web GUI`.

and `>110` in the column of `rated_line_voltage [kV]`, see Fig. 12. The user can click the button `Clear Filter` to clear all the entered filters.

The user can click the button `Reset Database` to delete an entire table in the database. Only the selected table will be deleted, and the other tables will not.

1.3. Use the Desktop GUI

1.3.1. First Use

When use unagi for the first time, you need the following actions before running a study.

1. Get your `username` and `password` from administrator. (For test, enter `admin` in both `username` and `password`). See chapter 1.3.2..
2. Choose a main folder to store the study results. It is the button `Set Report Folder` in `User Page`, see chapter 1.3.3..
3. Import data to database, see chapter 1.3.4..

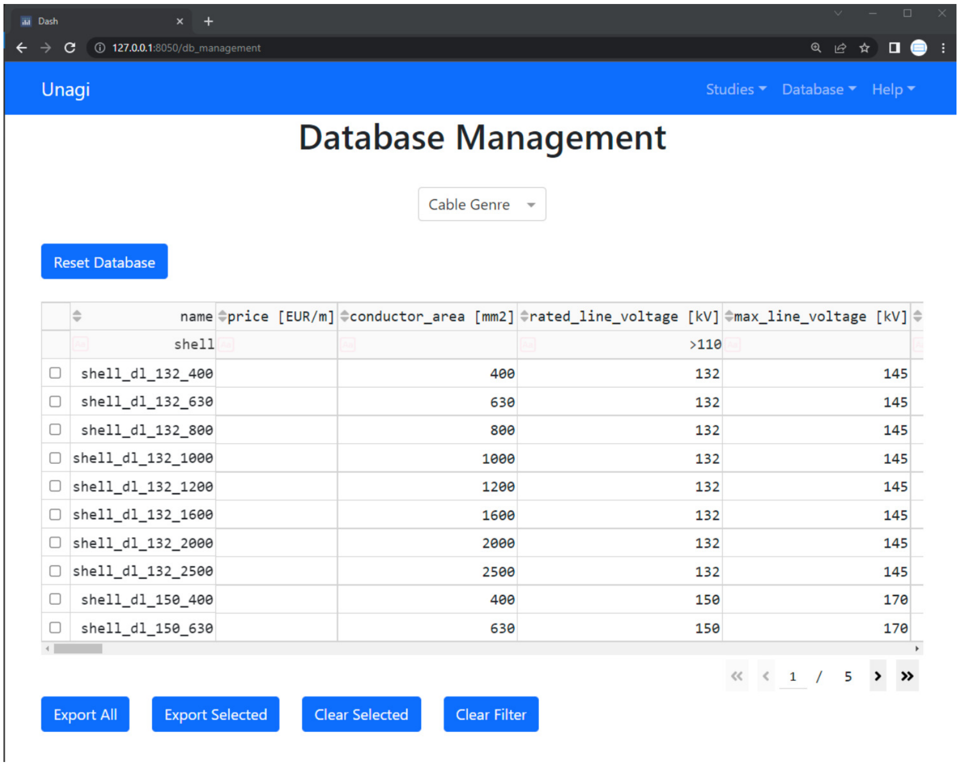

Figure 12: Example of filters to view data in the `Database Management Page` in the `Web GUI`.

4. Check the imported data in database, see chapter 1.3.5..
5. Choose a study and run.

And, of course, you can always check details in the user-manual.

1.3.2. Login Page

It is the first page each time unagi is launched. A valid combination of `username` and `password` is required. If an invalid combination is entered, a message in red color is displayed, and you can try another combination.

For test, enter `admin` in both `username` and `password`.

1.3.3. Home Page

After login successfully, the `Home Page` is shown.

User can choose to

- Visit various pages for study.
- Set report folder, which is the main folder to store study results.
- Import new data to database.
- Manage existing database.
- Get help from user-manual.

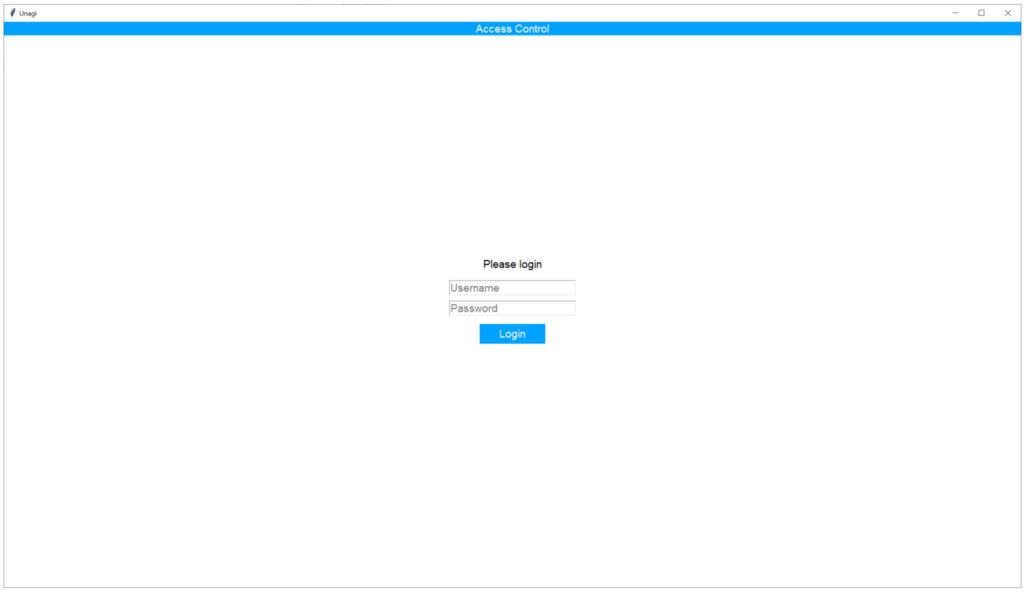

Figure 13: Login page.

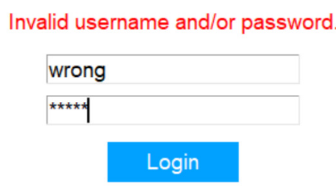

Figure 14: An example of invalid login.

Figure 15: Home page.

1.3.4. Database Import Page

This page can be accessed by clicking the button `Database Import Page` in the `Home Page`, see chapter 1.3.3.. This page is meant for importing new data from CSV files.

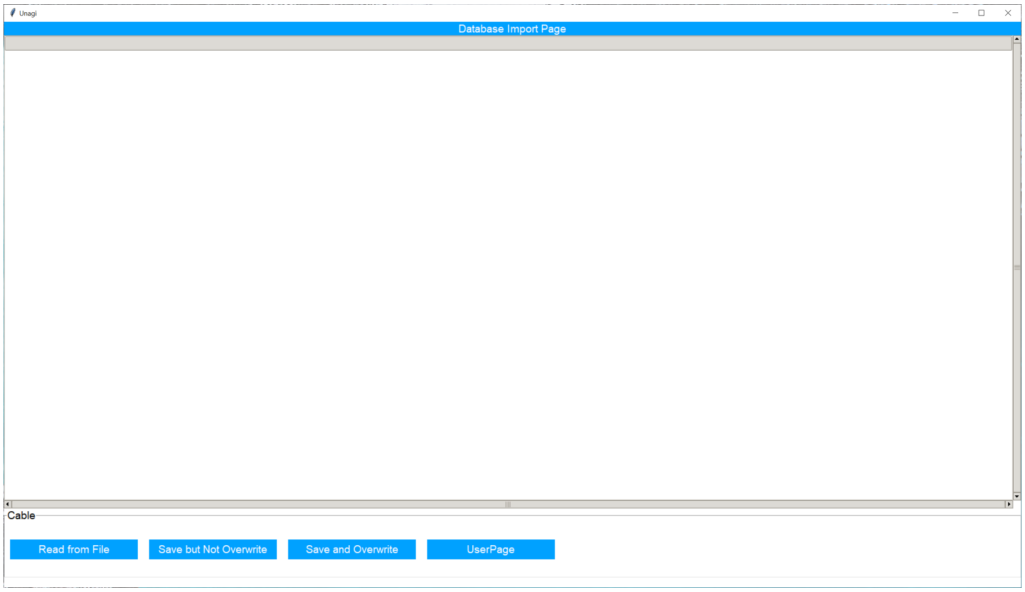

Figure 16: Database import page.

Read from File

User can click the button `Read from File` and select a file. The file content will be displayed. Note that the validity of the content is checked when either the button of `Save but Not Overwrite` or the button of `Save and Overwrite` is clicked, and only valid data can be saved. That means, any CSV file can be read and its content will be shown, even if the file does not contain the required columns for database. It is just that it cannot be save if its content is invalid.

Save to Database

When new data is read from a file and displayed, it is possible that the primary key (in the case of cable genre, the primary key is in the `name` column.) of the new data already exists in the database, and these rows are considered as duplicate data. Since the primary key must be unique of each row, user has two options:

- If user wants to use the version in the database and ignore the new version from the file, then click the button of `Save but Not Overwrite`. If there are duplicate data, the version from the file are exported to a CSV file designated by user.
- If user wants to replace the version in the database by the new version from the file, then click the button of `Save and Overwrite`.

1.3.5. Database Management

This page can be accessed by clicking the button `Database Management Page` in the `Home Page`, see chapter 1.3.3.. User can choose to

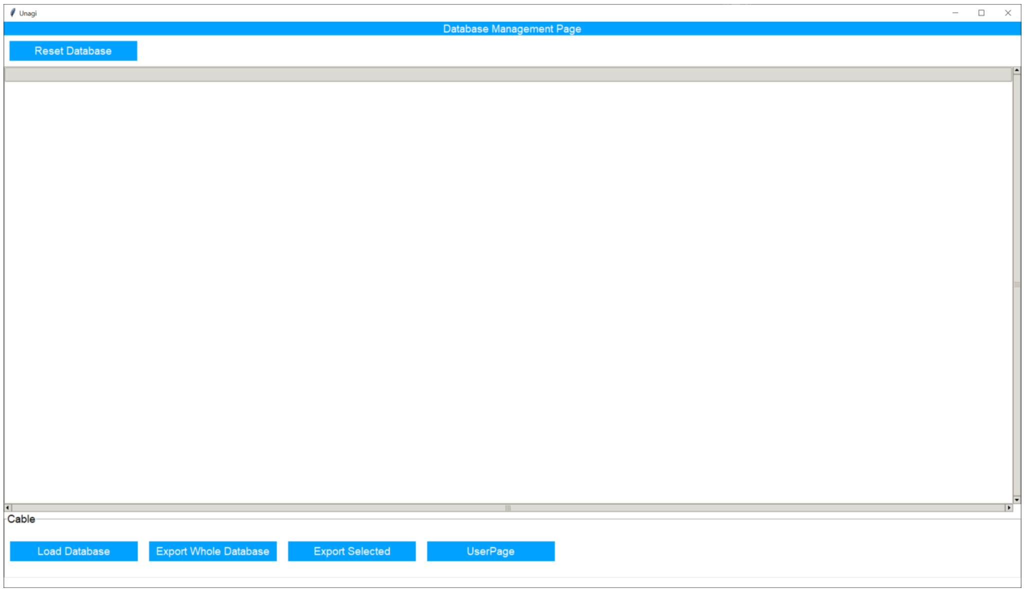

Figure 17: Database management page.

- Load data from database.
- Export the data from the whole database to a CSV file designated by user.
- Export the user-selected rows to a CSV file designated by user.
- Reset the database. This will empty the database, and all stored data will be removed.

Part II

Physics & Algorithm

2. High-level Algorithm

2.1. Study Model in the Backend

All studies' models in the backend adopt the same logic-flow, see Fig. 18.

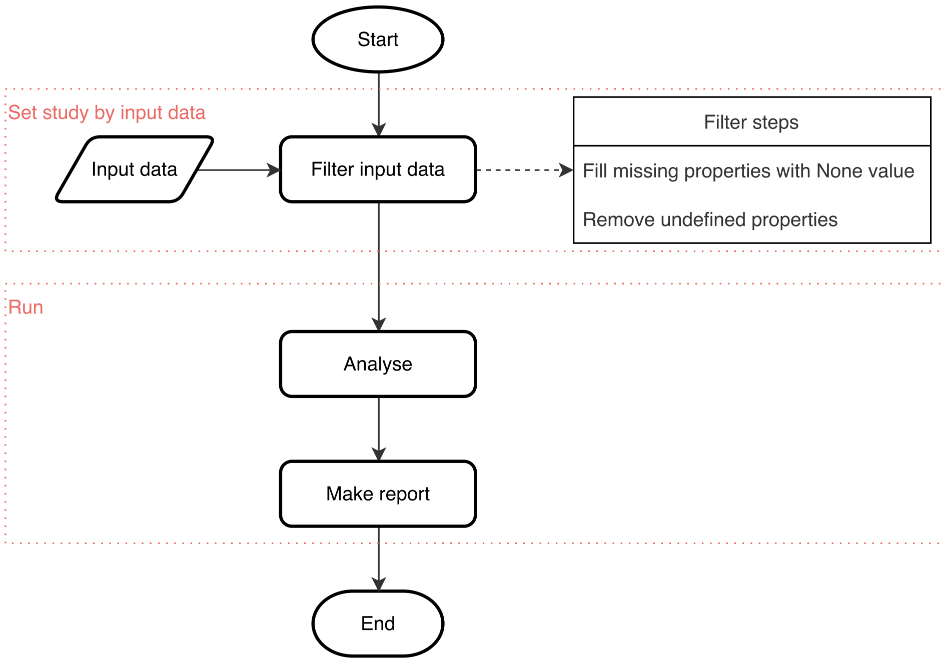

Figure 18: Common logic flow for all studies' models in the backend.

First, a raw input data is provided to a study model. Each model has its own defined schema for input properties. The raw input data may miss some properties or contain undefined properties. That's why the raw input data is filtered at the very beginning of the process. Then, all the technical calculations are done in the process called `analyse`, which generates study results in memory. Then the input data and study results are both used to make the report.

- If you want to have the report, then the `run` method of the study model should be used. This is the case when you use GUI, or when you use the backend model without using the gui for a complete study.
- If you just want to use the study results, then the `analyse` method of the study model should be used. This is the case when some study calls another study internally (e.g. `Cable Rating Study` calls `Cable Loss Study`), or when you want to use the backend model without using the GUI and you want to use the study results in memory for your own purpose.

3. Preliminary Study

Preliminary study provides high-level evaluation on technical solution for a connection. In short, it can:

- propose feasible cable genres for different cable sections (`Cable Genre Proposal Study`);
- check the feasibility of a user selected cable genre for each cable section (`Connection Study`).

3.1. Business Challenge

Suppose there is a need to transport 20 MW power over a distance of 120 km, which cable genres are technically feasible? To answer this question, a complete connection must be defined first.

- The frequency of the connection. The frequency of an AC grid can be 50 Hz (like Europe) or 60 Hz (like the U.S.).
- The specification of equivalent source representing the external grid.
- The specification of the static generator for wind-power generation.
- The specification of reactive power compensation.
- The specification of the cable route, which may have different derating factors.
- A group of cable genres to choose from.

3.2. Study Scope

The study allows different connection topology, from as simple as just one cable section without any reactive power compensator (Fig. 19) to as complicated as 6 cable sections with 3 different shunt reactors located at left, somewhere in the middle, and right side of the connection (Fig. 20). Each cable section can have unique length and derating factor. Note that the mid-point shunt can be located between any two neighbouring cable sections. Take a conneciton with 6 cable sections for example, the mid-point shunt can be at any point among $b_1, b_2, \ldots, b_5$.

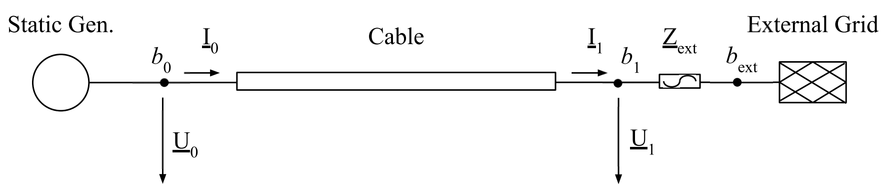

Figure 19: Cable connection with 1 cable section and no reactive power compensation.

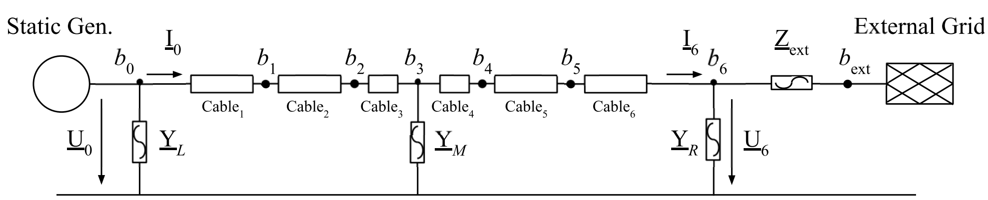

Figure 20: Cable connection with 6 cable sections and 3 shunts.

3.2.1. User to Specify

- Cable genres.
  - Rated voltage, in [kV].
  - Rated current, in [A].
  - Conductor AC resistance at $90\,^{\circ}\mathrm{C}$, in [Ω/km].
  - Inductance, in [mH/km].
  - Capacitance, in [μF/km].
- Cable sections:
  - Number of cable sections. Note that to add a mid-point shunt, at least 2 cable sections are required.
  - Name of each section.
  - Length of each section, in [km].
  - Derating factor of each section.
- Frequency: 50 Hz or 60 Hz.
- External Grid:
  - Voltage magnitude in [p.u.].
  - Voltage phase angle in [degree].
  - R/X ratio of the short-circuit impedance.
  - Short-circuit power in [MVA].
- Static Generator
  - Active power in [MW].
  - Power factor, which is between 0 and 1.
  - Mode, which can be `overexcited` or `underexcited`.
- Shunt
  - Reactive power compensation scheme. It allows 0, 1, 2, or 3 shunts, at 3 possible locations, left, mid, and right. Thus there are in total 8 different choices: ''No'', ''L'', ''M'', ''R'', ''L-M'', ''L-R'', ''M-R'', ''L-M-R''. Note that a shunt can only be connected to a bus, so the mid-point shunt should be connected to a bus between two neighbouring cable sections.
  - Split of the each shunt. The sum of the split of all shunts is always 1. Take scheme ''L-M-R'' for example, if the split of the left, middle, and right shunt is respectively 0.3, 0.4, 0.3, it means that the left shunt contributes 30 % of the total compensation. Likewise, the middle shunt contributes 40 %, and the right shunt contributes 30 %.
  - R/X ratio of the impedance of each shunt.
  - Total compensation ratio. It describes how much of the cable reactive power should be compensated. For example, 0.8 means 80 % of the cable reactive power.
- Operational limits. See section 3.2.5. for details.

For detailed information about components modelling, see Appendix 1..

3.2.2. User to Choose

The decision tree presented in Fig. 21 helps user choose a study.

To actually build such a connection, cable genre of each cable section must be known.

- If you already know them, you can simply provide them and run `Connection Study` to check the feasibility of this connection.

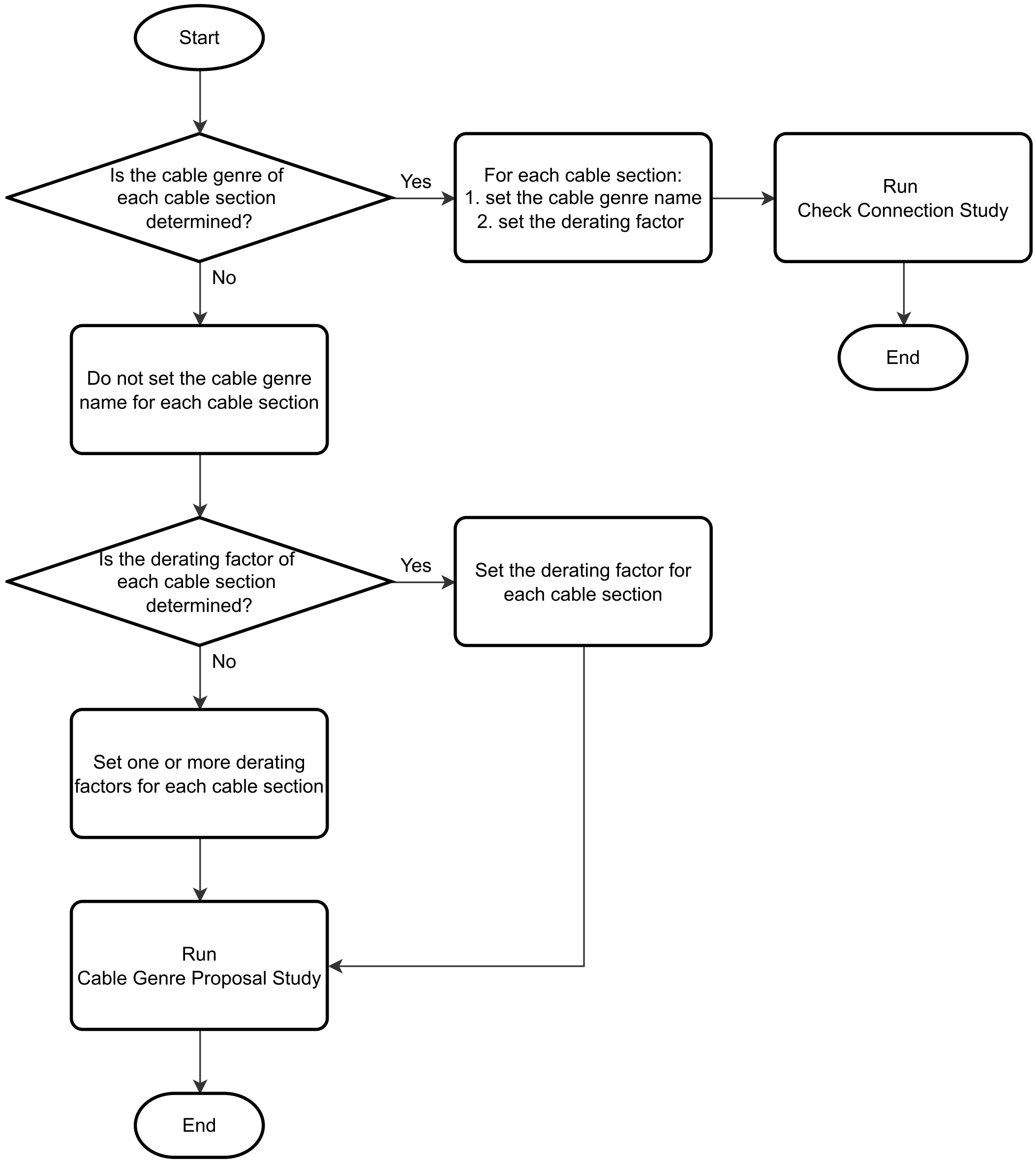

Figure 21: Decision tree of `Preliminary Study`.

- If you are not sure, you can, without providing them, simply run `Cable Genre Proposal Study` to let `Unagi` propose feasible cable genres for each cable section.

Note that for `Connection Study`, user should provide only one derating factor each cable section; while for `Cable Genre Proposal Study`, user can provide more than one derating factors for each cable section .

3.2.3. Logic Flow

Cable Genre Proposal Study

A high level logic flow of the `analyse` method in `Cable Gener Proposal Study` is shown in Fig. 22.

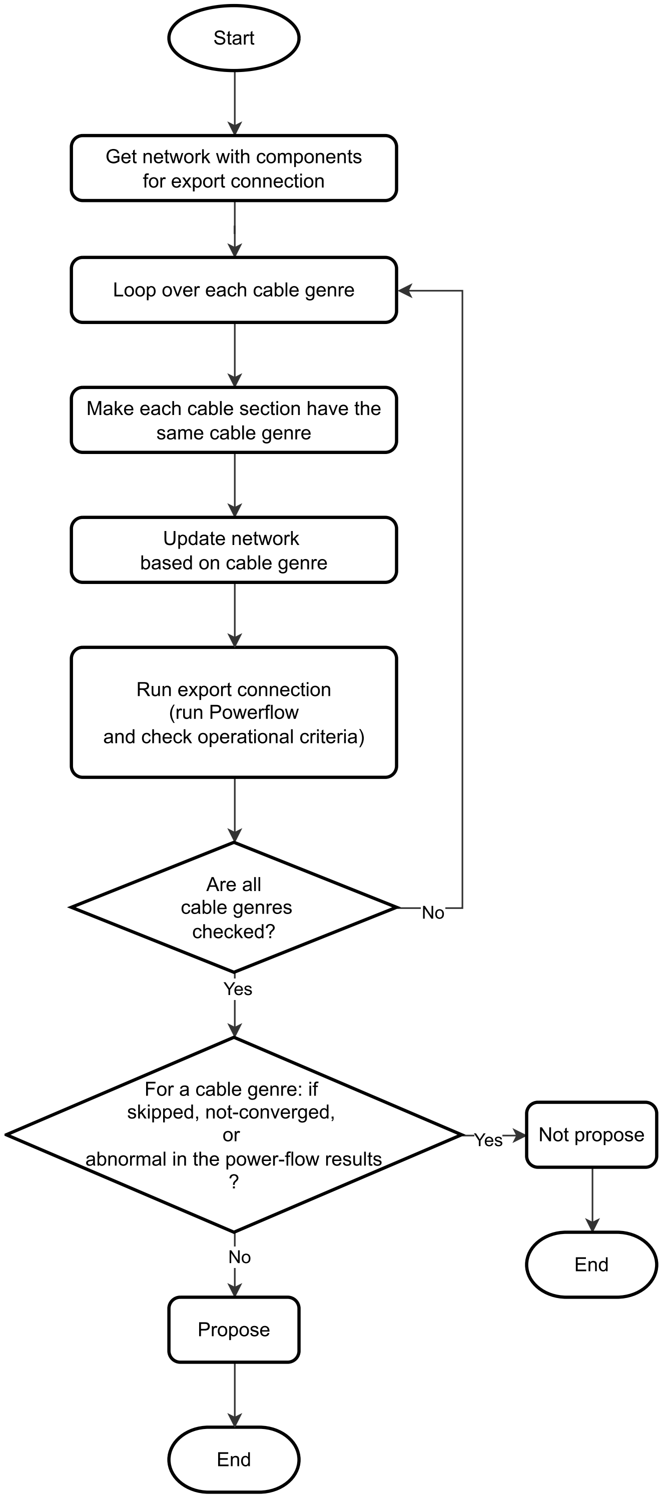

Figure 22: Logic flow of the `analyse` method in `Cable Genre Proposal Study`.

In reality each cable section can have a different cable genre, but here in each loop, all the cable sections are assumed to have the same cable genre. Otherwise, there can be too many combinations of assigning a cable genre for each individual cable section at a time. Suppose there are 6 cable sections and 10 cable genres to choose from. That means each cable section has 10 choices of genres independently. Then the total number of cases is 10^6. Therefore, when checking the feasibility of each cable genre, this study assumes all the cable sections have the same cable genre. Consequently, the proposed cable genres are only indications of possible choices. To check a connection in detail, user should designate one specific cable genre (and one derating factor) per cable section, and run `Connection Study`.

Check Connection Study

A high level logic flow of the `analyse` method in `Connection Study` is shown in Fig. 23.

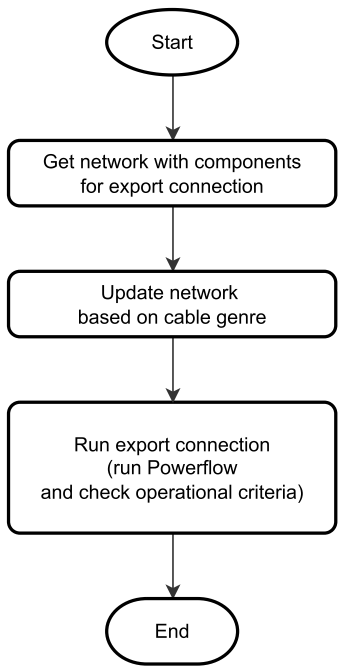

Figure 23: Logic flow of the `analyse` method in `Connection Study`.

3.2.4. Export Connection

For a certain connection, the choice of cable genre can affect the values of other components in the same network, e.g. the active and reactive power of shunts. Then the operational parameters (voltages and currents at different locations) of the network can be obtained using powerflow calculation. The results should then be checked with operational criteria specified by user. A high-level logic flow of run an export connection investigation is depicted in Fig. 24.

When updating the network based on cable genre, if the minimum rated voltage of cable genres is less than the nominal voltage of buses, then the investigation should be skipped.

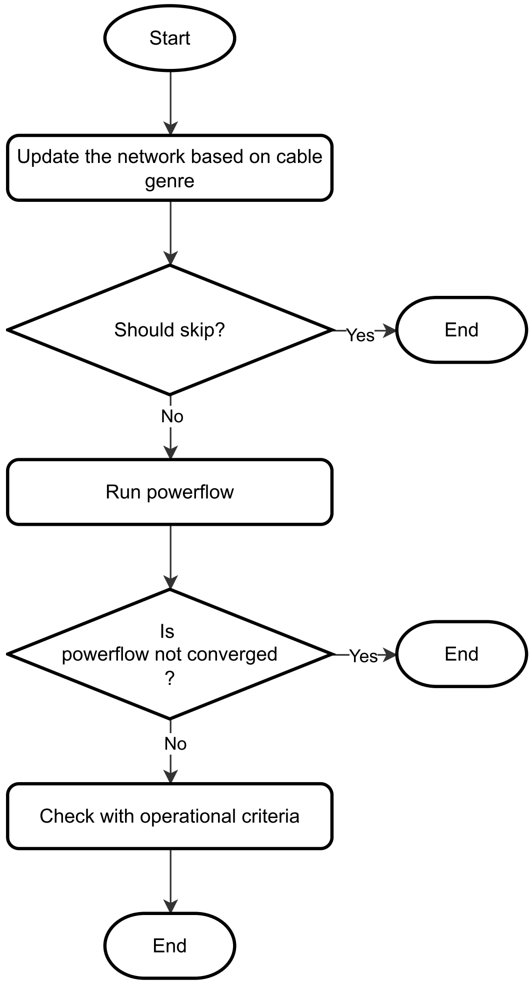

Figure 24: Logic flow of run an export connection investigation.

Update Network by Cable Genre

The logic flow of updating a network based on cable genre is presented in Fig. 25.

Unagi allows user to specify if the nominal voltage of the buses. If user chooses this way, then the nominal voltage of buses will be fixed and not depends on the rated voltage of cable genre. On the other hand, if user chooses that the nominal voltages of buses equals the rated voltage of cable genre, then the nominal voltage of buses should be updated every time when cable genre is changed. Note that, Unagi assumes the nominal voltage of all buses are always the same, but allows the cable genres at different cable sections to have different rated voltages. The minimum rated voltage of all used cable genres will be used as the nominal voltage of buses. If the nominal voltage of buses is independent from the rated voltage of cable genre, then only the cable genres whose rated voltage is higher to equal to the nominal voltage of buses can be used.

After the nominal voltage of buses is determined, the shunts should be updated. The logic flow is shown in Fig. 26. The shunts are designed to compensate a certain level of the reactive power from the cable sections, which is calculated at no-load operation.

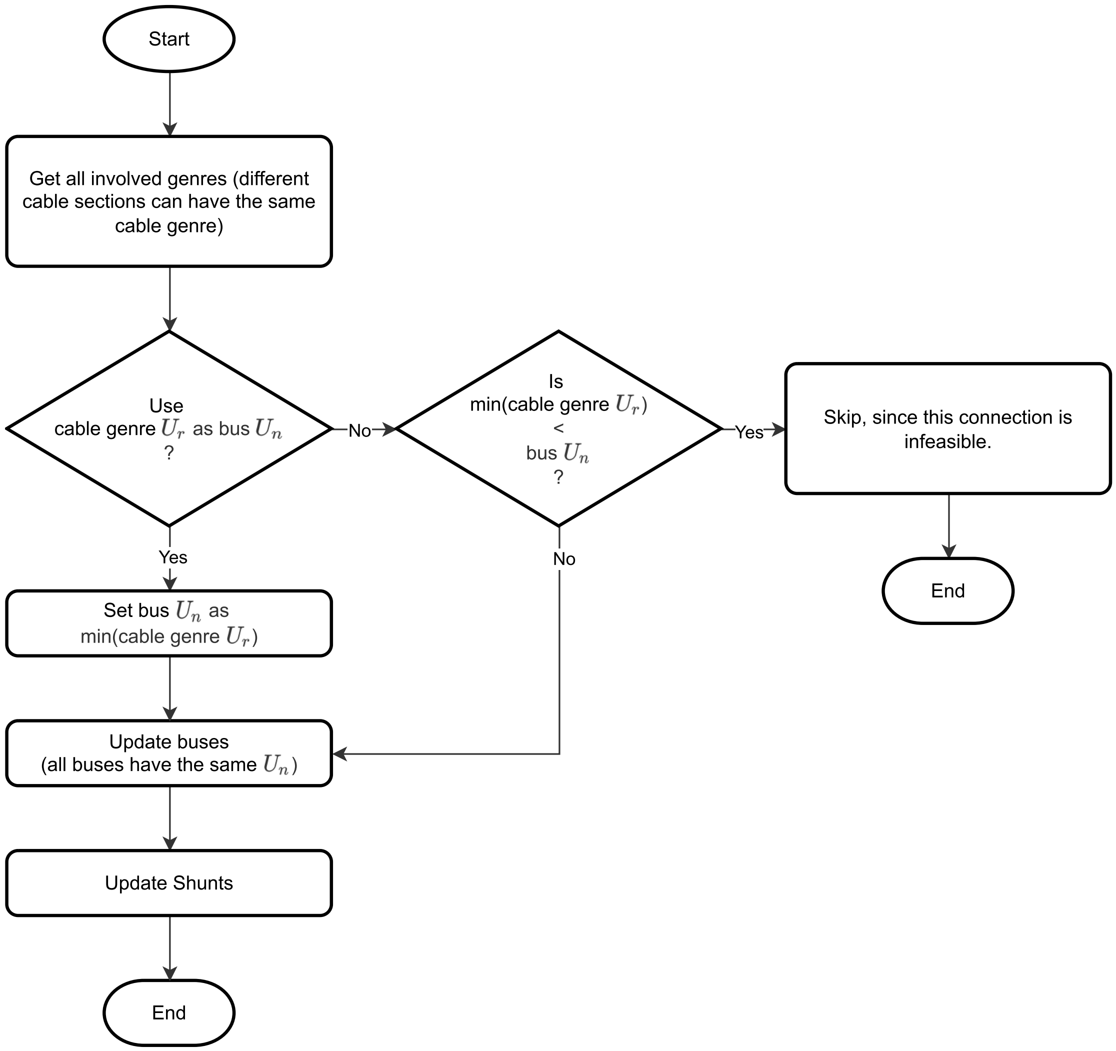

Figure 25: Logic flow of updating network by cable genre.

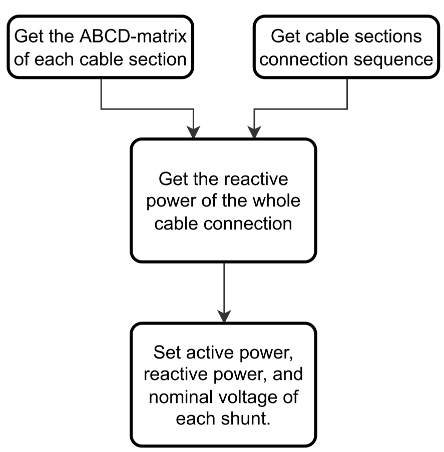

Figure 26: Logic flow of updating shunt by cable genre.

One way to quickly but roughly calculate is

$$Q_{\text{cable}} = U_n^2 \cdot \sum_{k=1}^{N} (\omega C_k \cdot \text{Length}_k) \tag{1}$$

where

N is the total number of cable sections;
k is the *k*th cable section in the actual connection sequence;
Q_{cable} is the total reactive power of all cable sections;
U_n is the nominal voltage of the buses;
C_k is the capacitance per unit length of the *k*th cable section;
Length_k is the length of the *k*th cable section.

This approach assumes that the voltage distributed across the cable sections is uniformly equal to the nominal voltage of the buses. However, this is not true due to *Ferranti effect*. Thus it is not used in Unagi. Unagi adopts a more accurate way explained as follows.

First, calculate the ABCD-matrix of the entire cable connection.

$$\begin{aligned}
\begin{bmatrix} \underline{U}_p \\ \underline{I}_p \end{bmatrix} &= \begin{bmatrix} \underline{A} & \underline{B} \\ \underline{C} & \underline{D} \end{bmatrix} \begin{bmatrix} \underline{U}_q \\ \underline{I}_q \end{bmatrix} \\
\begin{bmatrix} \underline{A} & \underline{B} \\ \underline{C} & \underline{D} \end{bmatrix} &= \prod_{k=1}^{N} \begin{bmatrix} \underline{A}_k & \underline{B}_k \\ \underline{C}_k & \underline{D}_k \end{bmatrix} \\
\underline{I}_q &= 0 \qquad \text{(no-load operation)}
\end{aligned} \tag{2}$$

where

N is the total number of cable sections;
k is the *k*th cable section in the actual connection sequence.
p refers to onshore terminal of the connection.
q refers to the offshore terminal of the connection.
$\underline{U}_p$ and $\underline{U}_q$ are the phase voltages of the two terminals.
$\underline{I}_p$ and $\underline{I}_q$ are the currents of the two terminals.

Then, calculate the reactive power of all cable sections by

$$\underline{S}_p = 3 \cdot \underline{U}_p \cdot \underline{I}_p^* = 3 \cdot \underline{U}_p \cdot \left(\frac{\underline{C} \cdot \underline{U}_p}{\underline{A}} \right)^* \tag{3}$$

$$Q_{\text{cable}} = \Im(\underline{S}_p) \tag{4}$$

where

$\Im$ means taking the imaginary part of a complex value.
* means taking the conjugate value of a complex value.
$\underline{U}_p = \frac{1}{\sqrt{3}} U_m e^{j\theta}$. And U_m and θ are, respectively, the magnitude and angle of the external grid voltage provided by user.

For further information about ABCD-matrix, see Appendix 4.1.. For details about how to calculate the needed parameters of each shunt based on the known reactive power of the entire cable connection, see Appendix 1.8..

3.2.5. Operational Criteria

When in service, the voltage and current at any location of the connection must be within operational limits. The voltage of each bus and the current in each branch can be calculated by powerflow calculation. Then, the voltage and current along the whole cable connection can be calculated by ABCD-matrix approach, see Appendix 4..

The implemented logic-flow of checking those criteria is shown in Fig. 27. The limit values of all checks are to be provided by user.

Derated Current

The operational limit of overcurrent is defined as the derated current I_{derated}. It is the rated current of a cable genre provided by its manufacturer datasheet multipled by a derating factor.

$$I_{\mathrm{derated}} = I_{\mathrm{rated}} \times \text{derating factor} \tag{5}$$

Suppose the rated current of a cable genre is 1000 [A], the derating factor is 0.9, and the actual current obtained via powerflow is 950 [A]. Then the comparison is

$$950 > 1000 \times 0.9 = 900$$

Consequently, the overcurrent is found.

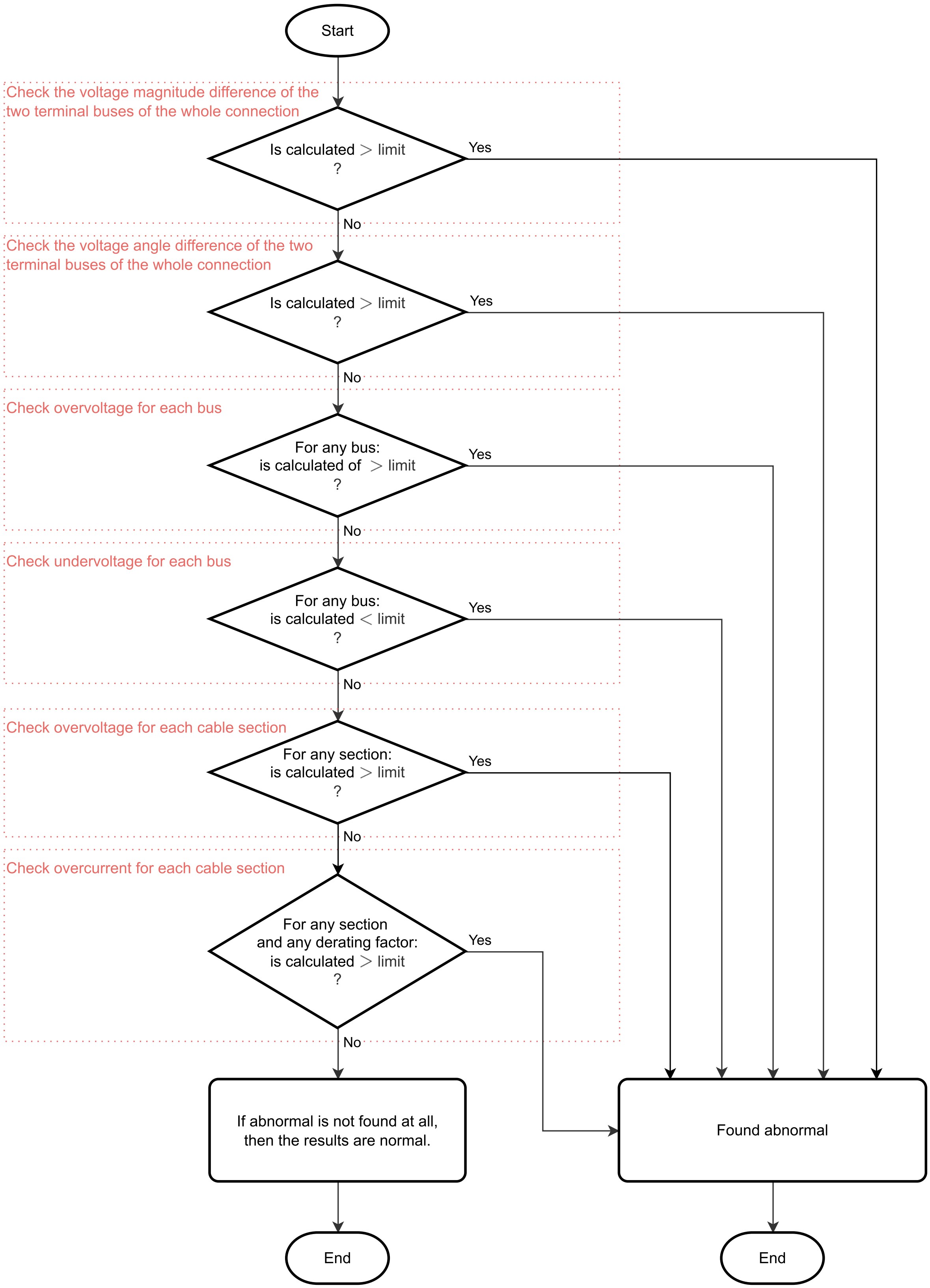

Figure 27: Logic flow of checking operational criteria.

4. Transfer Capacity Study

Transfer capacity study provides high-level evaluation of power transporting capability of a cable genre. In short, it calculates the maximum power that a cable genre can transfer without breaking any operational limits at different cable lengths.

4.1. Business Challenge

Suppose there is a need to transport some power over some distance, the actual power and/or the distance is uncertain but within some range. This transfer capacity study can quickly exclude those cable genres whose capability is below expectation. And the remaining cable genres can then be used for further detailed studies.

4.2. Study Scope

The study allows two kinds of connections:

- Only one cable section without mid-point reactive power compensation. Fig. 28 shows an example of one cable section with two shunts.
- Two identical cable sections with mid-point reactive power compensation. Fig. 29 shows an example of two cable sections with three shunts.

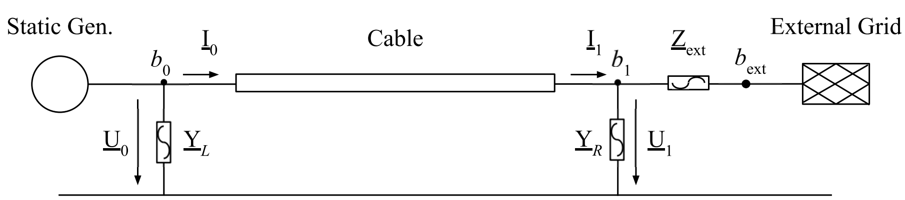

Figure 28: Cable connection with L-R reactive power compensation.

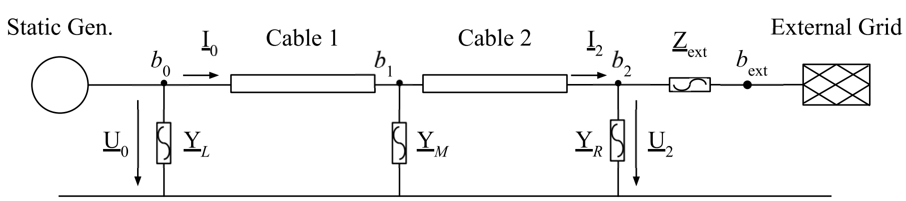

Figure 29: Cable connection with L-M-R reactive power compensation.

4.2.1. User to Specify

- Cable genres.
  - Rated voltage, in [kV].
  - Rated current, in [A].
  - Conductor AC Resistance at $90\,^{\circ}\mathrm{C}$, in [Ω/km].
  - Inductance, in [mH/km].

  - Capacitance, in [μF/km].
- User defined derating factors, which are caused by ambient temperature and thermal resistivity, respectively. In addition, user can choose a reference ambient temperature and a reference thermal resistivity.
- User defined points. Each point is defined by a length of cable connection and an active power of the static generator.
- Study choices: `Ranged Length` or `Heatmap`. Note that the user defined points mentioned above are optional for `Ranged Length` but mandatory for `Heatmap`. Because, for `Ranged Length` choice, they are plotted in addition to the curve of length vs max-power of cable genres so that user can easily see whether a curve is below or above their expected points. While for `Heatmap` choice, they provide the lengths at each of which the max-power of a cable genre is to be found.
- Frequency: 50 Hz or 60 Hz.
- External Grid:
  - Voltage magnitude in [p.u.].
  - Voltage phase angle in [degree].
  - R/X ratio of the short-circuit impedance.
  - Short-circuit power in [MVA].
- Static Generator
  - The power factor, which is between 0 and 1.
  - The mode, which can be `overexcited` or `underexcited`.
- Shunt
  - The reactive power compensation scheme. It allows 0, 1, 2, or 3 shunts, at 3 possible locations, left, mid, and right. Thus there are in total 8 different choices: ''No'', ''L'', ''M'', ''R'', ''L-M'', ''L-R'', ''M-R'', ''L-M-R''. Note that a shunt can only be connected to a bus, so the mid-point shunt should be connected to a bus between two neighbouring cable sections.
  - The split of the each shunt. The sum of the split of all shunts is always 1. Take scheme ''L-M-R'' for example, if the split of the left, middle, and right shunt is respectively 0.3, 0.4, 0.3, it means that the left shunt contributes 30 % of the total compensation. Likewise, the middle shunt contributes 40 %, and the right shunt contributes 30 %.
  - The R/X-ratio of the impedance of each shunt.
  - The total compensation ratio. It describes how much of the cable reactive power should be compensated. For example, 0.8 means 80 % of the cable reactive power.
- Operational limits. See section 3.2.5. for details.

For detailed information about components modelling, see Appendix 1..

4.2.2. Logic Flow

A high level logic flow of the `analyse` method in `Transfer Capacity Study` is shown in Fig. 30. Note that Unagi prepares batches for the loop process just for parallel computing. Because an iteration based on a specific cable genre, derating factor, and a length is an independent process. Moreover, in each batch, the shorter is checked first. This means that if at a certain length, the cable is not able not transfer almost any active power, then the cable should not checked used with even greater length. At this stage, the program will stop increasing the cable length for the on-going batch, and start to check a new batch.

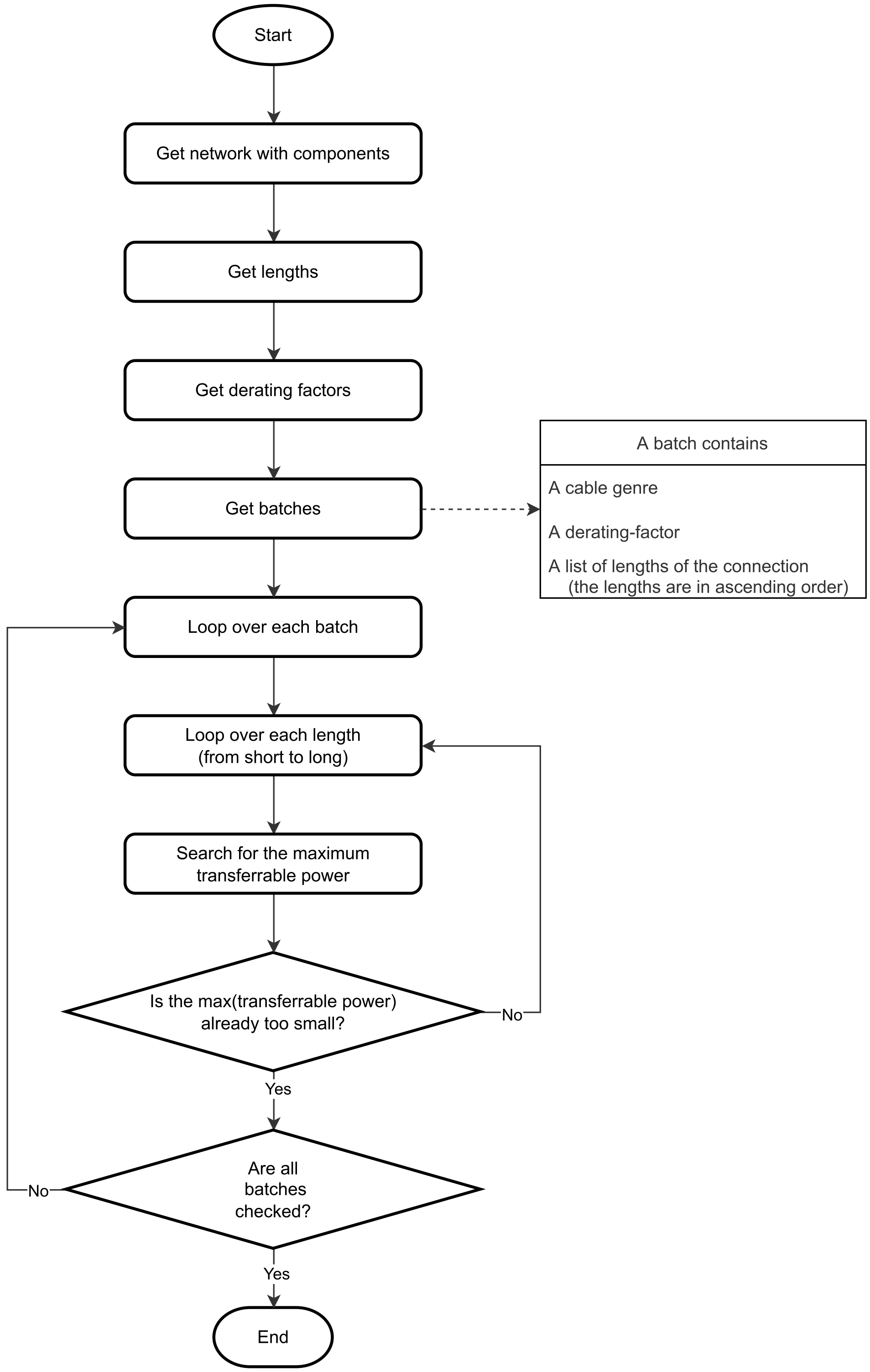

Figure 30: Logic flow of the `analyse` method in `Transfer Capacity Study`.

Set Lengths

The study initializes a set of lengths and then finds the maximum transferable power at each length. The 2 different study choices use different ways to determine the lengths.

- `Ranged Length` - It specifies the variation of cable length with the unit [km], in terms of start, stop, and step. For example, the default setting is $\text{start} = 3$, $\text{stop} = 300$, and $\text{step} = 3$. This means that the cable length begins with 3 km, each iteration the length is increased by 3 km, the maximum length to be checked is 300 km.
- `Heatmap` - It uses the user-defined points as reference. At user-defined length, the user-defined power is used as 100 %. Unagi calculates the maximum transferable power at that length and compares it with the user-defined power. The results are categorized into 3 different thresholds: low, mid, and high. The values of those thresholds, which are in percentage, should be provided by user. For example, if user defines a point of (20 [km], 400 [MW]) and the low threshold as 80 %. If the calculated maximum transferable power of a cable genre at the length of 20 [km] is 300 [MW]. Because $300\,[\mathrm{MW}] < 80\,\% \times 400\,[\mathrm{MW}] = 320\,[\mathrm{MW}]$. Then, it is clear that the cable genre cannot transfer 80 % of the expected power at the 20 [km].

Set Derating Factors

The ampacity of a cable genre varies according to different operational conditions. The actual mechanism of the influence are sophisticated and requires much detailed and accurate input data. For a quick assessment of the transfer capacity of cable genres, Unagi abstract the complicated process to a pre-defined (by user) derating factor as the net effect.

User should provide derating factor caused by different ambient temperature and thermal resistivity, respectively. Each variation of ambient temperature and thermal resistivity should have a derating factor on its own. And Unagi will use the combined derating factor calculated by multiplying a derating factor of ambient temperature with a derating factor of thermal resistivity. Suppose, user provides one derating factor of thermal resistivity: 0.7 at 1.2 $[\mathrm{Km/W}]$. It means that, if the environmental thermal resistivity is 1.2 $[\mathrm{Km/W}]$, then the cable genre can only conduct 70 % of its rated current. In addition, suppose the user gives another derating factor of thermal resistivity: 0.6 at 1.5 $[\mathrm{Km/W}]$, and two derating factors of ambient temperature: 0.9 at 15 $^\circ\mathrm{C}$ and 0.8 at 30 $^\circ\mathrm{C}$, then Unagi will calculate iteratively the maximum transferable power for, in total, 4 derating factors:

$$\begin{aligned} 0.7 \times 0.9 &= 0.63 \\ 0.7 \times 0.8 &= 0.56 \\ 0.6 \times 0.9 &= 0.54 \\ 0.6 \times 0.8 &= 0.48 \end{aligned}$$

Finding Maximum Transferable Power

A high-level logic flow of finding the maximum transferable power is Fig. 31.

Initially, the candidate for the maximum transferable power is set as 0, and the minimum boundary value as 0, and the maximum boundary value as 200 % of cable derated power, which equals to the rated current multiplied by a derating factor. Because, being operated at voltage near rated voltage, the cable cannot transfer 200 % of its derated power without having over-current issue.

Then, the mean value of the two boundaries are set as the trial value, which is used as the active power of the static generator. If the this trial value can be successfully transferred, then the current trial value is set as the candidate and a new higher trial value should be checked. Otherwise, a new less trial value should be checked. The increase of the trial value is achieved by letting the current trial value be the new minimum boundary value. On the contrary, the decease of the current trial value is achieved by letting the current trial value be the new maximum boundary value. However, if the current trial value is already very close to the current boundary, then there is no need for a new trial any more. The limit for checking $(\mathrm{trial\,value} - \mathrm{min.\,boundary})$ and $(\mathrm{max.\,boundary} - \mathrm{trial\,value})$ is set as 0.1 % of cable derated power. The reason is that the trial value is always between the two boundaries. And the algorithm will naturally converge to a value, since the gap between the two boundaries keeps decreasing as the iteration continues. Therefore, when the change is too small, it is sure that the next changing must be even smaller, thus it is not necessary to keep iterating.

Note that the operational criteria are described in section 3.2.5..

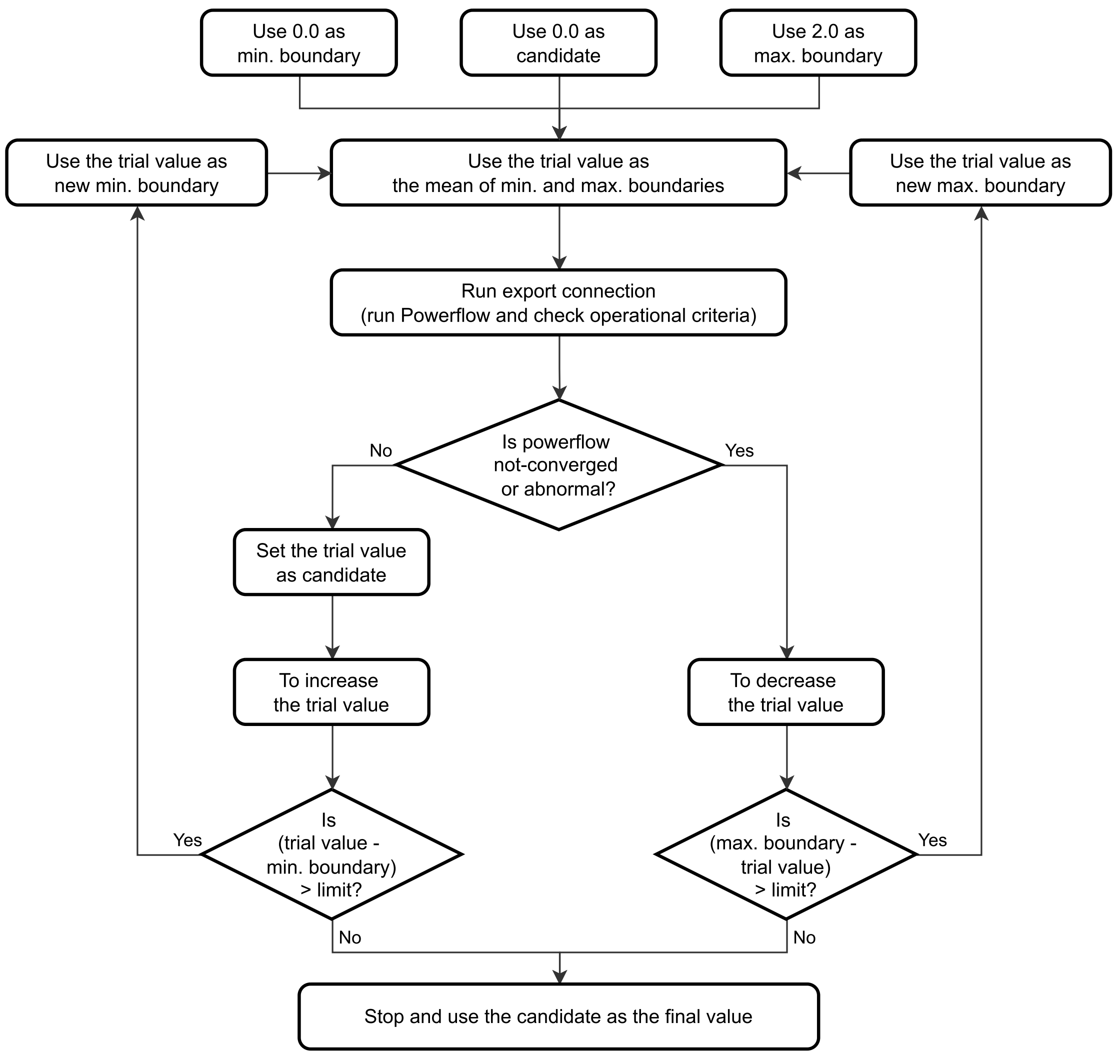

Figure 31: Logic flow of finding the maximum transferable active power.

5. Cable Loss Study

`Cable Loss Study` calculates the power losses in different parts of a cable at per-unit length with specific operational conditions. Unagi implements two different approaches: `IEC` and `Southampton`. They requires different input parameters of a cable genre.

5.1. Business Challenge

`Cable Loss Study` can be used a standalone study to compare different cable genres using the same operational conditions to found the one with the least loss. Or it can be used by other studies which needs cable loss for further calculations. For example, `Cable Rating Study` and `Cable Temperature Study`.

5.2. Study Scope

This study considers a cable section with unit length (1 [m]), no other network components are needed, since the load of cable is directly provided by user, not obtained from a powerflow calculation.

5.2.1. User to Specify

For either approach `IEC` or `Southampton`, these are common input:

- Frequency, in [Hz].
- Load current, in [A].
- Conductor Temperature, in [$^{\circ}\mathrm{C}$].
- Sheath Temperature, in [$^{\circ}\mathrm{C}$].
- Armour Temperature, in [$^{\circ}\mathrm{C}$].

For detailed Physics knowledge and logic-flow of the two approaches, see sections 5.3. and 5.4., respectively.

5.3. IEC Approach

A high level logic flow of the `analyse` method in `Cable Loss IEC Study` is shown in Fig. 32. The Physics knowledge are given by [3], and the key information are described in this section.

5.3.1. Conductor Losses

DC Resistance

$$R' = R_0 \left[1 + \alpha_{20} \left(\theta - 20\right)\right] \tag{6}$$

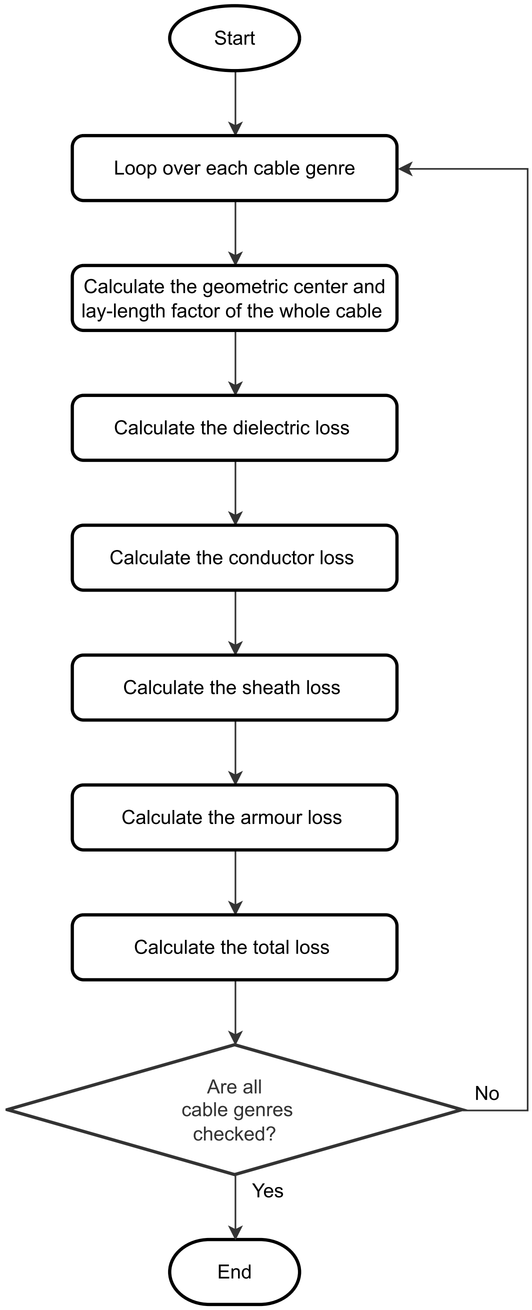

Figure 32: Logic flow of the `analyse` method in `Cable Loss IEC Study`.

AC Resistance

IEC [3] gives two cases to calculate AC resistance from DC resistance of the conductor.

1. No pipe-type cables (see section 2.1 in [3]).
2. Pipe-type cables (see section 2.1.5 in [3]).

Here only case 1 is used.

$$R = R' \left[1 + y_s + y_p\right] \tag{7}$$

Note that CIGRE B1.56 recommends a change in this equation. But it is still not published yet.

Skin Effect Factor y_s See section 2.1.2 in [3].

$$\begin{cases} \text{if } 0 < x_s \le 2.8, \quad y_s = \frac{x_s^4}{192+0.8x_s^4} \\ \text{if } 2.8 < x_s \le 3.8, \quad y_s = -0.136 - 0.0177x_s + 0.0563x_s^2 \\ \text{if } 3.8 < x_s, \quad y_s = 0.354x_s - 0.733 \end{cases} \tag{8}$$

$$x_s^2 = \frac{8\pi f}{R'}10^{-7}k_s$$

Proximity Effect Factor y_p IEC [3] gives different cases:

1. For two-core cables and for two single-core cables, section 2.1.3 in [3].
2. For three-core cables and for three single-core cables, section 2.1.4 in [3].
    (a) For circular conductor cables.
    (b) For shaped conductor cables.

In Unagi, only the case 2-(a) (three-core cables and for three single-core cables with circular conductor) is used.

$$y_p = \frac{x_p^4}{192 + 0.8x_p^4}\left(\frac{d_c}{s}\right)^2\left[0.312\left(\frac{d_c}{s}\right)^2 + \frac{1.18}{\frac{x_p^4}{192+0.8x_p^4} + 0.27}\right] \tag{9}$$

where,

$$x_p^2 = \frac{8\pi f}{R'}10^{-7}k_p$$

d_c is the diameter of conductor;
s is the distance between conductor axes.

This formula is accurate provided $x_p \le 2.8$.

5.3.2. Dielectric Losses

See section 2.2 in [3].

$$W_\mathrm{d} = \omega C U_0^2 \tan\delta \qquad (\mathrm{W/m}) \tag{10}$$

where,

$\omega = 2\pi f$;
C is the capacitance per unit length (F/m);
U_0 is the voltage to earth (V);
$\tan\delta$ is the loss factor of the insulation.

5.3.3. Loss Factor for Sheath

See section 2.3 in [3].

$$\lambda_1 = \lambda_1' + \lambda_1'' \tag{11}$$

where,

λ_1 is the loss factor for sheath;
λ_1' is the loss factor caused by circulating currents;

λ_1'' is the loss factor caused by eddy currents.

The sheath resistance, R_s in (Ω/m), at a given sheath temperature, θ_sc in (°C), can be determined by

$$R_\mathrm{s} = R_\mathrm{s0}\left[1 + \alpha_{20}\left(\theta_\mathrm{sc} - 20\right)\right] \qquad (\Omega/\mathrm{m}) \tag{12}$$

where,

α_{20} is the constant mass temperature coefficient at 20 °C per kelvin.
θ_{20} is the operating temperature of armour (°C).
R_s0 is the resistance of the cable sheath at 20 °C, (Ω/m).

Note that IEC [3] does not specify if R_s0 is AC or DC resistance. It should be AC resistance. However, since sheath is too thin, AC resistance can be considered as equal to DC resistance. In addition, IEC [3] does not provide formulae to calculate R_s0. It can be calculated by

$$R_\mathrm{s0} = R_\mathrm{s0,AC} = R_\mathrm{s0,DC} = \frac{\rho_\mathrm{s0}}{\pi\left[\left(\frac{\bar{d}_\mathrm{s}+t_\mathrm{s}}{2}\right)^2 - \left(\frac{\bar{d}_\mathrm{s}-t_\mathrm{s}}{2}\right)^2\right]} f_\mathrm{lay,core} \qquad (\Omega/\mathrm{m}) \tag{13}$$

where,

ρ_s0 is the resistivity of the sheath (Ω/m);
ρ_s0 is the resistivity of the sheath (Ω/m);
$\bar{d}_\mathrm{s}$ is the mean diameter of the sheath (m);
t_s is the thickness of the sheath (m);
$f_\mathrm{lay,core}$ is the lay-length factor of the core.

To calculate loss factor caused by circulating currents and eddy currents, IEC [3] gives formulae for 10 different cases:

1. Two single-core cables, and three single-core cables (in trefoil formation), sheaths bonded at both ends of an electrical section.
2. Three single-core cables in flat formation, with regular transposition, sheaths bonded at oth ends of an electrical section.
3. Three single-core cables in flat formation, without transposition, sheaths bonded at both ends of an electrical section.
4. Variation of spacing of single-core cables between sheath bonding points.
5. Single-core cables, with sheaths bonded at a single point or cross-bonded.
6. Two-core unarmoured cables with common sheath.
7. Three-core unarmoured cables wiht common sheath.
8. Two-core and three-core cables with steel tape armour.
9. Cables with each core in a separate lead sheath (SL type) and armoured.
10. Pipe-type cables.

In Unagi, only case 9 is used, see section 2.3.10 in [3].

Circulating Current Losses

$$\lambda_1' = \frac{R_\mathrm{s}}{R}\frac{1.5}{1 + \left(\frac{R_\mathrm{s}}{X}\right)^2} \tag{14}$$

where,

R is the AC resistance per unit length of the cable conductor;
R_{s} is the AC resistance per unit length of the cable sheath;
X is the reactance per unit length of sheath;

$$X = 2\omega 10^{-7} \ln \frac{2s}{d} \qquad (\Omega/\mathrm{m})$$

ω is the angular frequency;
s is the distance between conductor axes (m);
d is the mean diameter of the sheath (m).

Eddy Current Losses

$$\lambda_1'' = 0 \tag{15}$$

5.3.4. Loss Factor for Armour

See section 2.4 in IEC [3]. The armour resistance, R_{A} in (Ω/m), at a given armour temperature, θ_{ar} in (°C), can be determined by

$$R_{\mathrm{A}} = R_{\mathrm{A0}} \left[1 + \alpha_{20} \left(\theta_{\mathrm{ar}} - 20\right)\right] \qquad (\Omega/\mathrm{m}) \tag{16}$$

where:

α_{20} is the constant mass temperature coefficient at 20 °C per kelvin.
θ_{ar} is the operating temperature of armour (°C).
R_{A0} is the resistance of the cable armour at 20 °C, (Ω/m).

Note that IEC [3] does not specify if R_{A0} is AC or DC resistance. It should be AC resistance. However, IEC [3] provides an approach to convert the DC resistance of armour to AC resistance: *The a.c. resistance of armour wire varies from about 1.2 times the d.c. resistance of 2 mm diameter wires up to 1.4 times the d.c. resistance for 5 mm wires. The resistance does not critically affect the final result.* Therefore, the relationship between the armour AC resistance and DC resistance can be defined with the help of armour wire diameter $d_{\mathrm{A,W}}$ in (m), and factor, f_{ac}.

$$R_{\mathrm{A0}} = R_{\mathrm{A0,AC}} = f_{\mathrm{ac}} R_{\mathrm{A0,DC}} \tag{17}$$

where

$$f_{\mathrm{ac}} = 1.2 + \frac{1.4 - 1.2}{0.005 - 0.002} \times \left(d_{\mathrm{A,W}} - 0.002\right) \tag{18}$$

To calculate the loss factor, IEC [3] gives formulae for different cases:

1. Non-magnetic armour or reinforcement.
2. Magnetic armour or reinforcement.
   (a) Single-core lead-sheathed cables - steel wire armour, bonded to sheath at both ends.
   (b) Two-core cables - steel wire armour.
   (c) Three-core cables - steel wire armour.
      i. Round conductor cable
      ii. Sector conductor cable
   (d) Three-core cables - steel tape armour or reinforcement.
   (e) SL type cables.

3. Steel pipes.

In this software, the used formula is derived from case 2-(c)-i (section 2.4.2.3.1 in [3]) with a correction factor from case 2-(e) (section 2.4.2.5 [3]).

$$\lambda_2 = 1.23 \frac{R_\mathrm{A}}{R} \left(\frac{2c}{d_\mathrm{A}} \right)^2 \frac{1}{\left(\frac{2.77 R_\mathrm{A} 10^6}{\omega} \right)^2 + 1} \left(1 - \frac{R}{R_\mathrm{s}} \lambda_1' \right) \tag{19}$$

where,

R is the AC resistance per unit length of the cable conductor (Ω/m);
R_A is the AC resistance per unit length of the cable armour (Ω/m);
R_s is the AC resistance per unit length of the cable sheath (Ω/m);
λ_1' is the loss factor for the sheath caused by circulating currents, see section 5.3.3.;
ω is the angular frequency;
d_A is the mean diameter of armour (m);
c is the distance between the axis of a conductor and the cable centre (m).

Note that in section 2.3.10 in [3], ''SL sheath'' stands for ''separate lead sheath''. But this equation can be generalised to model ''separate sheath'', even if the material is not lead but aluminium or copper.

5.3.5. Calculate DC resistance of Sheath

In this software, the following different types of sheath are considered:

1. Solid sheath
2. Wire sheath
   (a) without foil
   (b) with foil
3. Tape sheath
   (a) tapes are rounded on the cable without overlap
   (b) tapes are rounded on the cable with overlap
   (c) tapes are longitudinally folded on the cable

5.3.6. Calculate DC resistance of Armour

In this software, armour with only 1 layer of wires is considered.

The armour wires are actually longer thant the cable, since the wires are rounded on the cable, see Fig. 33. The DC resistance is a value of per unit cable length, not per unit armour wire length.

Therefore, the formulae to calculate DC resistance of armour is

$$R_\mathrm{A0,DC} = f_\mathrm{lay,armour} \cdot \frac{\rho_\mathrm{A}}{N\pi (d_\mathrm{A,wire}/2)^2}$$

$$f_\mathrm{lay,armour} = \frac{\text{armour actual length}}{\text{armour lay-length}} = \frac{\sqrt{(\pi d_a)^2 + p_\mathrm{a}^2}}{p_\mathrm{a}}$$

where

$f_\mathrm{lay,armour}$ is the lay-length factor of the armour wires.

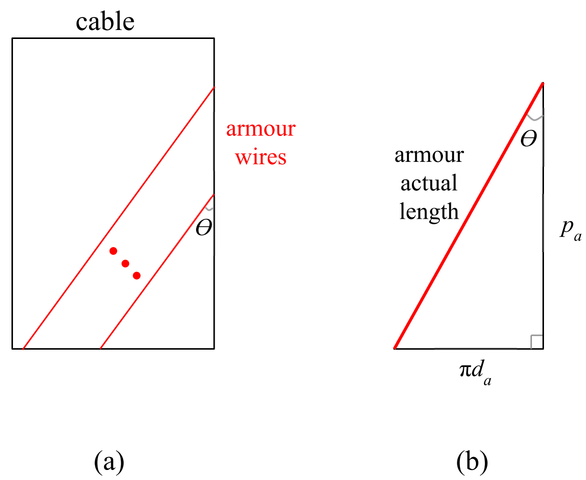

Figure 33: Illustration of armour lay-length factor calculation.

p_{a} is the lay-length of the armour wires (m);
d_{a} is the mean diameter of the armour layer (m);
ρ_{A} is the resistivity of the armour wires (Ωm);
$d_{\mathrm{A,wire}}$ is the diameter of the armour wires (m);
N is the number of the armour wires (m);

5.4. Southampton Approach

A high level logic flow of the `analyse` method in `Cable Loss Southampton Study` is shown in Fig. 34. The alogrithm is derived from on the xlsx-file based tool from Shell, [6], and the key information are described in this section.

5.4.1. User Sheet

Calculate Relative Permeability of Armour

This refers to cells P27, P28, P38, and P39. These are user-input to specify the complex value of relative permeability of armour (layer 1 and layer 2). However, cells R27 and R28 give calculated complex value of relative permeability of layer 1 armour. And they are marked as ''If these values differ from the real and imaginary values in the green cells, then enter these numbers into the green cells''. This means, user can enter an initial values for cells P27 and P28, then the xlsx-tool calculates values for them, if the calculated are different than the initial, then replace the initial by the calculated. Again, the xlsx-tool will calculate another values based on the calculated in the first round. If the calculated values in the second round are different than the calculated in the first round, enter the calculated values in the second round into cells P27 and P28. Repeat this process until the entered values almost equal to the corresponding calculated values, i.e. cells P27 and P28 are almost equal to cells R27 and R28. Nevertheless, the xlsx-tool does not calculate for cells P38 and P39.

Thus, the Python tool (unagi) implements this algorithm to auotmate the whole process. The user can enter arbitrary initial values for all the armour layers. Then user can choose to let the pro-

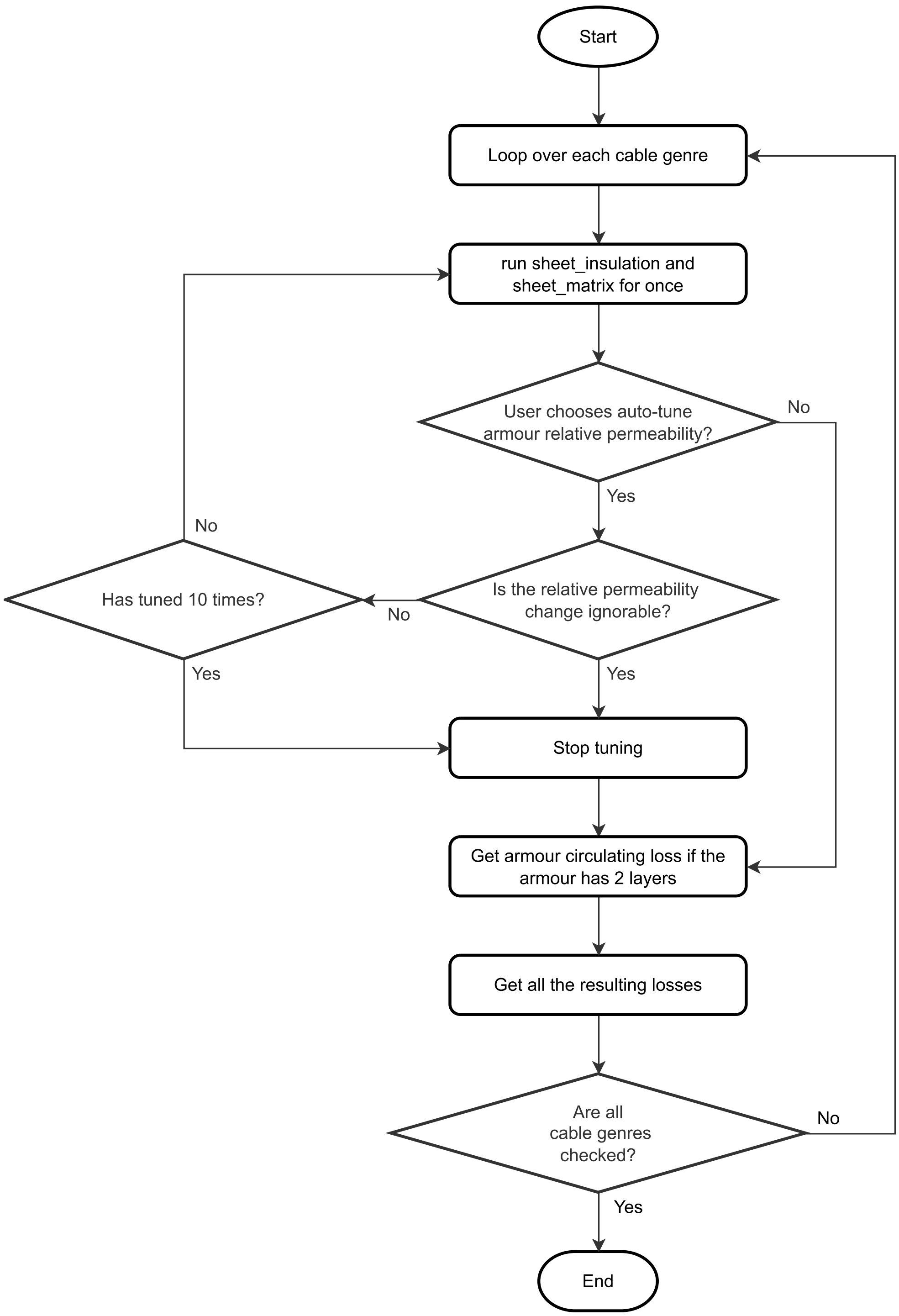

Figure 34: Logic flow of the `analyse` method in `Cable Loss Southampton Study`.

gram calculate cable loss with or without adjusting the entered values. To automatically adjust the values of armour relative permeability, Unagi calculates the corresponding values and compare them with initial ones at integer level (decimal points are rounded up to integers), if they are different then use the integer values of the calculated ones. And repeat the process, until the calculated values in the latest 2 rounds are the same. However, due to the choice of initial values, it is possible that they are never the same. To avoid dead loop in the process, the program only repeat the process for 10 rounds, which is usually sufficient. If no match after 10 rounds, the program gives a warning message and the calculated values at the 10th round. User can use these values and run the program again.

Calculate Loss Factor for Sheath (λ_1) and Armour (λ_2)

Sheath loss factor (λ_1) is the ratio between sheath loss (per core) to conductor loss (per core). Armour loss factor (λ_2) is the ratio between armour loss to total conductor loss (all cores). These 2 loss factors are useful for calculating cable temperature by the temperature solver described in section 7.3.. The cable loss IEC approach provides formulas to calculate them, while the cable loss Southampton approach (this excel-tool) does not. Thus, unagi program provides the formulas for it.

$$\lambda_1 = \frac{P_\mathrm{s}}{P_\mathrm{c}}$$
$$\lambda_2 = \frac{P_\mathrm{a}}{NP_\mathrm{c}}$$

where

N is the number of cores. Thus for a 3-core cable, $N = 3$.
P_c is the cable conductor loss per core, $\mathrm{W/m}$.
P_s is the cable sheath loss per core, $\mathrm{W/m}$.
P_a is the cable armour loss, $\mathrm{W/m}$.

5.4.2. Sheath Sheet

Calculate Z_0 for Solid Sheath

Note the xlsx-tool allows only lead for solid sheath, see cells B3 and B5 in Sheath sheet in the xlsx-tool.

Calculate Z_0 for Tape Sheath

This refers to Cell C18 in Sheet Sheath in the xlsx-tool. The xlsx-tool calculates the z_0 using equation (8) in section 3.3.1 in [7], with no explanation. I have tried to derive its Physics principle for its real part, which is illustrated by Fig. 35. First, the tape is not placed in parallel with the cable, but with a certain angle β, Fig. 35-a. Note that this angle β is the same as the angle β in Fig. 1 in section 3.3.1 in [7]. The tape itself is a long rectangluar shape with width w and thickness t, Fig. 35-b. To calculate the real part of $z0$ (i.e. resistance) per unit length along the cable direction, we could visually unwrap the tape and put it on a flat surface, with the help of a right triangle, Fig. 35-c.

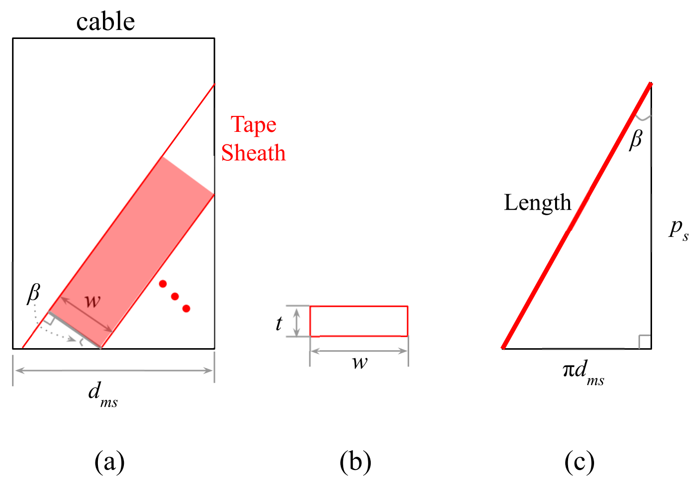

Figure 35: Illustration of z_0 calculation.

As the tape makes exactly one round on the cable, the length along the cable is the lay-length (p_s), so the actual length of the tape is

$$\text{Length} = \sqrt{(\pi d_{ms})^2 + p_s^2}$$

where

d_{ms} is the mean diameter of the tape layer;
p_s is lay length of the tape.

Practically, the width of a tape is much less than its actual length, so the shape of the tape is assumed to be a perfect rectangle, indicated by the shaded-red area in Fig. 35-a, the white triangle on its two side are ignored. Thus, the cross-sectional area (S) is

$$S = w \times t$$

where w and t are respectively the width and thickness of the tape in its cross-sectional view, Fig. 35-b.

Therefore, the equivalent resistance of the tape per unit length in the direction of lay-length is

$$R_0 = \frac{\rho_s}{n} \frac{\text{Length}}{S} \frac{1}{p_s} = \frac{\rho_s}{n\, p_s} \frac{\sqrt{(\pi d_{ms})^2 + p_s^2}}{w \times t} \tag{20}$$

where

ρ_s is the resistivity of the tape material;
n is the number of tape in parallel, indicated by the 3 dots in Fig. 35-a.

Note the xlsx-tool allows only copper for tape sheath, see cells B3 and B5 in Sheath sheet in the xlsx-tool.

Calculate $Z_{1,2,3}$ for Tape Sheath

The subscripts 1, 2, 3 of the impedances are the number of pole pairs. These impedances are calculated based on the equations (10-12) in section 3.3.1 in [7]. Note:

- There is a typo in equation (10) there, $E_0(w/\sin(\beta)$. The left parenthesis, (, after E_0 should be removed.
- The equation (10) there only provides the formula to calculate the real part of the impedances $Z_{1,2,3}$. Their imaginary parts are all zero.

Calculate Z_0 for Wire Sheath

This refers to Cell J18 in Sheet Sheath in the xlsx-tool. The xlsx-tool calculates the z_0 with no explanation, even though section 3.3.2 in [7] provides incomplete formulae for its imaginary part. I have tried to derive its Physics principle for its real part, which is illustrated by Fig. 36.

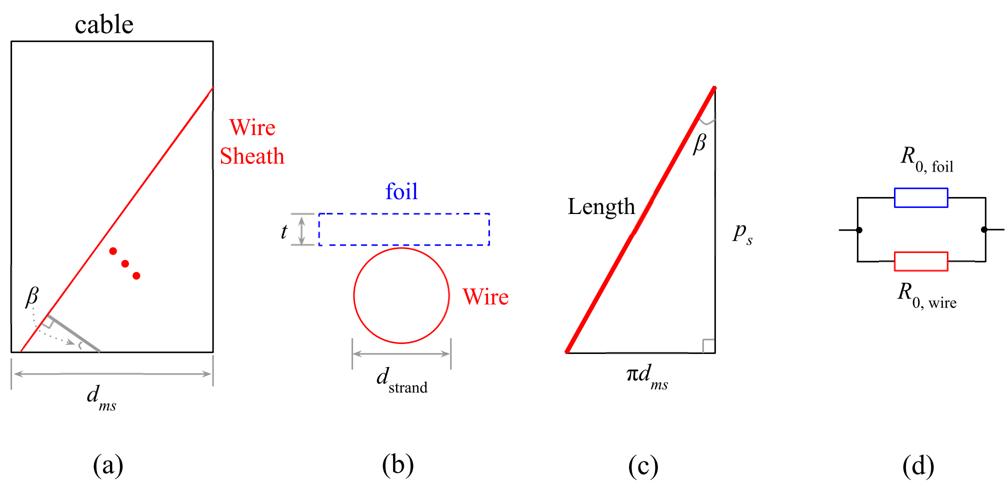

Figure 36: Illustration of z_0 calculation.

First, for wire-type sheath, the xlsx-tool always makes the sheath composed of wires and foil. The wires are not placed in parallel with the cable, but with a certain angle β, Fig. 36-a. A wire itself is a long cylinder shape with diameter d_{strand}, Fig. 36-b. To calculate the resistance of wires per unit length along the cable direction, we could visually unwrap a wire and put it on a flat surface, with the help of a right triangle, Fig. 36-c. The foil is a thin solid layer that covers the wires. Thus the total resistance of the sheath is the equivalent resistance to parallel connected resistances of wire and foil, see Fig. 36-d.

As the wire makes exactly one round on the cable, the length along the cable is the lay-length (p_s), so the actual length of the wire is

$$\text{Length} = \sqrt{(\pi d_{ms})^2 + p_s^2}$$

where

d_{ms} is the mean diameter of the wire layer;
p_s is lay length of the wire.

According to Fig. 36-b, the cross-sectional area (S) is

$$S = \pi \frac{d_{\text{strand}}^2}{4}$$

Therefore, the equivalent resistance of the tape per unit length in the direction of lay-length is

$$R_{0,\text{wire}} = \frac{\rho_s}{n}\frac{\text{Length}}{S}\frac{1}{p_s} = \frac{\rho_s}{n\,p_s}\frac{4\sqrt{(\pi d_{ms})^2 + p_s^2}}{\pi d_{\text{strand}}^2} \tag{21}$$

where

ρ_s is the resistivity of the wire material.
n is the number of wires in parallel, indicated by the 3 dots in Fig. 36-a.

Note the xlsx-tool allows only copper for wire sheath and aluminum for foil, see cells B3, B5, J5, J6, and J18 in Sheath sheet in the xlsx-tool.

The foil is a thin layer just on top of the wires. Thus its resistance can be calculated by

$$R_{0,\text{foil}} = \pi d_f t \tag{22}$$

where

d_f is the foil mean diameter;
t is the foil thickness.

Thus, the total resistance of the sheath R_0 is

$$R_0 = \frac{R_{0,\text{wire}} R_{0,\text{foil}}}{R_{0,\text{wire}} + R_{0,\text{foil}}} \tag{23}$$

The formulae for the imaginary part of $Z_0 = R_0 + jX_0$ in the xlsx-tool can be re-written in a more readable way, by the help of formulae provided by section 3.3.2 in [7].

$$L_0 = \frac{\pi d_m^2}{4}\frac{\mu_0}{p_s^2}\left(\frac{R_{0,\text{foil}}}{R_{0,\text{wire}} + R_{0,\text{foil}}}\right)^2 + \frac{\mu_0}{2\pi n}\left(0.25 - \ln\frac{n d_{\text{strand}}}{d_m}\right) \tag{24}$$

$$X_0 = 2\pi f L_0 \tag{25}$$

Calculate $Z_{1,2,3}$ for Wire Sheath

For wire sheath, Z_1, Z_2, and Z_3 are all zero. See cells I19:I21 and C25:C27 in sheet Sheath in the xlsx-tool.

5.4.3. Armour_Mu_1 Sheet

The transverse permeability uses the equation from section 2.1 in [8].

$$\mu_t = \mu_0\left[(0.2 + 0.8\mu_{\text{l,r,real}}) + j0.8\mu_{\text{l,r,imag}}\right] \tag{26}$$

where,

μ_t is the transverse permeability;
$\mu_{\text{l,r,real}}$ and $\mu_{\text{l,r,imag}}$ is the real part and imaginary part of the relative longitudinal permeability, respectively.

Calculate s_f

The xlsx-tool calculates s_f, but gives no explanation of what s_f is about. Reference [4] only gives a simplified drawing of s_f, but the drawing does not directly indicate the formula to calculate s_f for an actual cable. Without explanation, the tool is difficult to validate. Based on the formula used in the xlsx-tool, I have tried to derive the Physics principle of the formula, which is illustrated by Fig. 37. I think s_f is the distance between the center of two neighboring armour wires. Suppose wire k and wire $k+1$. They are in parallel, and have an angle θ with cable cross-section. The formula to calculate s_f is

$$s_f = s_{f,1} \cdot \cos\theta \tag{27}$$

where

$s_{f,1}$ is the distance between the center of two wires on the surface of a cable cross-section. So it can be calculated using the circumference of the cable (with the mean diameter of the armour layer) (πd_a) divided by the number of armour wires (n_f).

$$s_{f,1} = \frac{\pi d_a}{n_f} \tag{28}$$

$\cos\theta$ can be calculated by the right triangle formed by the absolute value of the lay-length of the armour $|p_a|$ and the circumference of the cable (with the mean diameter of the armour layer) (πd_a).

$$\cos\theta = \frac{|p_a|}{\sqrt{(\pi d_a)^2 + |p_a|^2}} \tag{29}$$

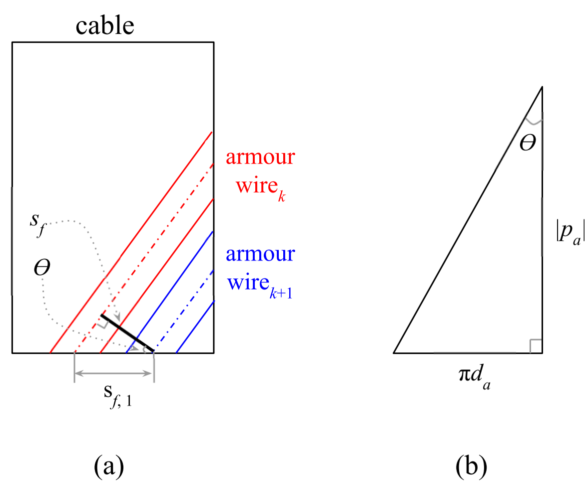

Figure 37: Illustration of s_f calculation.

Calculate cells Q91 and R91

The default precision, i.e. the number of digits after decimal point, of float numbers is 14 in Microsoft Excel, but is 15 in numpy in Python. Usually this difference is not an issue. But it is a problem for armour with 1 layer, 2-out-of-3 spacing. If the xlsx-tool and Python tool use the same values shown in Table 1,

Table 1: Example values for cells R66:Q84 in the xlsx-tool.

Column Q66:Q84	Column R66:R84
9.99697565260235000E-01	1.46133982992000000E-02
1.20388799908033000E+00	2.41750023054120000E-02
4.14718054796296000E+03	9.27518592328012000E+01
3.27428020853277000E+10	8.56431280100037000E+08
3.40918284216364000E+17	1.02248035330518000E+16
3.57337646831969000E+24	1.20883938804503000E+23
3.74618647863225000E+31	1.41108248638489000E+30
3.92732067998968000E+38	1.63008943598413000E+37
4.11715322092310000E+45	1.86699932163968000E+44
4.31609805978382000E+52	2.12302978601061000E+51
4.52458946336622000E+59	2.39947446575089000E+58
4.74308226527787000E+66	2.69770720749854000E+65
4.97205280861438000E+73	3.01918677474961000E+72
5.21199995437299000E+80	3.36546183074084000E+79
5.46344613748730000E+87	3.73817620389510000E+86
5.72693847199012000E+94	4.13907445111374000E+93
6.00304990754496000E+101	4.57000773532530000E+100
6.29238043971084000E+108	5.03294003459714000E+107
6.59555837641327000E+115	5.52995470105150000E+114

then the resulting value for cell Q91 is:

$$
\begin{aligned}
\text{Xlsx-tool} \qquad \mathrm{Q91} &= -5.529954197757540\mathrm{E}+114 \quad + \quad 5.529954197757540\mathrm{E}+114 \\
&= 0 \\
\text{Python} \qquad \mathrm{Q91} &= -5.529954197757542\mathrm{E}+114 \quad + \quad 5.529954197757541\mathrm{E}+114 \\
&= -1.093625362391506\mathrm{E}+99
\end{aligned}
$$

There are extremely large difference in the value for cell Q91, even though the difference is just the 15th digit in the float after decimal point (0 in the xlsx-tool but 2 in Python). This means if Microsoft Excel increases its precision to 15 or even higher, it may generate unwanted results.

To make Python generate the same results as the xlsx-tool, the precision of numpy in Python is restricted by the following code.

```
k_vector = k_vector.astype(np.clongdouble)
...
qr91 = np.dot(signs, k_vector).astype(np.cdouble)\
    + qr104.astype(np.cdouble)  # refers to cells Q91:R91

```

5.4.4. Questions in the xlsx-Tool

The results from the xlsx-tool cannot be validated because of the following issues. Even if the results can be very close to some measurements, it can just indicate that the impact of the issues are small, at least to those scenarios defined by the measurements.

Cross Sheet

Conductor, sheath, and armour all have the parameter lay-length, see cells G20, K27, K33, P20, and P35 in sheet User in the xlsx-tool. These values are used in other sheet, but only the lay-length of armour is taken its absolute value in cell N59 in sheet Armour_Mu_1. It seems like the lay-length can be negative value, but no explanation is found whether the input values in sheet User are allowed to be negative.

Sheet User

1. Cell C23. It is to calculate the capacitance per unit length of cable, in order to calculate dielectric loss of the cable. However, a cable phase-core is not straight but with a certain lay-length defined by the lay-length of the conductor, see cell G20. In other words, the cable phase-core is longer than cable length. Therefore, the calculated capacitance by cell C23 should be multiplied by a factor

   $$\text{factor} = \frac{\text{actual conductor length}}{\text{conductor lay-length}} = \frac{\sqrt{(2\pi\frac{s}{\sqrt{3}})^2 + p_C^2}}{p_C}$$

   where
   s is the conductor spacing;
   p_C is the conductor lay-length.
2. Cell R27 is different from Table 5 in [9].

   $$\begin{aligned} \text{Cell R27}, \quad & 84 + (0.85 * H) \\ \text{Table 5}, \quad & 85 + (0.85 * H) \end{aligned}$$

3. Cell R28 is different from Table 5 in [9].

   $$\begin{aligned} \text{Cell R28}, \quad & -144 - 0.69 * (H - 300) \\ \text{Table 5}, \quad & -144 - 0.69 * H \end{aligned}$$

4. Cell U19, V19, U20, V20, and W24. They are reflection factors and circulating loss when the armour has 2 layers with special form (not round wires). Those values are to be provided by user. However, practically speaking, how can user get those values?
5. Cells R27 and R28 give calculated values for cells P27 and P28, which are the complex value of relative permeability of layer 1 armour. And they are marked as ''If these values differ from the real and imaginary values in the green cells, then enter these numbers into the green cells''. But the xlsx-tool does not calculate for cells P38 and P39. Should the tool also calculate them?
6. Cells U10, P18, and P33. They are for the choice of special (not round) armour wire and armour strand diameter of layer 1 and layer 2, respectively. I think the strand diameter is only meaningful when armour wire is round. So if armour wire is special, then strand diameter can be disabled. But the xlsx-tool still uses strand diameter. For example, if cell U10 is 2, changing P18 will change the resulting cable losses.

7. Cell P15. It is for the temperature of armour. However, this value is not used in the xlsx-tool. If the value in cell P15 is changed, the output cable losses are not changed. The armour loss is calculated based on cells P29 and P40, which are the conductivity of armour layer 1 and 2, respectively. I think making cells P29 and P40 as user input is not meant for the corresponding conductivity at user-given temperature of armour, since user usually does not have those values. One thing to note is that the entered value of both cells in the default version is $7.246\text{E}6\ \text{S/m}$. According to table 1 in IEC [3], the resistivity of steel at 20 $^\circ\text{C}$ is $13.8\text{E}-8\ \Omega\text{m}$, so the conductivity of steel at 20 $^\circ\text{C}$ is $1/(13.8\text{E}-8) \approx 7.246376\text{E}6\ \text{S/m}$. So I believe that the entered values in the default version are based on 20 $^\circ\text{C}$, not based on user-given temperature in cell P15. The Python tool (unagi) automatically calculates the corresponding conductivity at user-given armour temperature, with this equation.

$$\rho_\theta = \rho_{20}\left[1 + \alpha_{20}(\theta - 20)\right] \tag{30}$$

   where

   ρ_{20} and ρ_θ are respectively the resistivity of armour at 20 $^\circ\text{C}$ and user-given temperature θ.
   α_{20} is the temperature coefficient per K at 20 $^\circ\text{C}$.

   Note, ρ_{20} and α_{20} of armour can be found in table 1 in IEC [3].
8. Cell Q41 is supposed to be the unit of resistivity between 2 layers of armour, which should be Ωm. However, it is written as ''W m'', which I think is a mistake. Thus, cell P41 has the same issue of temperature-dependency as cells P29 and P40 mentioned above. Therefore, equation (30) is also applied to automatically adjust the resistivity between armour layers in the Python tool (unagi). The value of ρ_{20} is the resistivity between armour layers at 20 $^\circ\text{C}$.

Sheet Conductor

1. Cell N21, O21, N22, O22 are the real and imaginary part of $I_0(x)$ and $I_1(x)/x$, respectively. They are different from equation (5) in section 3, and equation (1) in section 7, in [7]. In the xlsx tool, Cell N7, N9, N11, N13, N15, N17, N19 should be zero, in order to be the same as equation (1) in section 7 in [7]. The same applies to Cell O8, O10, O12, O14, O16, O18. I would prefer the version in [7], since the equation is sound and can be understood. The relationship of $x^2 = ix_s^2$ can be used for a quick check. In equation (1), there is only even number in the power of x, that means each element is either purely real or purely imaginary. For example, x^2 is purely imaginary, $x^4 = (i)^2 x_s^4 = -x_s^4$ is purely real, $x^6 = (i)^3 x_s^6 = -ix_s^6$ is purely imaginary, etc. But the xlsx-tool version introduces some whole numbers of 1, 2, 3, 4, 5, 6, 7 in the real and imaginary part of some x^n. These whole numbers have no proof, just like magic numbers. However, because these values are multiplied with very small values in the matrix of Cells S3:AH4, the effect of these whole numbers are very small. A further check is that, equation (1) in section 7 is used because xlsx-tool cannot perform bessel function with complex argument. I used Python with Scipy package to calculate $I_0(x)$, it gives the same results if I replace all the magic whole numbers in the xlsx-tool by 0. The investigation can be reproduced by the Python code below.

```
import numpy as np
import scipy.special as ss


w = 2*np.pi*50
```

```
mu = 4*1e-7*np.pi
rho_copper = 1.724e-8
rho_c = 1.02 * rho_copper * (1 + 3.93e-3*(90 - 20))
alpha = np.sqrt(1j * w * mu / rho_c)
r_c = 45.135166684e-3 / 2

x = alpha * r_c
i0 = ss.iv(0, x)

print(i0)  # result is -0.2127649524913902+1.93273495844029j

```

Note that, the value of `rho_copper` is taken from the xlsx-tool, Sheet Conductor, Cell G2. The value of the diameter (`2*r_c`) is taken from the xlsx-tool, Sheet User, Cell G18. The value of `rho_c` is calculated with a factor of 1.02, according to the xlsx-tool, Sheet Conductor, Cell B5.

2. Cell B5. The formula contains a factor of 1.02. The reason why 1.02 is used is not mentioned in the [7, 9]. I suppose it is a correction factor for using solid conductor to represent stranded conductor. This correction factor can be calculated instead of being a constant as 1.02.
3. Cell B21:B24, C21:C24. They are labled as Z_{internal} in xlsx-tool. The equation (6) in section 3.2.2 [7] is the definition of internal impedance.

$$Z_n = \frac{R_{\text{DC}}}{k_p} \frac{\alpha r_c \mathbf{I_n}(\alpha r_c)}{\mathbf{I_{n+1}}(\alpha r_c)} \tag{31}$$

However, $n = 1, 2, 3$ are used in the xlsx-tool, but it is not explained why these value(s) n should take in [7]. It is worth to mention that, this equation is derived by (see equation (6) in [7])

$$Z_n = \frac{j\omega\mu}{2\pi r_c} \frac{\mathbf{I_n}(\alpha r_c)}{\alpha \mathbf{I'_n}(\alpha r_c) - (n/r_c)\mathbf{I_n}(\alpha r_c)} \tag{32}$$

$$\frac{k_p}{R_{\text{DC}}} = \pi r_c^2 \sigma \tag{33}$$

In IEC [3], k_p is defined as the ''factor used in calculating x_p (proximity effect)'', which takes experimental values like 1, 0.8, etc depending on different types of cable. But the xlsx-tool hard-coded k_p as 0.64 with a comment: ''This value will need to be determined based on measured data for many conductors. ''

Sheath Sheet

1. Cell C18. It is supposed to be the AC resistance of the sheath at given temperature for tape sheath. However, practically there are in general 3 different types of tape sheath, see section 5.3.5.. This xlsx-tool calculates only for tapes rounded on cable without overlap.
2. Cell R11. It is supposed to be the mean diameter of the sheath layer for solid sheath. However, I have a question about the used formula. Why is the second formula not used?

$$\text{formula in the xlsx-tool} = \sqrt{\frac{d_{\text{i}}^2 + d_{\text{o}}^2}{2}}$$

$$\text{formula in my opinion} = \frac{d_{\text{i}} + d_{\text{o}}}{2}$$

where
d_{i} is the inside diameter of the sheath layer (m);
d_{o} is the outside diameter of the sheath layer (m).

Armour_Mu_1 Sheet

1. Cell B59 and C59. They are for real and imaginary part of permeability, but they use different equations.

$$\text{Cell B59} = 0.2 + 0.8\mu_{\mathrm{r,real}}$$
$$\text{Cell C59} = 0.8\mu_{\mathrm{r,imag}}$$

   But, section 2.1 in [8] says ''However, the assumption that the transverse permeability of the steel is $80\ \%$ of the longitudinal permeability was clearly not appropriate for aluminium or stainless steel, as it would produce values below 1; this has been changed to $0.2 + 80\ \%$ of the longitudinal permeability. Thus, most of the special cases become standard cases.'' It does not say distinguish the real and imaginary parts.

2. Cell P60. It uses a formula that is different from section VI.A in [4].

$$\text{Cell P60} = \frac{d_f}{2s_f}$$
$$\text{Section VI.A in reference [4]} = \frac{d_f}{s_f}$$

   Since neither of the xlsx-tool and [4] gives the explanation of the formulae, I have tried to determine which one is correct. I have manually changed the formula in the xlsx-tool to d_f/s_f, then with the default input, the output is ''#NUM!'' (see Fig. 38), meaning the xlsx-tool cannot produce numerical results. Therefore, I think the original formula used in the xlsx-tool is correct: $d_f/(2s_f)$.

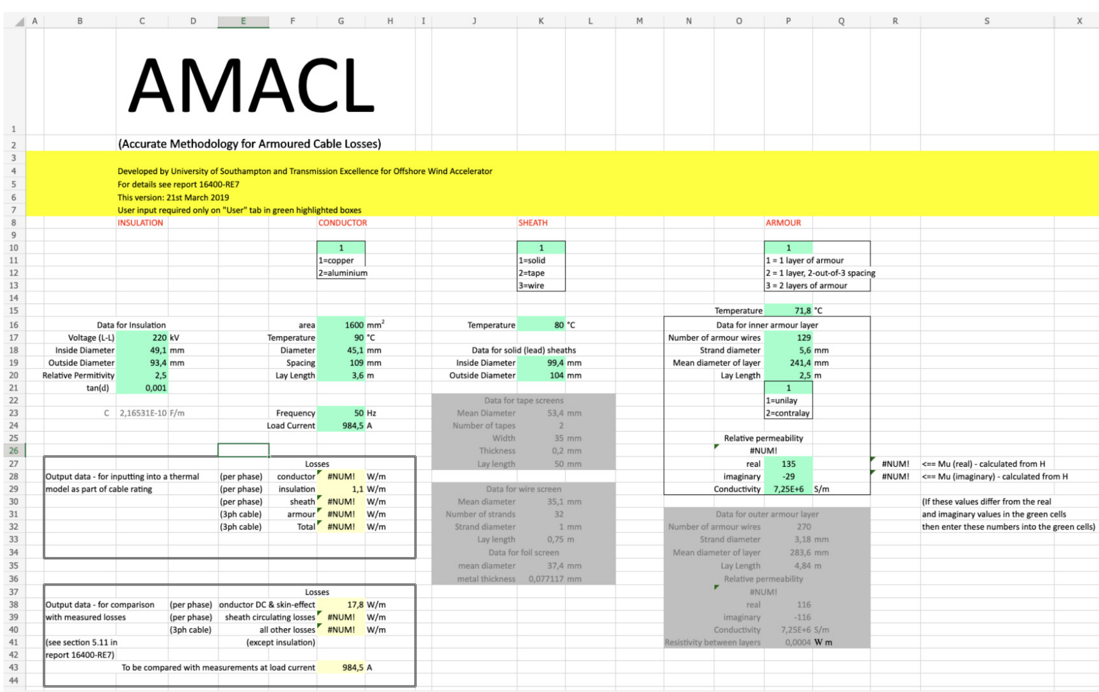

Figure 38: Default input of the xlsx-tool for cable loss calculation.

3. Cell AF61:BB83. They are for calculating K_r, but they use formulae that are not obviously linked to the formulae mentioned in the [4]. Reference [4] says: ''The elements of K_r have four factors'':

$$k_r = f_1 f_2 f_3 f_4 \tag{34}$$
$$f_1 = \left(\frac{d_f}{s_f}\right)^{(p+p_1)} \tag{35}$$
$$f_2 = \frac{(p+p_1-1)!p_1}{p!p_1!} \tag{36}$$
$$f_3 = 2\Sigma_{k=1}^{\infty} k^{-(p+p_1)} \tag{37}$$
$$f_4 = f_r \quad \text{referred to } p_1 \tag{38}$$

Note that, the formula of f_1 is incorrect according to the issue above, I think it should be $[d_f/(2s_f)]^{(p+p_1)}$. And f_r is reflection factor, see equations (26) and (29) in [4].
The xlsx-tool does not use factorial function to calculate f_2, and it does not use sum to ∞ to calculate f_3.

- For f_2, it uses the matrix of cells AF28:BB50. The row index is p_1 and the column index is p.
- For f_3, it uses the vector of cells AA61:AA106. The even rows are all 0, and the odd rows are given as:

$$[\frac{\pi^2}{3}, \frac{\pi^4}{45}, \frac{\pi^6 2}{945}, \frac{\pi^8}{4725}, 2.001988903, 2.000492164, 2.000122496, 2.000030565, 2.000007635$$
$$2.000001908, 2.00000047690101, 2+2^{-23}, 2+2^{-25}, 2+2^{-27}, 2+2^{-29}, 2+2^{-31}, \tag{39}$$
$$2+2^{-33}, 2+2^{-35}, 2+2^{-37}, 2+2^{-39}, 2+2^{-41}, 2+2^{-43}, 2+2^{-45}]$$

  Some elements are calculated by some formulae; while other elements are hard-coded values. It is very difficult to understand the meaning and validate them. I have tried to compare them with f_3 by Python code.

```
import numpy as np

p_plus_p1 = 2
k = np.arange(1, 1000000001)
f3 = 2 * np.sum(1/k**p_plus_p1)  # result is 3.289868131696402
cell_AA62 = np.pi**2 / 3  # result is 3.289868133696453
```

  In the Python code above, `f3` is calculated according to equation (37) by using a very large number 1000000001 instead of ∞. `cell_AA62` is calculated using the first formula in (39), which is $\pi^2/3$. They are almost equal. Therefore, I think the elements in this vector in the xlsx-tool are the values of f_3 for different p and p_1.
- For f_4. In the xlsx-tool, f_r is a vector containing 23 complex values, cells F92:G114. To calculate an element in the matrix of K_r, both p and p_1 should be given to indicate the column and row in that matrix. The xlsx-tool uses the value of p_1 to choose the element in the vector of f_r (see, e.g. Cell AF88), even though reference [4] says ''The final factor is the reflection factor for fields of the output pole-pair number p in an isolated armor wire.''.

4. Cell U70. It calculates the value of t, which uses a complex-vector K. This vector is somehow established by the matrix K_r. However, [4] does not directly provide the formula to do it. Even if vector K is made, the formulae to calculate t in the xlsx-tool are different than the equations (21) till (23) in [4]. Therefore, these two processes in the xlsx-tool are directly re-programmed in the Python code.

(a) the process from the matrix K_r to the vector K;
(b) the process from vector K to the value t.

5. Cells Z5, Z6, AC5, AC6. They are using bessel functions from Excel. They give slightly different results as Scipy from Python. Take Cell Z5 for example.
   - Python: `scipy.special.k1(0.2155481626213)` gives `4.405746469429914`.
   - Excel: `BESSELK(0.2155481626213; 1)` gives `4.40574647496986` .

   I have asked online "Excelchat Concierge" service, they said: *The difference is due to difference in environment and architecture. Even different Excels running in different environments(OS, PCs) can give slightly different results. It is because of deep down how Excel does calculations and stores values internally.*
6. Cell AC12. It seems like to calculate the imaginary part of the "MMF" of 4-pole of the inner armour. However, the formulae could have 2 mistakes.
   (a) The formula to calculate the corresponding real part (see Cell AB12) has a factor of 2; but cell AC12 for the imaginary part does not have it. I think it should also have a factor of 2.
   (b) The formula to calculate the corresponding real part (see Cell AB12) uses cells U72 and V72; but cell AC12 for the imaginary part uses cells X72 and Y72. But cell X72 is an empty cell, and cell Y72 is a hard-coded number for a special armour form ("2-out-of-3 spacing"), which is not in line with the purpose of cell A12. I think the formula of cell AC12 should also use cells U72 and V72.
7. Cell S60. It gets the DC resistance of the armour per unit length along cable. It uses a factor which converts the length of actual armour wire to the length of cable. There, the formula of the factor in xlsx is given as `(1+(K60/M59)^2)`. Its meaning is

$$\text{factor} = 1 + \left(\frac{\pi d_{\text{A}}}{p_{\text{A}}}\right)^2$$

   where
   d_{A} is the mean diameter of armour layer;
   p_{A} is the lay-length of armour wire.
   However, I think it should be

$$\text{factor} = \frac{\text{armour wire actual length}}{\text{armour wire lay-length}} = \sqrt{1 + \left(\frac{\pi d_{\text{A}}}{p_{\text{A}}}\right)^2}$$

   Because resistance is proportional to length, not to square of length. And the actual length of armour wire is $\sqrt{(\pi d_{\text{A}})^2 + p_{\text{A}}^2}$. Nevertheless, based on my finding, this value is only used in sheet IEC 60287, not impacting cells G31 and G32 in sheet User. Thus, it is not used by the actual Southampton approach.

Sheet Armour_Mu_2

1. Cell AD17 and AE17. They are marked as the real and imaginary parts of "flux ratio". It seems more natural to be calculated by a division operation between 2 complex values, as

$$\text{flux ratio: } AD17 + AE17j = \frac{\text{linkage: } AD16 + AE16j}{\text{inner armour flux: } Y13 + Z13j} \tag{40}$$

   where
   flux ratio refers to cells AD17:AE17 in sheet Armour_Mu_2;

linkage refers to cells AD16:AE16 in sheet Armour_Mu_2;
inner armour flux refers to cells Y13:Z13 in sheet Armour_Mu_1;

However, the actual formula is

$$AD17 = \frac{AD16 \cdot Y13 - AE16 \cdot Z13}{|Y13 + Z13j|^2}$$
$$AE17 = \frac{AE16 \cdot Y13 - AD16 \cdot Z13}{|Y13 + Z13j|^2}$$

It is not clear whether the actual formula is correct or not, since I cannot find relevant information in [4, 6–9].

Sheet Matrix

The formulae used in this sheet cannot be found in the references [4, 7, 9], except for the formulae in table II and IV in [4]. Thus, those formulae in this sheet are directly translated to Python code.

Sheet IEC 60287

1. Cell B5. It calculates y_s value, but it does not check the value of x_s. Section 2.1.2 in IEC [3] mentions that different formula for y_s should be used depending on the value of x_s, also see equation (8).
2. Cell B19. It gets the DC resistance of the armour per unit length along cable. This value is calculated at cell S60 in sheet Armour_Mu_1, which I think is not correct. See the issue of cell S60 in sheet Armour_Mu_1, section 5.4.4..

6. Cable Thermal Resistance Calculation

This is not implemented as a standalone "study" in Unagi. It is used by `Cable Rating Study` and `Cable Temperature Study`. However, due to its own complexity and importance, this document uses this dedicated chapter to describe.

The calculation approach refers to IEC [1], and the key information are presented here.

6.1. Thermal Resistance of the Constituent Parts of A Cable, T_1, T_2, T_3

6.1.1. Thermal Resistance between One Conductor and Sheath T_1

IEC [1] section 4.1.2 mentioned the following cases:

1. Single-core cables
2. Belted cables
   (a) Two-core belted cables with circular conductors
   (b) Two-core belted cables with sector-shaped conductors
   (c) Three-core belted cables with circular conductors
   (d) Three-core belted cables with oval conductors
   (e) Three-core belted cables with sector-shaped conductors
3. Three-core cables, metal shape screened type
   (a) Screened cables with circular conductors
   (b) Screened cables with oval-shaped conductors
   (c) Screened cables with sector-shaped conductors
4. Oil-filled cables
   (a) Three-core cables with circular conductors and metallized paper core screens and circular oil ducts between the cores.
   (b) Three-core cables with circular conductors and metal tape core screens and circular oil ducts between the cores.
   (c) Three-core cables with circular conductors, metal tape core screens, without fillers and oil ducts, having a copper woven fabric tape binding the cores together and a corrugated aluminium sheath.
5. SL and SA type cables.
   (a) Non-corrugated sheaths.
   (b) Corrugated sheaths.
6. Pipe-type cables.

Here only case 5-(a) is used, see section 4.1.2.5 in [1]. The corresponding equation is given in section 4.1.2.1 [1]. Note the first line in the equation is from [1]; while the second line is a mathematical equivalent, which directly uses the cable genres parameters in the database of unagi.

$$\begin{aligned} T_1 &= \frac{\rho_T}{2\pi} \ln\left(1 + \frac{2t_1}{d_c}\right) \\ &= \frac{\rho_T}{2\pi} \ln\left(\frac{d_s}{d_c}\right) \end{aligned}$$

where

ρ_T is the thermal resistivity of insulation $[\mathrm{K \cdot m/W}]$;
t_1 is the thickness of insulation between conductor and sheath $[\mathrm{m}]$; which is the distance between conductor surface and the sheath inside surface.
d_c is the diameter of conductor $[\mathrm{m}]$;
d_s is the inside diameter of sheath $[\mathrm{m}]$.

6.1.2. Thermal Resistance between Sheath and Armour T_2

IEC [1] section 4.1.3 mentioned the following cases:

1. Single-core, two-core and three-core cables having a common metallic sheath.
2. SL and SA type cables.
3. Pipe-type cables.

Here only case 2 is used, see section 4.1.3.2 in [1], with the following equation.

$$T_2 = \frac{\rho_T}{6\pi}\overline{G} \tag{41}$$

where

ρ_T refers to the thermal resistivity of the filler between sheath and armour, $[\mathrm{K \cdot m/W}]$.
$\overline{G}$ is the geometric factor.

The formula of $\overline{G}$ is directly given by [1]. However, section 5.6 in [1] gives formulae to calculate 2 curves of G: lower curve and upper curve. The value of $\overline{G}$ for a cable can be derived from these 2 curves.

Denote X is the thickness of material between sheaths and armour expressed as a fraction of the outer diameter sheath.0

$$X = \frac{\text{thickness}_{\text{armour}-\text{sheath}}}{\text{sheath outside diameter}}$$

The lower curve G_{lower}, which is for the case when sheaths are touching meaning the thickness of material between sheaths is 0, is given by:

$$\begin{aligned} 0 < X \le 0.03, &\quad G_{\text{lower}} = 2\pi(0.00020238 + 2.03214X - 21.6667X^2) \\ 0.03 < X \le 0.15, &\quad G_{\text{lower}} = 2\pi(0.0126529 + 1.101X - 4.56104X^2 + 11.5093X^3) \end{aligned}$$

The upper curve G_{upper}, which is for the case when the thickness of material between sheaths is equal to the thickness of material between sheath and armour, is given by:

$$\begin{aligned} 0 < X \le 0.03, &\quad G_{\text{upper}} = 2\pi(0.00022619 + 2.11429X - 20.4762X^2) \\ 0.03 < X \le 0.15, &\quad G_{\text{upper}} = 2\pi(0.0142108 + 1.17533X - 4.49737X^2 + 10.6352X^3) \end{aligned}$$

Thus, the $\overline{G}$ can be calculated as

$$\overline{G} = G_{\text{lower}} + \left(1 - \frac{\text{thickness}_{\text{sheath-sheath}}}{\text{thickness}_{\text{armour-sheath}}}\right)(G_{\text{upper}} - G_{\text{lower}}) \tag{42}$$

6.1.3. Thermal Resistance of Outer Covering (Serving) T_3

IEC [1] section 4.1.4 mentioned the following cases:

1. General case.
   (a) Non-corrugated sheaths.
   (b) Corrugated sheaths.
2. Unarmoured three-core cables with extruded insulation and individual copper tape screens on each core.
3. Pipe-type cables.

Here only case 1-(a) is used, see section 4.1.4.1 in [1]. The corresponding equation is as follows. Note the first line in the equation is from [1]; while the second line is a mathematical equivalent, which directly uses the cable genres parameters in the database of unagi.

$$\begin{aligned} T_3 &= \frac{1}{2\pi}\rho_T \ln\left(1 + \frac{2t_3}{D'_{\text{a}}}\right) \\ &= \frac{1}{2\pi}\rho_T \ln\left(\frac{D'_{\text{serving}}}{D'_{\text{a}}}\right) \end{aligned}$$

where

ρ_T refers to the thermal resistivity of the outer serving, $[\text{K} \cdot \text{m/W}]$.
t_3 is the thickness of serving $[\text{m}]$;
D'_{a} is the external diameter of the armour $[\text{m}]$.
D'_{serving} is the external diameter of the serving $[\text{m}]$.

6.2. External Thermal Resistance T_4

IEC [1] section 4.2 mentioned the following cases:

1. Cables laid in free air
   (a) Cables protected from direct solar radiation
   (b) Cables directly exposed to solar radiation
2. Single isolated buried cable
3. Groups of buried cables (not touching)
   (a) Unequally loaded cables
   (b) Equally loaded cables
      i. Two cables having equal losses, laid in a horizontal plane, spaced apart.
      ii. Three cables having approximately equal losses, laid in a horizontal plane, equally spaced apart.
      iii. Three cables having unequal sheath losses, laid in a horizontal plane, equally spaced apart.

4. Groups of buried cables (touching) equally loaded
   (a) Two single-core cables, flat formation
      i. Metallic sheathed cables
      ii. Non-metallic sheathed cables
   (b) Three single-core cables, flat formation
      i. Metallic sheathed cables
      ii. Non-metallic sheathed cables
   (c) Three single-core cables, trefoil formation
      i. Metallic sheathed cables
      ii. Part-metallic covered cables (where helically laid armour or screen wires cover from 20 % to 50 % of the cable circumference)
      iii. Non-metallic sheathed cables
5. Buried pipes.
6. Cables in buried troughs
   (a) Buried troughs filled with sand
   (b) Unfilled troughs of any type, with the top flush with the soil surface and exposed to free air.
7. Cables in ducts or pipes

Here case 2 is considered, see section 4.2.2 in IEC [1]. The corresponding equation to calculate T_4 is

$$T_4 = \frac{1}{2\pi}\rho_{\mathrm{T}} \ln\left(u + \sqrt{u^2 - 1}\right)$$
$$u = \frac{2L}{D_{\mathrm{e}}}$$

where

ρ_{T} is the thermal resistivity of the covering material, $[\mathrm{K} \cdot \mathrm{m/W}]$.
L is the cable burial depth referring to the center axis of the cable, m.
D_{e} is the external diameter of the cable, also called serving outside diameter, m.

7. Cable Rating Study

`Cable Rating Study` calculates the maximum allowed load current in steady state with a given conductor temperature limit and a specific operational condition.

7.1. Business Challenge

A rated current of a cable genre can usually be found on the datasheet provided by manufacturer. However, this value is true with the required operational condition. In other operational conditions, user can use this study to obtain the corresponding rated current. And user can compare different cable genres and find the one with the highest rated current.

7.2. Study Scope

This study evaluates the rated current of a cable genre in steady state according to an user-defined operational condition and conductor temperature limit. An iterative process is used to find the rated current by tuning the conductor temperature toward the user-defined limit. This is because the temperature of cable conductor, sheath, and armour are presumed to be unknown to user. Besides, their values are interrelated and should be calculated according to 7.3..

7.2.1. User to Specify

- Cable genres. The required parameters for `Cable Loss Study` and `Cable Thermal Resistance Calculation`, which are used in `Cable Rating Study`, are needed. See appendix 1.1. for details.
- Loss method.
  - IEC. It calls `Cable Loss IEC Study`.
  - Southampton. It calls `Cable Loss Southampton Study`.
- Frequency, in [Hz].
- Conductor temperature limit, in [$^\circ\mathrm{C}$].
- Environment temperature, in [$^\circ\mathrm{C}$].
- Burial condition.
  - Covering thermal resistivity, in [Km/W].
  - Covering depth, in [m]. It is from the soil surface to the outer surface of the cable, not to the geometric center of the cable. It is easier for user to change different cable genres at the same depth, since different cable genres can have different diameters.

7.2.2. Logic Flow

A high level logic flow of the `analyse` method in `Cable Rating Study` is shown in Fig. 39. The parameters in the diagram are explained below.

P_c is the conductor loss per phase $[\mathrm{W/m}]$.
P_d is the dielectric loss per phase $[\mathrm{W/m}]$.

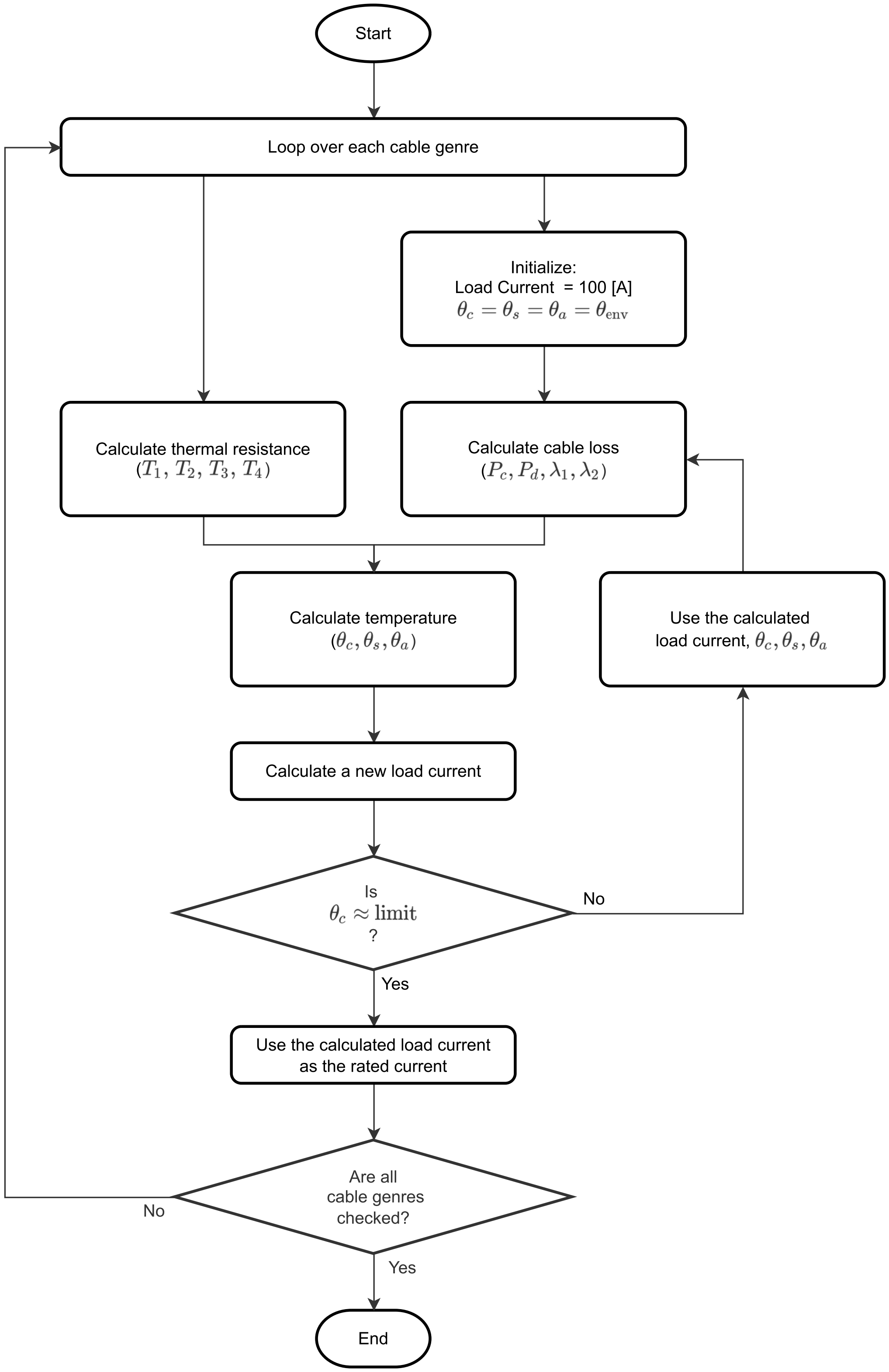

Figure 39: Logic flow of the `analyse` method in `Cable Rating Study`.

λ_1 is the so-called sheath loss factor, see section 5.3.3. and 5.4.1..
λ_2 is the so-called armour loss factor, see section 5.3.4. and 5.4.1..
T_1 is the thermal resistance between conductor and sheath, $[\mathrm{K \cdot m/W}]$, see section 6.1.1..
T_2 is the thermal resistance between sheath and armour, $[\mathrm{K \cdot m/W}]$, see section 6.1.2..
T_3 is the thermal resistance of cable outer covering (serving), $[\mathrm{K \cdot m/W}]$, see section 6.1.3..
T_4 is the thermal resistance cable external environment, $[\mathrm{K \cdot m/W}]$, see section 6.2..
θ_c is the conductor temperature, $[^\circ\mathrm{C}]$.
θ_s is the sheath temperature, $[^\circ\mathrm{C}]$.
θ_a is the armour temperature, $[^\circ\mathrm{C}]$.
θ_env is the environment temperature, $[^\circ\mathrm{C}]$.

At beginning, Unagi sets load current with a pre-defined value, 100 [A], and assumes the temperature of conductor, sheath, and armour all equal to the environment temperature. It then calls cable loss model described in chapter 5., where 2 approaches are given: IEC (see section 5.3.) and Southmapton (see section 5.4.). User needs to specify which approach to use. It also calls cable thermal resistance model described in chapter 6.. The output of both cable loss model and cable thermal resistance model is inserted to a cable thermal circuit solver to calculate the temperature of conductor, sheath, and armour, see section 7.3.. Then, the calculated conductor temperature is compared with the limit, which is given by user. If the limit is reached, then output the corresponding load current as the maximally allowed value in steady state operation. Otherwise, the load current is updated to a new value and re-run the calculation. The detailed approach to compare and update is described in Fig. 40. Unagi accepts deviation from the limit by $\pm 0.1 [^\circ\mathrm{C}]$.

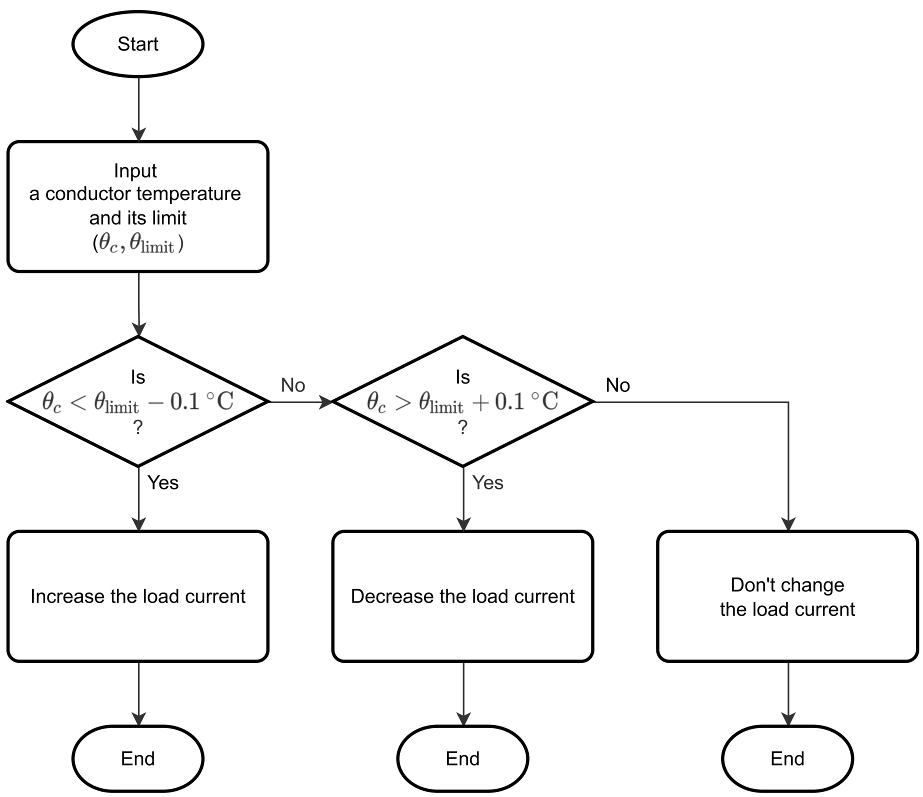

Figure 40: Logic flow of updating load current for cable rating study

If the load current of the on-going iteration ($I_\mathrm{on-going}$) is too high, then the load current should be decreased; if it is too low, then load current should be increased. The equations are shown below:

$$\text{Decrease} \qquad I_{\text{next}} = \frac{\theta_{\text{limit}}}{\theta_c} \cdot I_{\text{on-going}}$$
$$\text{Increase} \qquad I_{\text{next}} = (2 - \frac{\theta_c}{\theta_{\text{limit}}}) \cdot I_{\text{on-going}}$$

With equations above, the adjustment from $I_{\text{on-going}}$ to I_{next} is more if θ_c is further away from θ_{limit}.

7.3. Cable Thermal Circuit Solver

This temperature solver calculates steady-state temperature of conductor, sheath, and armour based on the method provided by [2]. The relationship between temperature and power loss can be conveniently described by a thermal circuit diagram, where temperature, power loss, thermal resistor are respectively like node voltage, current source, and resistor in electric circuit, see Fig. 41. Thus, the temperature can be calculated by

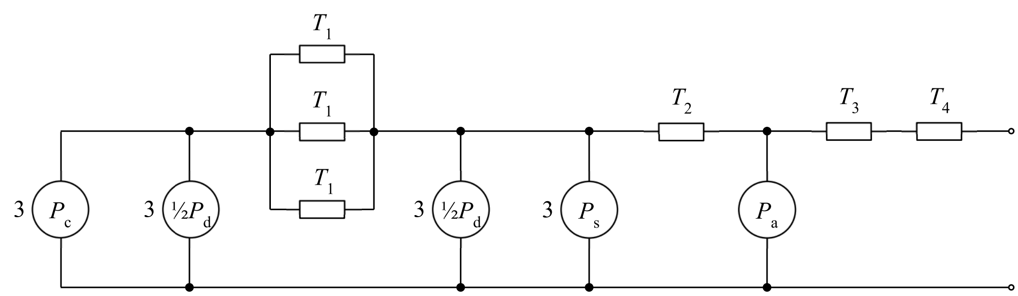

Figure 41: Thermal circuit diagram of cable temperature solver

$$\theta_{\text{a}} = \theta_{\text{env}} + [P_{\text{c}} \cdot (1 + \lambda_1 + \lambda_2) + P_{\text{d}}] \cdot N \cdot (T_3 + T_4)$$
$$\theta_{\text{s}} = \theta_{\text{a}} + [P_{\text{c}} \cdot (1 + \lambda_1) + P_{\text{d}}] \cdot N \cdot T_2$$
$$\theta_{\text{c}} = \theta_{\text{s}} + \left(P_{\text{c}} + \frac{1}{2}P_{\text{d}}\right) \cdot T_1$$

where

N is the number of cores. Thus, for a 3-core cable, $N = 3$.
P_{c} is the conductor loss per phase $[\text{W/m}]$.
P_{d} is the dielectric loss per phase $[\text{W/m}]$.
P_{s} is the sheath loss per phase $[\text{W/m}]$.
P_{a} is the armour loss $[\text{W/m}]$.
λ_1 is the so-called sheath loss factor, see section 5.3.3. and 5.4.1..
λ_2 is the so-called armour loss factor, see section 5.3.4. and 5.4.1..
T_1 is the thermal resistance between conductor and sheath, $[\text{K} \cdot \text{m/W}]$, see section 6.1.1..
T_2 is the thermal resistance between sheath and armour, $[\text{K} \cdot \text{m/W}]$, see section 6.1.2..
T_3 is the thermal resistance of cable outer covering (serving), $[\text{K} \cdot \text{m/W}]$, see section 6.1.3..

T_4 is the thermal resistance cable external environment, $[\mathrm{K} \cdot \mathrm{m/W}]$, see section 6.2..
θ_c is the conductor temperature, $[^\circ\mathrm{C}]$.
θ_s is the sheath temperature, $[^\circ\mathrm{C}]$.
θ_a is the armour temperature, $[^\circ\mathrm{C}]$.
θ_env is the environment temperature, $[^\circ\mathrm{C}]$.

8. Cable Temperature Study

`Cable Temperature Study` calculates the corresponding temperature of conductor, sheath, and armour in steady state with a given load current and a specific operational condition.

8.1. Business Challenge

When current going through cable, heat is generated within the cable and is transferred to the environment. This process increases the temperature at different parts of the cable. Overheating can damage the cable. Usually, in the datasheet of a cable genre from manufacturer, the rated current will cause the steady-state conductor temperature to be 90 $^{\circ}\mathrm{C}$. With this study, user can calculate the cable temperatures at different load current and different operational conditions. Besides, user can compare different cable genres and find the one with the lowest temperature.

8.2. Study scope

This study evaluates the temperature of conductor, sheath, and armour of a cable genre. An iterative process is used to find the temperature of conductor, sheath, and armour. This is because these temperatures are interrelated and should be calculated according to 7.3..

8.2.1. User to Specify

- Cable genres. The required parameters for `Cable Loss Study` and `Cable Thermal Resistance Calculation`, which are used in `Cable Temperature Study`, are needed. See appendix 1.1. for details.
- Loss method.
  - IEC. It calls `Cable Loss IEC Study`.
  - Southampton. It calls `Cable Loss Southampton Study`.
- Frequency, in [Hz].
- Load current, in [A].
- Environment temperature, in [$^{\circ}\mathrm{C}$].
- Burial condition.
  - Covering thermal resistivity, in [Km/W].
  - Covering depth, in [m]. It is from the soil surface to the outer surface of the cable, not to the geometric center of the cable. It is easier for user to change different cable genres at the same depth, since different cable genres can have different diameters.

8.2.2. Logic Flow

A high level logic flow of the `analyse` method in `Cable Temperature Study` is shown in Fig. 42. The parameters in the diagram are explained below.

P_{c} is the conductor loss per phase $[\mathrm{W/m}]$.
P_{d} is the dielectric loss per phase $[\mathrm{W/m}]$.

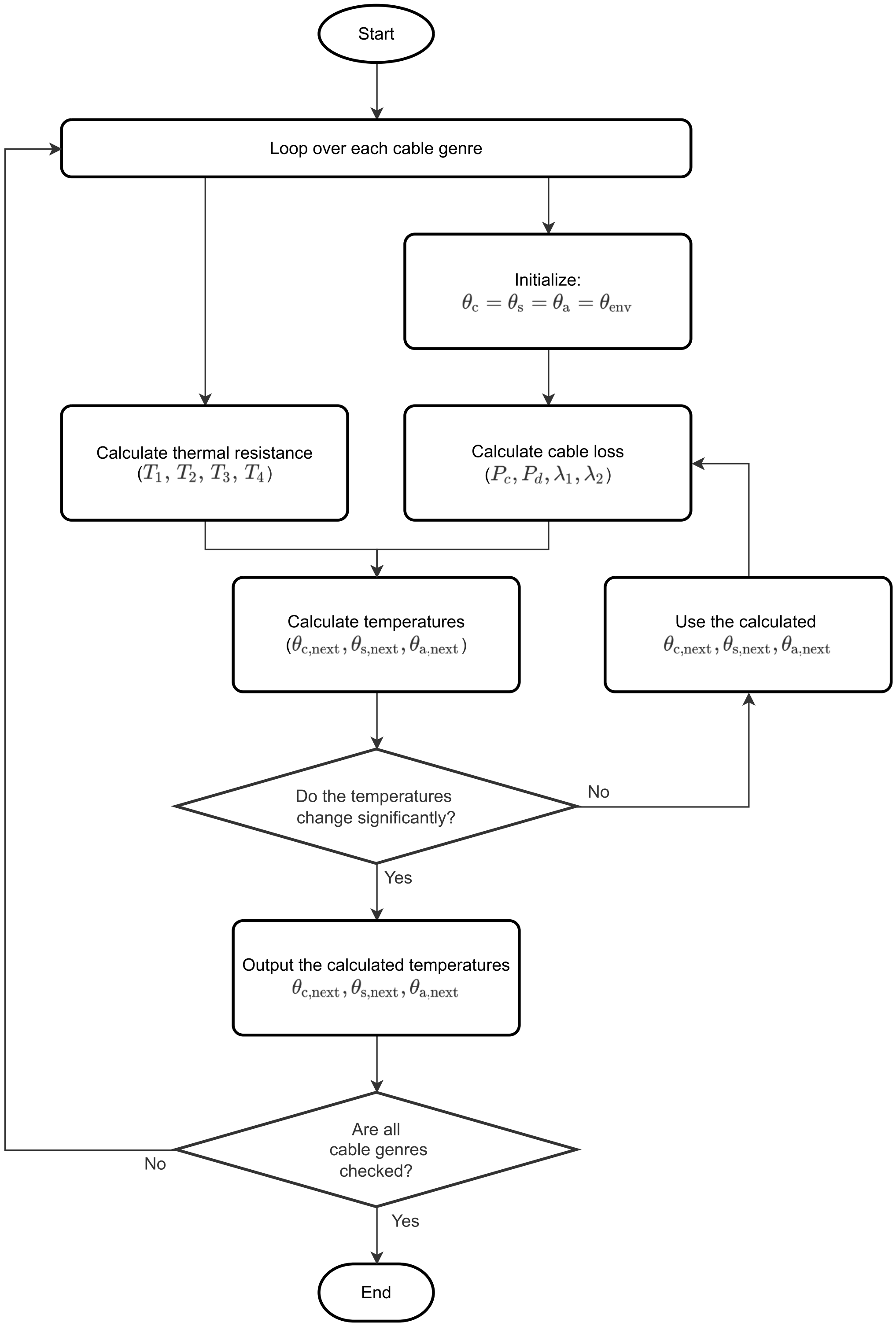

Figure 42: Logic flow of the `analyse` method in `Cable Temperature Study`.

λ_1 is the so-called sheath loss factor, see section 5.3.3. and 5.4.1..
λ_2 is the so-called armour loss factor, see section 5.3.4. and 5.4.1..
T_1 is the thermal resistance between conductor and sheath, $[\mathrm{K} \cdot \mathrm{m/W}]$, see section 6.1.1..
T_2 is the thermal resistance between sheath and armour, $[\mathrm{K} \cdot \mathrm{m/W}]$, see section 6.1.2..
T_3 is the thermal resistance of cable outer covering (serving), $[\mathrm{K} \cdot \mathrm{m/W}]$, see section 6.1.3..
T_4 is the thermal resistance cable external environment, $[\mathrm{K} \cdot \mathrm{m/W}]$, see section 6.2..
θ_c is the conductor temperature, $[^\circ\mathrm{C}]$.
θ_s is the sheath temperature, $[^\circ\mathrm{C}]$.
θ_a is the armour temperature, $[^\circ\mathrm{C}]$.
θ_env is the environment temperature, $[^\circ\mathrm{C}]$.

At beginning, Unagi assumes the temperature of conductor, sheath, and armour all equal to the environment temperature. It then calls cable loss model described in chapter 5., where 2 approaches are given: IEC (see section 5.3.) and Southmapton (see section 5.4.). User needs to specify which approach to use. It also calls cable thermal resistance model described in chapter 6.. The output of both cable loss model and cable thermal resistance model is inserted to a cable thermal circuit solver to calculate the temperature of conductor, sheath, and armour, see section 7.3.. Then, the calculated cable temperatures ($\theta_\mathrm{c,next}$, $\theta_\mathrm{s,next}$, $\theta_\mathrm{a,next}$) should be compared with their previous values (θ_c, θ_s, θ_a). Unagi internally uses $0.1\,[^\circ\mathrm{C}]$ as the threshold. Only if the changes of all cable temperatures are within the threshold, should the iteration stop and output the most recently calculated temperatures.

$$|\theta_\mathrm{c,next} - \theta_\mathrm{c}| <= 0.1\,[^\circ\mathrm{C}]$$
$$|\theta_\mathrm{s,next} - \theta_\mathrm{s}| <= 0.1\,[^\circ\mathrm{C}]$$
$$|\theta_\mathrm{a,next} - \theta_\mathrm{a}| <= 0.1\,[^\circ\mathrm{C}]$$

9. Cable CAPEX and OPEX Study

`Cable CAPEX and OPEX Study` calculates the CAPEX and OPEX (net present value) of a cable section based on different power generation profiles, considering the impact of the cost of CO2 emissions.

9.1. Business Challenge

The total cost of a cable connection consists of the CAPEX and OPEX. The CAPEX is the purchase price at the beginning time point of concern; while the OPEX is situational and paid at different time points multiple years. The most economically efficient cable connection is the one with the least sum of CAPEX and OPEX, which is converted to the same moment of CAPEX in terms of net present value (NPV). A cable genre using copper instead of aluminium has higher CAPEX. But copper has less resistance resulting less OPEX. So the overall cost of cable genre using copper may be less than the one using aluminium.

The OPEX of a cable section depends on the cable genre and its operational conditions. This study can be used to compare different operational conditions including different generation profiles. Moreover, it can compare different cable genres with the same operational condition. The one with least OPEX is also the most environmentally friendly.

9.2. Study Scope

This study evaluates the CAPEX and OPEX of a cable section with different cable genres and operational conditions including different power generation profiles. It allows different forms of power generation: `annual` or `series`.

For power form of `annual`, each profile is several pairs of duration and power within one year (8760 hours), it is assumed that each year has the same pattern. Unagi will calculate the energy loss over the year and repeat it for N years. Note that the sequence of those duration-power pairs is ignored, and each profile can have different number of pairs.

For power form of `series`, each profile is a time-series of power. The timestep is fixed and the timespan defines the number of years, and all profiles must have the same timestep but can have different timespan. In addition, Unagi allows user to specify the temperature form for the conductor temperature of the cable: `constant` or `variable`. If the conductor temperature is `constant`, then the temperature of sheath and armour are also constant in steady-state. And all of them are independent from cable load current. On the other hand, if the conductor temperature is `variable`, then the temperatures of conductor, sheath, and armour are all variable. Unagi uses the moving average load current certain time-window, e.g. 7 days (168 hours), to calculate those temperatures in steady-state.

The power form of `annual` is the quickest option to run, since it needs just aggregated profiles. But its results have the least details. While the power form of `series` with the temperature form of `variable` is the slowest, since it needs to calculate for each time point (for a timestep of 1 hour, there are 8760 time points per year). But its results have the most details.

User should choose based the profiles at hand and the waiting time for the study to finish.

9.2.1. User to Specify

- Cable genres. The required parameters for `Cable Loss Study` and `Cable Thermal Resistance Calculation`, which are used in `Cable CAPEX and OPEX Study`, are needed. See appendix 1.1. for details.
- Loss method.
  - IEC. It calls `Cable Loss IEC Study`.
  - Southampton. It calls `Cable Loss Southampton Study`.
- Cable length, in [km].
- Frequency, 50 Hz or 60 Hz.
- Conductor temperature limit, in [$^{\circ}\mathrm{C}$].
- Environment temperature, in [$^{\circ}\mathrm{C}$].
- Burial condition.
  - Covering thermal resistivity, in [Km/W].
  - Covering depth, in [m]. It is from the soil surface to the outer surface of the cable, not to the geometric center of the cable. It is easier for user to change different cable genres at the same depth, since different cable genres can have different diameters.
- Economic price, in [EUR/MWh].
- Interest rate, in [%].
- CO2 emission, in [kg/kWh].
- CO2 price, in [EUR/t].
- Power
  - Power factor, between 0 and 1.
  - Power unit: [W], [kW], or [MW].
  - Scaling factor. It is a multiplication factor to the power defined in the profiles.
- Power form: *annual* or *series*.
  - For *annual*
    - Rated active power, in the unit defined by *Power unit* above.
    - Number of years.
    - Duration-power profiles file. It is a csv-file from user's computer.
  - For *series*
    - Start timestamp. It is in the format of `YYYY-MM-DD HH:MM:SS`, e.g. `2022-06-10 01:00:00`. It is the starting moment of the power profiles. All profiles must have the same starting moment.
    - Timestep, in [h]. It is the timestep of the power profiles. All profiles must have the same timestep.
    - WTG Power profiles form: *power* or *pattern*.
      - For *power*. User directly provides a csv-file of WTG Power containing one or more time-series profiles.
      - For *pattern*. User provides two csv-files. One is for WTG Power Curve containing the relationship between wind speed and WTG power. And other is for wind speed containing one or more time-series profiles.
    - temperature form: *constant* or *variable*.
      - For *constant*. User provides a constant conductor temperature, in [$^{\circ}\mathrm{C}$].
      - For *variable*. User provides a time-window for the moving average of WTG power.

9.2.2. Logic Flow

A high level logic flow of the `analyse` method in `Cable CAPEX and OPEX Study` is shown in Fig. 43.

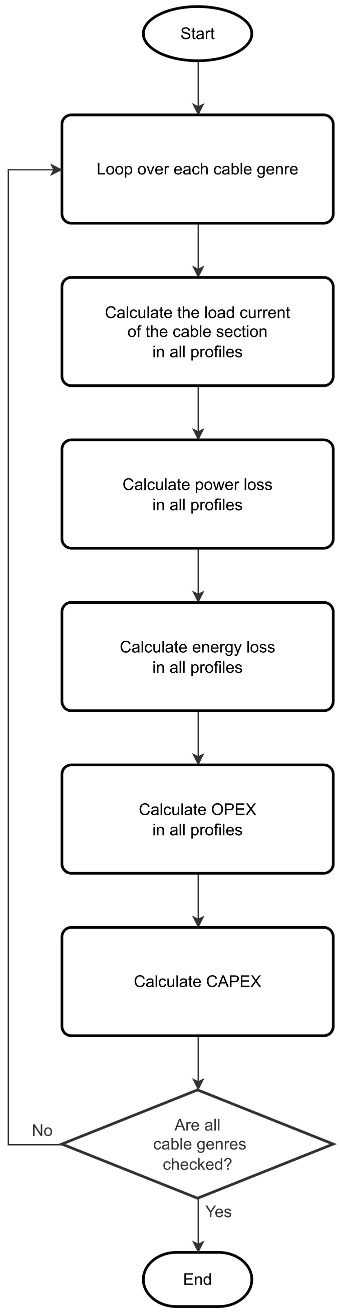

Figure 43: Logic flow of the `analyse` method in `Cable CAPEX and OPEX Study`.

The details of the process are explained in the following sections in this chapter.

9.3. Calculate Load Current

It is the load current that generates heat and loss in the cable. However, user normally does not have the profiles of load current. Unagi allows user to provide profiles of WTG-power generation at one side of cable, and it will automatically calculate the corresponding load current afterwards. Fig. 44 shows the accepted forms to obtain WTG-power.

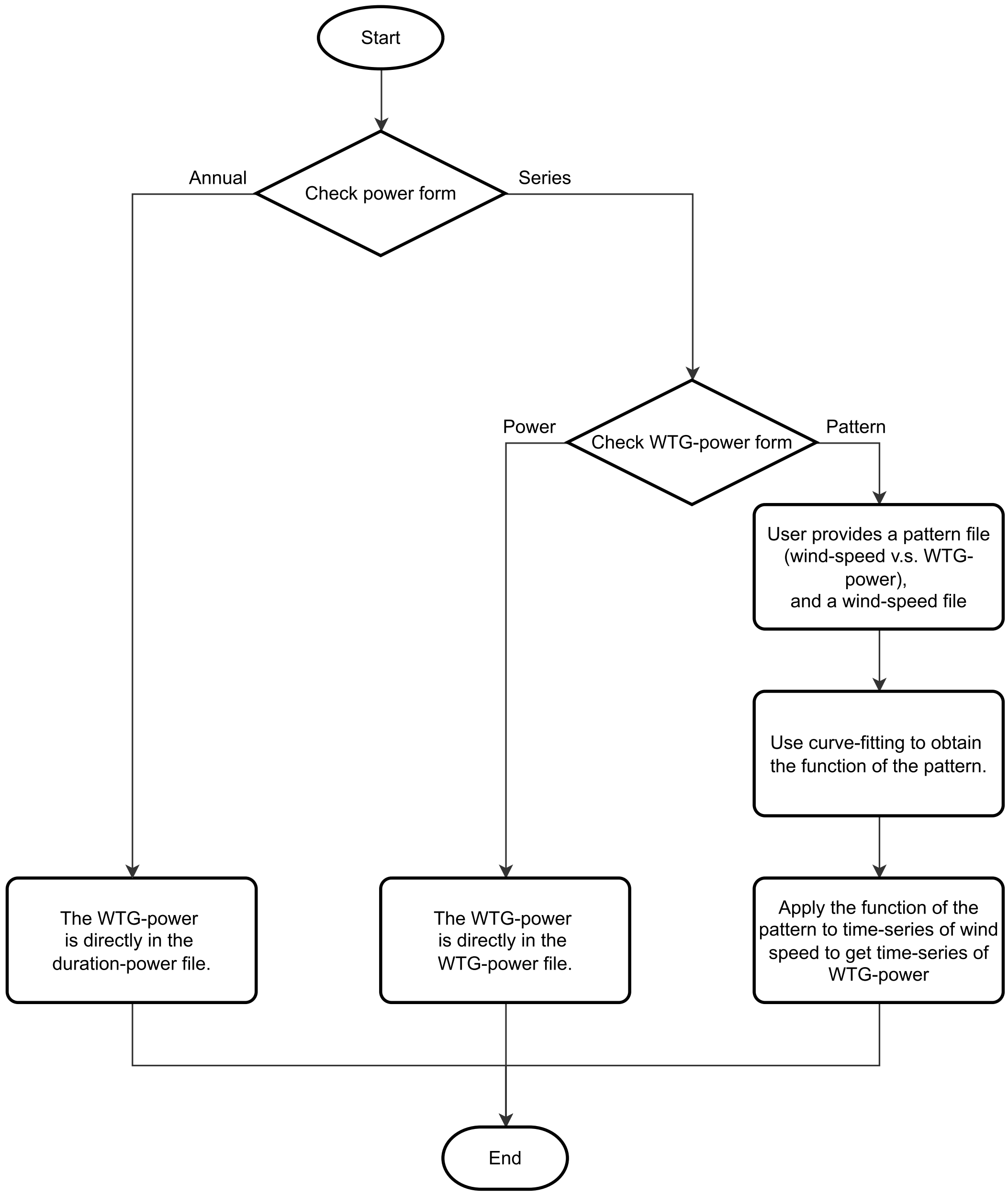

Figure 44: Logic flow of obtaining WTG-power.

For power form of `annual` and power form of `series` with WTG-power form of `power`, user directly provides the WTG-power in the specified file. However, for the power form of `series` with WTG-power form of `pattern` user provides other files, based on which Unagi will derive the corresponding WTG-power, see 9.3.1..

9.3.1. WTG Power Derivation

If the actual profiles of time-series power are usually not directly available from user, user can provide two files:

- one for WTG Power Curve;
- and the other for one or more profiles of time-series of wind speed.

The WTG Power Curve serves as a pattern between wind speed and WTG power. Then, for each value in the time-series of wind speed, a corresponding power value can be found by the pattern. The algorithm is implemented by `scipy.interpolate.interp1d`, see [5]. Mathematically, it is the so-called *Spline* interpolation of third order.

Fig. 45 serves as an example of the curve-fitting approach. It compares exemplary provided points with the fitted curve. Note that the raw results of fitted function can produce negative values for power see Fig. 45-top, which is meaningless in the study. Thus, unagi automatically converts the negative values to 0, see Fig. 45-bottom. And if a value of time-series wind speed is outside the range given by the pattern, the corresponding value of WTG power will be set to 0.

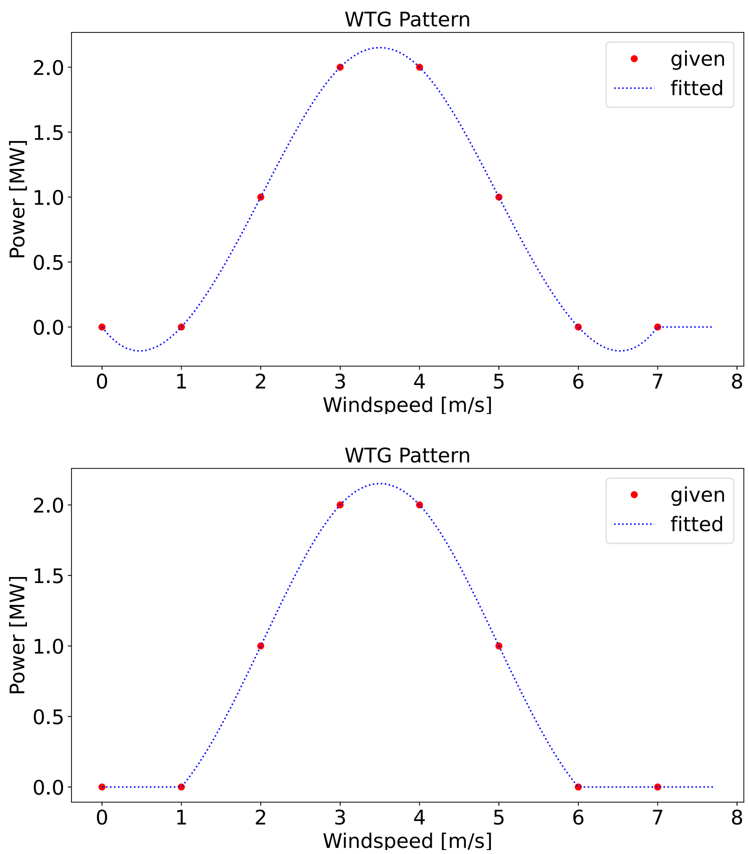

Figure 45: Curve-fitting for WTG pattern. Top: raw function that can have negative output. Bottom: modified function that converts the negative output to 0, which is implemented in unagi.

9.3.2. Cable load current calculation

After obtaining WTG power profiles. Unagi uses the following approach to calculate the load current of cable.

$$I = \frac{P}{\sqrt{3}U_n \times \text{Power Factor}} \tag{43}$$

where

I is the load current, [A].
P is the WTG power, [W].
U_n is the system nominal voltage, [V].

Note that both U_n and power factor are provided by user.

9.4. Cable Loss Profiler

Unagi implements a module `Cable Loss Profiler` to calculate the power loss of a cable section with given profiles of load current. A high level of logic flow of the process is depicted in Fig. 46. The power loss of cable at a time point depends on cable temperatures and load current at the that moment. However, the cable temperature at one time point is not caused by the load current at that time point but by historical values and durations of load current. However, if a load current stays unchanged long enough for a thermal equilibrium to be reached. Afterwards, the cable temperatures at any time point are related to the load current at the same moment, since the historical load current is equal to the load current at this moment. Different approaches are used to determine the cable temperatures for different power forms and temperature forms, the details are presented in this section.

Note that the cable power loss per unit length is calculated first, which is then multiplied by cable length to get the power loss of the entire cable.

9.4.1. Power Form of Annual

For the power form of `annual`, each profile of load current is a list of pairs of duration and power. Each pair is an aggregated amount, and the sequence of the pairs does not matter. Thus, each load current in each profile is considered as steady state current, and it is used to determine the cable temperature for the same duration. And the resulting cable power loss can be calculated with the help of `Cable Temperature Study`, see chapter 8..

9.4.2. Power Form of Series

For the power form of `series`, the load current in each profile is a time-series variable, accompanied by a list of time points with a constant time step. A common time step is 1 [h], which is too short for cable temperatures reach steady-state. Thus, Unagi first calculates the corresponding time-series of cable temperatures for each profile. With the obtained cable temperatures and load currents at all time points, cable loss study, `Cable Loss IEC Study` or `Cable Loss Southampton Study`, can be used to calculate the corresponding cable power loss at all time points.

Below presents the different approaches of cable temperatures calculation used for different temperature forms: `constant` and `variable`.

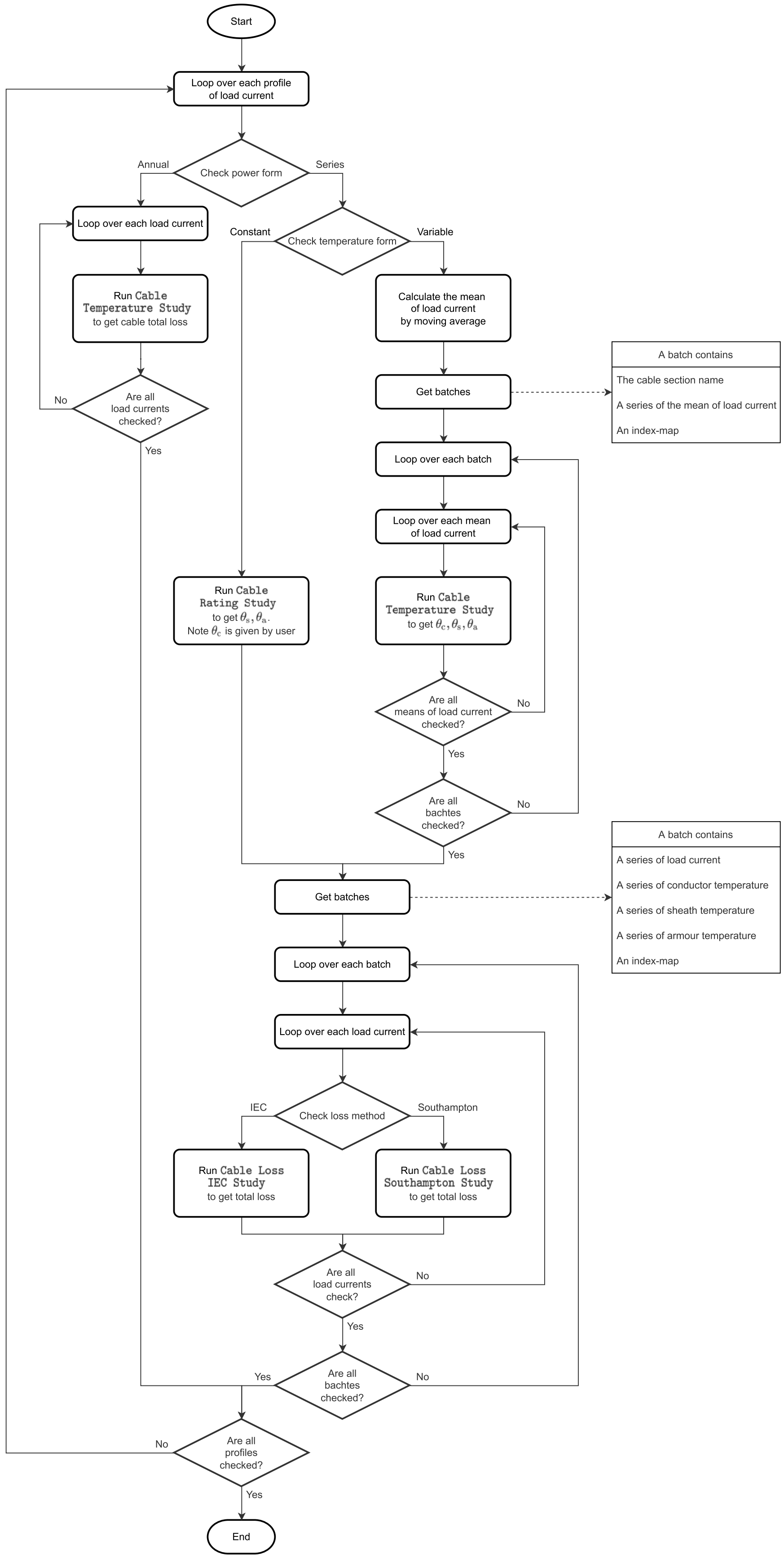

Figure 46: Logic flow of cable loss profiler.

Temperature Form of Constant

Temperature form of `constant` assumes the cable temperatures constant. That means the cable temperatures are not related to the load current at any moment. Thus, the thermal dynamics is irrelevant, and the approach from chapter 7. and IEC [1] is used. This approach is well-known for steady-state situation. Unagi uses the user-defined conductor temperature as the input parameter of `conductor temperature limit` for `Cable Rating Study`, see 7.. Thus the corresponding temperature of sheath and armour can be calculated.

Temperature Form of Variable

For temperature form of `series`, an accurate approach should take the dynamic behaviour of cable temperatures into account. The approach that directly follows the thermal dynamic behaviour of a cable is advanced yet very complicated, and thus out of scope of this project. On the other hand, the approach from chapter 8. and IEC [1] is well-known for steady-state situation. It assumes a load current is stays unchanged long enough so that the temperatures of conductor, sheath, armour no longer change (thermal equilibrium). Practically, it can take days for cable to reach a thermal equilibrium. Thus, for load current that varies frequently (e.g. every hour), its mean value over certain period can then be used to calculate temperatures. Unagi uses the moving average with window-size of 7 days, which is 168 hours. Fig. 47 illustrates the approach for an example of 2 days (336 hours).

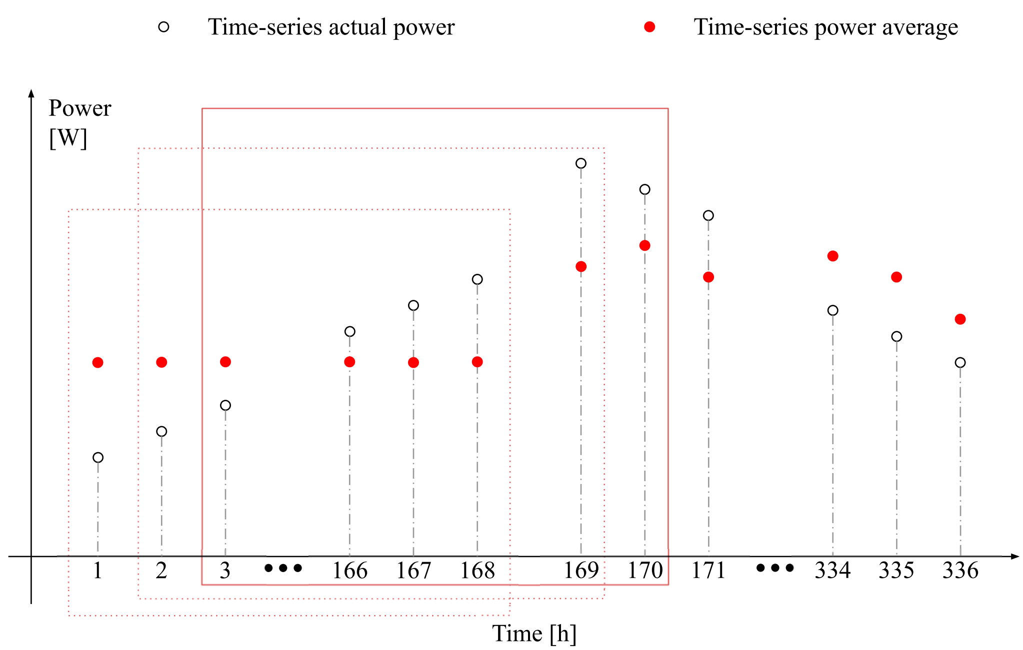

Figure 47: Moving average power calculation

For a window-size of 168 hours, the first moving average power is calculated based on the very first 168 hours, i.e. from the 1st hour to the 168th hour, and the moving average value is assigned to the 168th hour. Like wise, he second moving average, which is at the 169th hour, is calculated from the 2nd hour to the 169th hour. The third moving average, which is at the 170th hour, is calculated from the 3rd hour to the 170th hour, and so on. Note that the first 167 hours (from the 1st hour to the 167th hour) do not have enough data for the moving average. Thus, the moving average of the 168th hour is used for every hour from the 1st hour to the 167th hour.

The averaging algorithm makes sure that, within a windowed duration, the averaged load current and the actual load current generate exactly the same amount of energy. Therefore, at each time point, the averaged load current is used to calculate the corresponding steady-state temperature of conductor, sheath, and armour, see chapter 8..

9.5. Energy Loss Calculation

Based on the calculated power loss of cable, Unagi uses different approach to calculate energy loss for power forms of `annual` and `series`. The results is a vector of energy loss flows for each profile. The term *flow* comes from the economical term *cash flow*, making it easier to relate the calculation of *net present value* for OPEX. Note that the flows start from year 1, since year 0 is the beginning moment.

9.5.1. Power Form Annual

For each pair of duration and power in one profile, the power loss of cable should be multiplied by the duration to produce the energy loss of that duration. Then the total energy loss per year equals to the sum of the energy loss of each duration.

$$E = \sum_{k=1}^{M} P_k t_k \tag{44}$$

where

E is the total energy loss per year, in [Wh].
M is the number of pairs of duration and power.
Δt_k is the duration in the kth pair.
P_k is the calculated power loss for duration k.

Consequently, the same total energy loss per year is applied to each year. The resulting energy flows are is shown in Fig. 48.

9.5.2. Power Form Series

When the time-series power loss of cable is calculated, Unagi calculates the energy loss in two steps. First, it calculates the energy loss of each time step, e.g. every hour, see Fig. 49, which is a dual y-axis plot.

The equation is

$$E = P \times \Delta t \tag{45}$$

where

E is the energy loss per time step, $[\mathrm{Wh}]$.
P is the power loss at each time step, $[\mathrm{W}]$.
Δt is the time step, $[\mathrm{h}]$.

Then the duration of the entire time-series is grouped by the corresponding years, and the total energy loss in each year is calculated and regarded as *energy loss flows*, see Fig. 50.

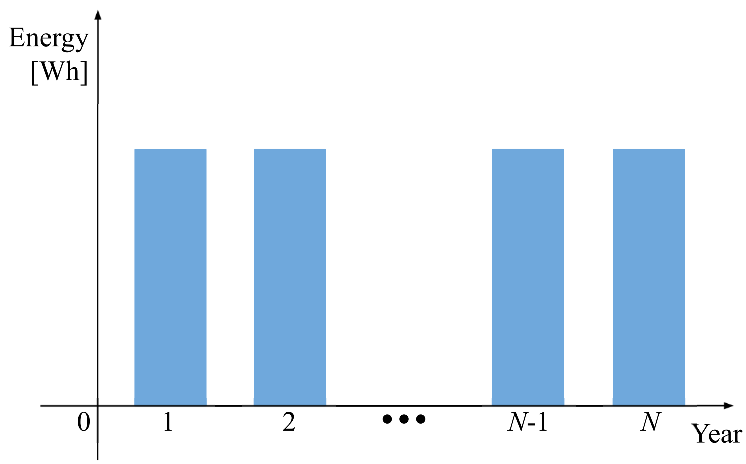

Figure 48: Energy loss flows from power form of `annual`.

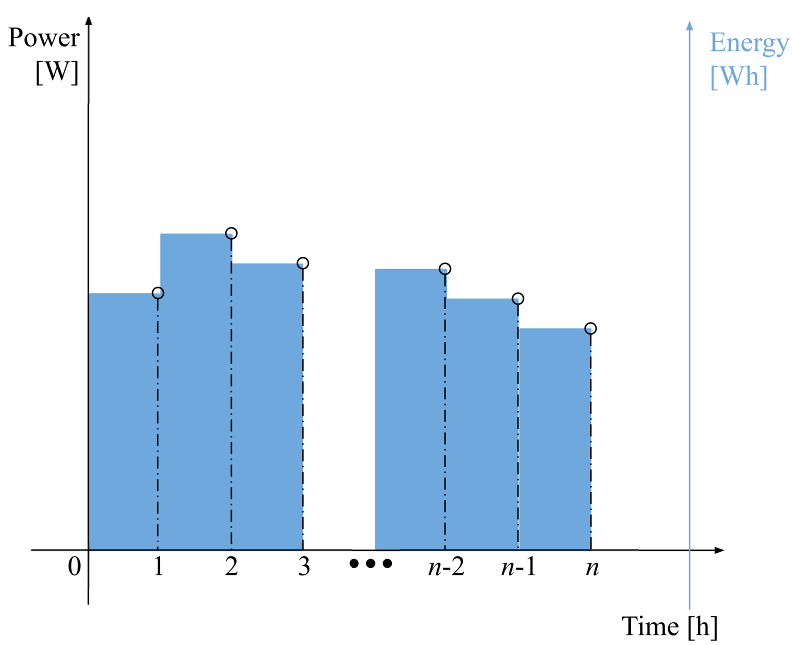

Figure 49: Energy loss per time step for power form of `series`. Each circle is a power, and each rectangular area is the corresponding energy.

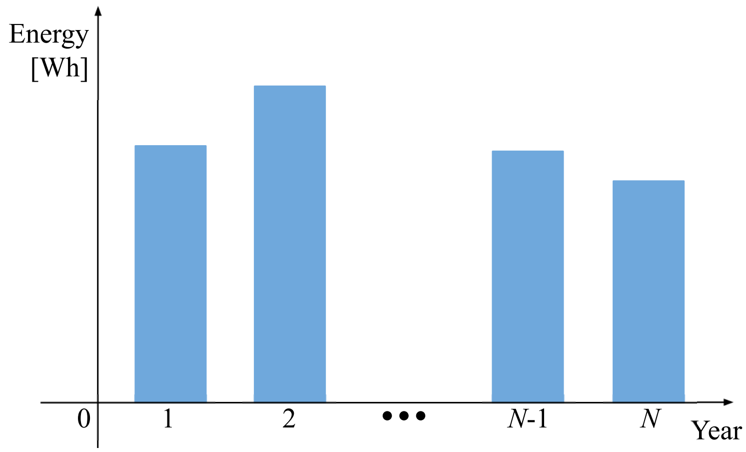

Figure 50: Energy loss flow.

9.6. Cable OPEX Calculation

With the energy loss flows calculated in section 9.5., the OPEX flows and OPEX npv can both be calculated. The OPEX of cable consists of cost of energy loss and CO2 emission cost. The OPEX is calculated as yearly cash flows first, and then the net present value (npv) so that it can be evaluated at the same moment as CAPEX.

The OPEX in a year is calculated by

$$\mathrm{OPEX}_k = E_k \times \mathrm{Price}_{\mathrm{energy}} + E_k \times \mathrm{Emission}_{\mathrm{CO2}} \times \mathrm{Price}_{\mathrm{CO2}} \tag{46}$$

where,

k refers to year k.
OPEX_k is the OPEX in year k, in $[\mathrm{EUR}]$.
E_k is the energy loss in year k, in $[\mathrm{Wh}]$.
$\mathrm{Price}_{\mathrm{energy}}$ is the energy price, in $[\mathrm{EUR/Wh}]$.
$\mathrm{Price}_{\mathrm{CO2}}$ is the CO2 emission price, in $[\mathrm{EUR/kg}]$.
$\mathrm{Emission}_{\mathrm{CO2}}$ is the CO2 emission by producing energy E_k, in $[\mathrm{kg/Wh}]$.

Fig. 51 shows the calculated OPEX flows. Due to inflation, the worth of money changes over time. Thus, net present value of OPEX is evaluated based on the calculated OPEX flow above. The equation is

$$\mathrm{OPEX}_{\mathrm{npv}} = \sum_{k=1}^{N} \frac{\mathrm{OPEX}_k}{(1+\mathrm{rate})^k} \tag{47}$$

where

k refers to year k.
N is the total number of years.
OPEX_k is the OPEX in year k, $[\mathrm{EUR}]$.
$\mathrm{OPEX}_{\mathrm{npv}}$ is the net present value (npv) of OPEX, $[\mathrm{EUR}]$. It refers to the beginning moment, i.e. year 0.
rate is the interest rate of money, $[\%]$

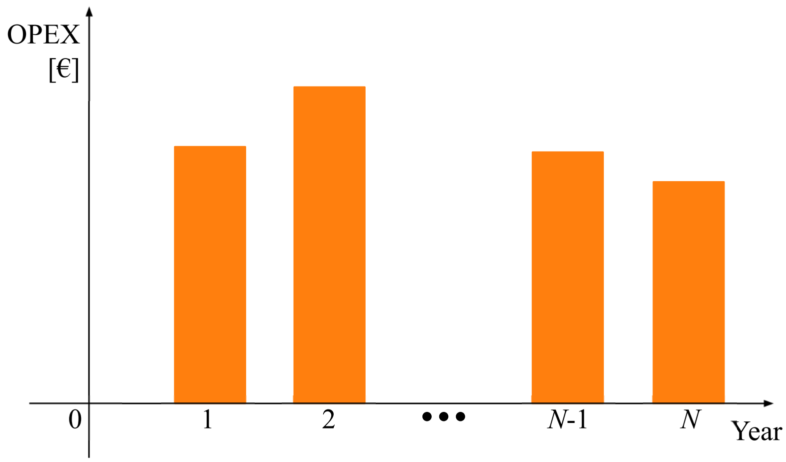

Figure 51: OPEX flow.

9.7. CAPEX Calculation

The CAPEX of a cable is calculated as the cost of purchase at the beginning of the concerned time duration, referred as time 0 year.

$$\text{CAPEX} = \text{Price per unit length} \times \text{Length} \tag{48}$$

9.8. Total Cost Calculation

Due to the fact that the worth of money varies over time, a common approach for comparison is to convert the money in different years to the beginning moment, i.e. year 0. The CAPEX, which is the purchase cost occurs at year 0. And with the help of the approach in section 9.6., unagi can calculate the net present value of OPEX at year 0. Thus, the total cost can be obtained by

$$\text{Total Cost} = \text{CAPEX} + \text{OPEX}_{\text{npv}} \tag{49}$$

10. IAC Loss Study

10.1. Business Challenge

`IAC Loss Study` calculates the energy loss flows (a series of yearly loss) of an entire offshore wind farm based on different power generation profiles at different operation variants of off-shore substation. The term IAC stands for *Inter-Array Connection*.

The energy loss of an entire offshore wind farm consists of the losses of all inter-array cables and WTG-transformers, which in turn depend on their corresponding power loss over certain period of time. The power losses of all components are correlated, since they are in the same network. This study helps user find the optimal design of IAC layout, which has the least energy loss. In addition, it provides insightful comparison to find the best operation variant at the offshore substation.

10.2. Study Scope

Fig. 52 illustrates a typical IAC network, where the rest of the power system is represented as an *external grid* at the busbar of the offshore substation. Each circle is a WTG, which is connected to an IAC cable via a WTG-transformer.

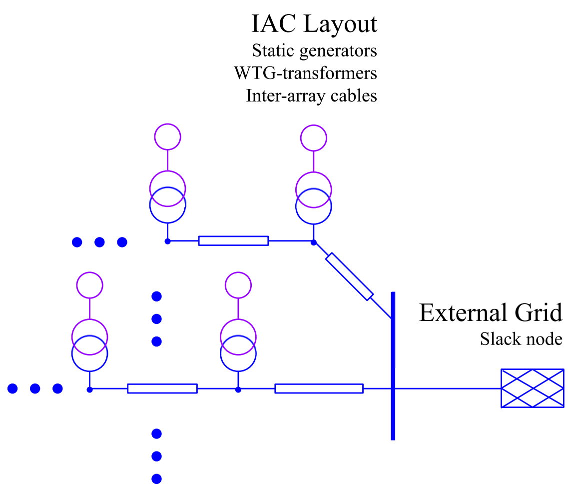

Figure 52: Network representation of IAC.

The power losses of all the components depends on the active power and the power factor of each WTG, as well as the voltage at the busbar of the offshore substation.

To calculate energy losses of all components, this study uses a similar process as `Cable CAPEX and OPEX Study`. It allows different forms of power generation: `annual` or `series`. For power form of `annual`, each profile is several pairs of duration and power within one year (8760 hours), it is assumed that each year has the same pattern. Unagi will calculate the energy loss over the year and repeat it for N years. Note that the sequence of those duration-power pairs is ignored, and each profile can have different number of pairs.

For power form of `series`, each profile is a time-series of power. The timestep is fixed and the timespan defines the number of years, and all profiles must have the same timestep but can have different timespan. In addition, Unagi allows user to specify the temperature form for the conductor temperature of the cable: `constant` or `variable`. If the conductor temperature is `constant`, then the temperature of sheath and armour are also constant in steady-state. And all of them are independent from cable load current. On the other hand, if the conductor temperature is `variable`, then the temperatures of conductor, sheath, and armour are all variable. Unagi uses the moving average load current certain time-window, e.g. 7 days (168 hours), to calculate those temperatures in steady-state.

The power form of `annual` is the quickest option to run, since it needs just aggregated profiles. But its results have the least details. While the power form of `series` with the temperature form of `variable` is the slowest, since it needs to calculate for each time point (for a timestep of 1 hour, there are 8760 time points per year). But its results have the most details.

User should choose based the profiles at hand and the waiting time for the study to finish.

10.2.1. Assumptions

- It assumes only one offshore bus. And all buses whose name starting with `"SS"` are represented by one bus.
- All static generators are the same, i.e. the same power profile and the same power factor.
- All WTG-transformers are the same, i.e. the same transformer genre. And they are modelled by a 2-winding transformer genre.

10.2.2. User to Specify

- Frequency, 50 Hz or 60 Hz.
- Conductor temperature limit, in [$^\circ\mathrm{C}$].
- Environment temperature, in [$^\circ\mathrm{C}$].
- Operation variant file, which is a csv-file.
- Burial condition.
  - Covering thermal resistivity, in [Km/W].
  - Covering depth, in [m]. It is from the soil surface to the outer surface of the cable, not to the geometric center of the cable. It is easier for user to change different cable genres at the same depth, since different cable genres can have different diameters.
- External Grid:
  - Voltage phase angle in [degree].
  - R/X ratio of the short-circuit impedance.
  - Short-circuit power in [MVA].
- Wind Power Generator
  - Power unit: [W], [kW], or [MW].
  - Number of years.
  - Duration-Power profiles file, which is a csv-file.
- Power form: *annual* or *series*.
  - For *annual*
    - Rated active power, in the unit defined by *Power unit* above.
    - Number of years.

  - Duration-power profiles file, which is a csv-file.
- For *series*
  - Start timestamp. It is in the format of `YYYY-MM-DD HH:MM:SS`, e.g. `2022-06-10 01:00:00`. It is the starting moment of the power profiles. All profiles must have the same starting moment.
  - Timestep, in [h]. It is the timestep of the power profiles. All profiles must have the same timestep.
  - WTG Power profiles form: *power* or *pattern*.
    - For *power*. User directly provides a csv-file of WTG Power containing one or more time-series profiles.
    - For *pattern*. User provides two csv-files. One is for WTG Power Curve containing the relationship between wind speed and WTG power. And other is for wind speed containing one or more time-series profiles.
  - temperature form: *constant* or *variable*.
    - For *constant*. User provides a constant conductor temperature, in [$^\circ\mathrm{C}$].
    - For *variable*. User provides a time-window for the moving average of WTG power.

- IAC-Layout
  - IAC layout file, which is a csv-file.
  - IAC nominal voltage, in [kV].
  - Default loss method.
    - IEC. It calls `Cable Loss IEC Study` by default.
    - Southampton. It calls `Cable Loss Southampton Study` by default.
  - A map from cable genre code to cable genre name. This is because the IAC layout file contains a genre code for each cable section. A code indicates the conductor cross-sectional area and its metal material. There are probably more than one cable genre matching this code. User needs to specify one cable genre name to each code.
- The name of WTG-transformer genre. It is a 2-winding transformer, and its rated HV voltage must match the IAC nominal voltage mentioned above.

Unlike other studies, this study does not let user directly provide the genres of cables and transformers. Instead, user needs to only provide the names of existing genres in the database.

For cable genres, only those containing all the required parameters for `power-flow`, `Cable Loss Study`, and `Cable Thermal Resistance Calculation` can be used. See appendix 1.1. for details.

For transformer genres, only those with rated HV voltage matching the IAC nominal voltage can be used. See appendix 1.2. for details.

10.2.3. Logic Flow

A high level logic flow of the `analyse` method in `IAC Loss Study` is shown in Fig. 53.

It first builds up the network of wind-farm. The nominal voltage of the bus between WTG and WTG-transformer is set to be equal to the rated LV winding voltage of the WTG-transformer genre.

Then for each pair of operation variant, which are the voltage magnitude at the offshore busbar (connected to the external grid in Fig. 52) and the power factor of each WTG, the module of `Network Profiler` is used to calculate the energy losses. `Network Profiler` uses `power-flow` to obtain the current and voltage of each cable section and the power loss of WTG-transformers.

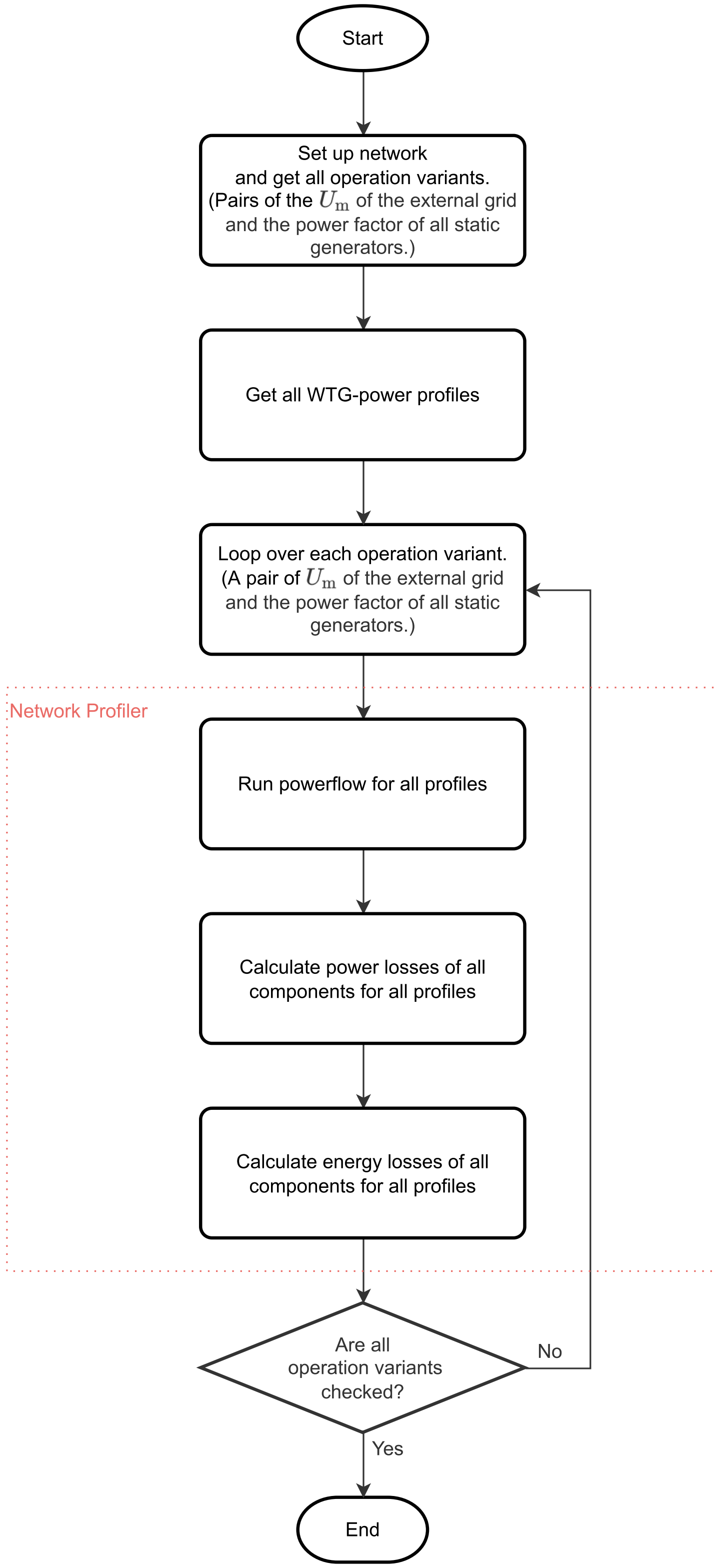

Figure 53: Logic flow of the `analyse` method in `IAC Loss Study`.

Then it uses `Cable Loss Study` and `Cable Thermal Resistance Calculation` to obtain the power loss of each cable section. Note that the WTG-power profiles are obtained using the same approach described in the 44 and section 9.3.1..

A high level logic flow of the `Network Profiler` is shown in Fig. 54. This is for general application which can have shunts and transformers. For `IAC Loss Study`, there are no shunts but many WTG-transformers.

With each WTG-power value, a powerflow calculation is performed. The power loss of a WTG-transformer can be obtained directly from the powerflow results. This is a simplified method, which ignores the influence of harmonic current and temperature. The power loss of a cable section cannot be obtained directly from the powerflow results. Instead, the voltage and current at the *to-bus* of the cable section is obtained from the powerflow results. Then the `Cable Loss Profiler` is used to obtain its power loss, see 9.4.. Note that the voltage and current at the *to-bus* of a cable section is used to represent the voltage and current along the entire cable section. Thus, the difference of these values at different position on the same cable section is ignored, since a cable section in an IAC network is usually not longer than a few [km]. And it is much more computationally efficient than having the extra step to calculate these values at different internal positions along the section, see appendix 4..

After the power loss of each component is obtained, the corresponding energy loss can be calculated over time, see section 9.5. for details.

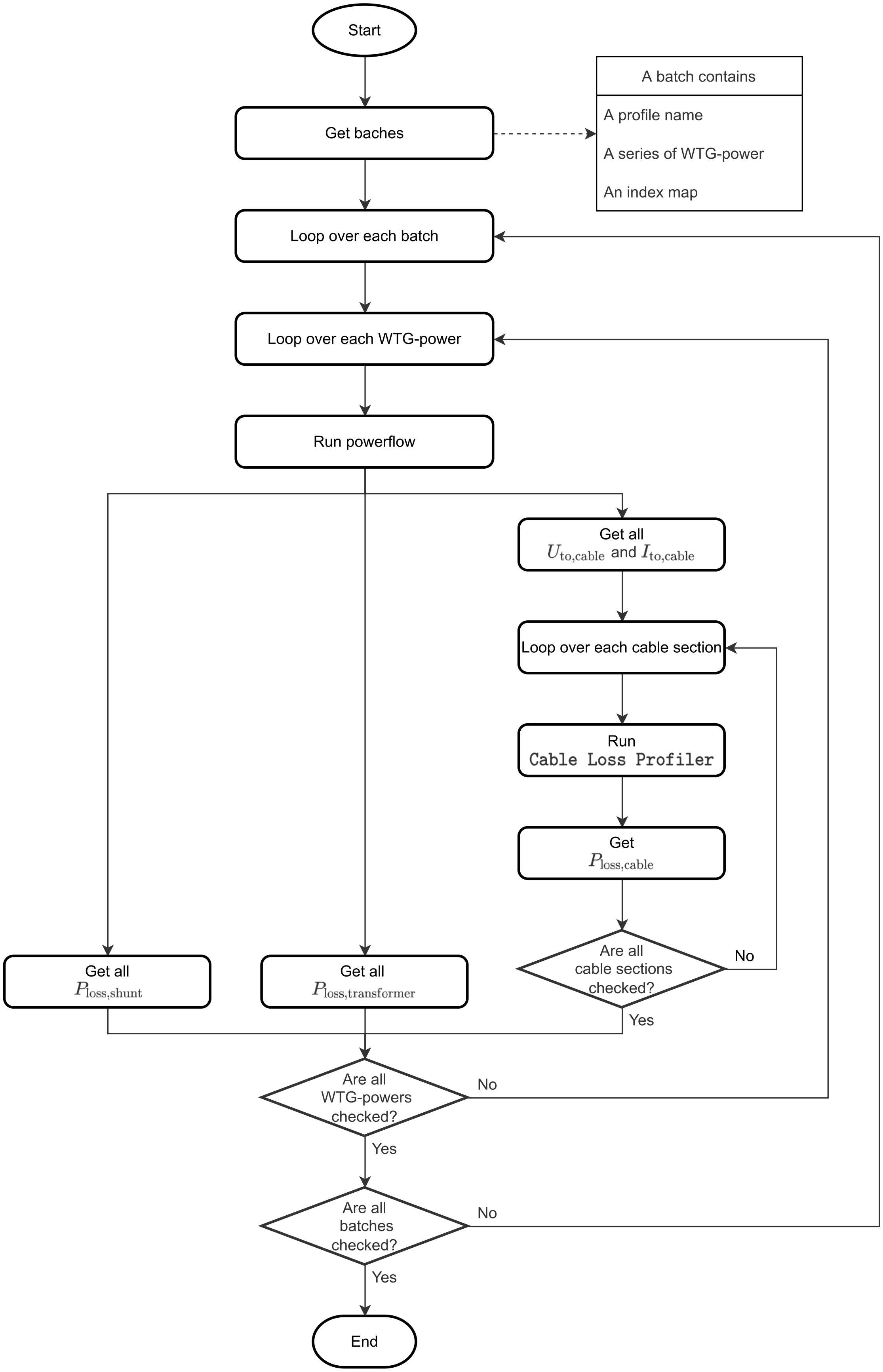

Figure 54: Logic flow of the `Network Profiler` for general application.

11. AC/DC Concept Study

This chapter describes the principles of AC/DC Concept study.

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APPENDIX 1. Component Modelling

1.1. Cable Genre

A cable genre consists of a group of parameters that independent from the length and location of a cable section. The needed parameters depend on the involved calculations. These parameters can be obtained from cable manufacturers.

1.1.1. Power-Flow Calculation

The parameters needed for power-flow calculation are as follows.

- Resistance per unit length.
- Inductance per unit length.
- Capacitance per unit length.

Note the resistance per unit length of a cable genre can vary at different frequency and temperature. For power-flow purpose, Unagi uses the conductor AC resistance at 90 $^\circ\mathrm{C}$, which is commonly available by the datasheet provided by cable manufacturers.

1.1.2. Cable Loss Calculation

The parameters needed for cable loss calculation are many more and much detailed than power-flow calculation. Different approaches require different parameters. Unagi implemented two widely used approaches: IEC and Southampton.

IEC Approach

The parameters need for cable loss calculation with IEC approach are as follows. For details see [3].

- Rated line voltage
- Capacitance per unit length (optional). Unagi will calculate it if not provided.
- Core overall diameter
- Core lay length
- Insulation
  - Inside diameter
  - Outside diameter
  - Relative permittivity
  - Loss factor $\tan\delta$
- Conductor
  - Form. It can be `Round Solid` or `Round Stranded`.
  - Metal. It can be `Aluminium` or `Copper`.
  - Cross-sectional area
  - Nominal diameter
  - DC resistance per unit length at 20 $^\circ\mathrm{C}$.
- Sheath

  - Form. It can be `Solid`, `Tape`, or `Wire`.
  - Metal. It can be `Aluminium`, `Copper`, or `Lead`.
  - DC resistance per unit length at 20 $^{\circ}\mathrm{C}$ (optional). Unagi will calculate it if not provided.
  - Solid type
    - Inside diameter
    - Outside diameter
  - Tape type
    - Mean diameter
    - Number of tapes
    - Tape width
    - Tape thickness
    - Lay length.
  - Wire type
  - Mean diameter
  - Number of wires
  - Wire diameter
  - Lay length
  - Foil part (optional). A sheath can have foil, but not a must.
    - Foil metal. It can be `Aluminium` or `Copper`.
    - Foil mean diameter.
    - Foil thickness.
- Armour
  - Magnetic form. It can be magnetic or not.
  - Metal. It can be `Aluminium`, `Steel` or `Stainless Steel`.
  - DC resistance per unit length at 20 $^{\circ}\mathrm{C}$ (optional). Unagi will calculate it if not provided.
  - Form. It can be `1` or `2` layers.
  - Layer 1 (inner layer)
    - Number of wires
    - Wire diameter
    - Layer mean diameter
    - Layer lay length
  - Layer 2 (outer layer). Not considered by IEC approach.

Note that IEC gives guidance to model only solid type sheath [3]. If you have a cable genre with tape type sheath or wire type sheath, and you want to use IEC approach to calculate cable loss, Unagi will adapts the methods presented in Southampton approach to model the sheath, and the rest part of the calculation follows the IEC approach.

Moreover, IEC approach considers only single-layer armour. For an armour with 2 layers, the electro-magnetic field will be screened mostly within the inner layer. Therefore, the induced current (i.e. power loss) in the outer layer can be ignored [10]. If you have a cable genre with 2 layers of armour, and you want to use IEC approach to calculate cable loss, Unagi will ignore the outer layer of the armour.

Southampton Approach

The parameters need for cable loss calculation with Southampton approach are as follows. For details see [6].

- Rated line voltage
- Capacitance per unit length (optional). Unagi will calculate it if not provided.
- Core overall diameter
- Core lay length
- Insulation
  - Inside diameter
  - Outside diameter
  - Relative permittivity
  - Loss factor $\tan \delta$
- Conductor
  - Metal. It can be `Aluminium` or `Copper`.
  - Cross-sectional area
  - Nominal diameter
- Sheath
  - Form. It can be `Solid`, `Tape`, or `Wire`.
  - Metal. It can be `Aluminium`, `Copper`, or `Lead`.
  - Solid type
    - Inside diameter
    - Outside diameter
  - Tape type
    - Mean diameter
    - Number of tapes
    - Tape width
    - Tape thickness
    - Lay length.
  - Wire type
  - Mean diameter
  - Number of wires
  - Wire diameter
  - Lay length
  - Foil part.
    - Foil metal. It can be `Aluminium` or `Copper`.
    - Foil mean diameter.
    - Foil thickness.
- Armour
  - Metal. It can be `Aluminium`, `Steel` or `Stainless Steel`.
  - Wire form. It can be `Round` or `Special`.
  - Form. It can be `1 layer`, `1 layer, 2-out-of-3 spacing`, or `2 layers`.
  - Layer 1 (inner layer)
    - Number of wires
    - Wire diameter (optoinal), needed only if the wire form is `round`.
    - Layer mean diameter
    - Layer lay length
    - Layer lay form. It can be `unilay` or `contralay`.
    - Conductivity
    - Relative permeability (complex value)

  - Layer 2 (outer layer)
    - Number of wires
    - Wire diameter (optoinal), needed only if the wire form is `round`.
    - Layer mean diameter
    - Layer lay length
    - Layer lay form. It can be `unilay` or `contralay`.
    - Conductivity
    - Relative permeability (real and imaginary parts)
    - Armour resistivity between the two layers.
  - Parameters only if the wire form is `special`
    - Reflection factor of 2-pole (real and imaginary parts)
    - Reflection factor of 4-pole (real and imaginary parts)
    - Armour circulating loss

Note that the Southampton approach only allows wire type sheath with foil [6]. If you have a cable genre with wire type sheath but without foil, then you cannot use Southampton approach to calculate cable loss. You can only use IEC approach.

1.1.3. Cable Thermal Resistance Calculation

The parameters need for cable thermal resistance calculation are as follows. For details see [1].

- Core overall diameter
- Insulation
  - Thermal resistivity
- Filler
  - Thermal resistivity
- Serving
  - Outside diameter
  - Thermal resistivity
- Conductor
  - Nominal diameter
- Sheath
  - Inside diameter
  - Outside diameter
- Armour
  - Form. It can be `1 layer` or `2 layers`.
  - Layer 1 (inner layer)
    - Wire diameter.
    - Layer mean diameter
  - Layer 2 (outer layer)
    - Wire diameter.
    - Layer mean diameter

Note that, to calculate cable thermal resistance for a cable genre, we need the inside and outside diameters of the sheath for all sheath types (solid, tape, and wire).

1.2. 2-Winding Transformer Genre

A 2-winding transformer genre consists of a group of parameters that independent from the location of a 2-winding transformer.

1.2.1. Power-Flow Calculation

The parameters needed for power-flow calculation are as follows.

- $U_{r,\mathrm{HV}}$, rated voltage of HV winding
- $U_{r,\mathrm{LV}}$, rated voltage of LV winding
- S_r, rated apparent power
- u_k, impedance voltage from short-circuit test.
- p_k, copper loss from short-circuit test.
- i_0, no-load current from open-circuit test.
- p_0, no-load power loss from open-circuit test.

1.3. 3-Winding Transformer Genre

A 3-winding transformer genre consists of a group of parameters that independent from the location of a 3-winding transformer.

1.3.1. Power-Flow Calculation

The parameters needed for power-flow calculation are as follows.

- $U_{r,\mathrm{HV}}$, rated voltage of HV winding
- $U_{r,\mathrm{MV}}$, rated voltage of MV winding
- $U_{r,\mathrm{LV}}$, rated voltage of LV winding
- $S_{r,\mathrm{HV}}$, rated apparent power of HV winding
- $S_{r,\mathrm{MV}}$, rated apparent power of MV winding
- $S_{r,\mathrm{LV}}$, rated apparent power of LV winding
- $u_{k,\mathrm{HV-MV}}$, impedance voltage from short-circuit test from HV winding to MV winding.
- $u_{k,\mathrm{HV-LV}}$, impedance voltage from short-circuit test from HV winding to LV winding.
- $u_{k,\mathrm{MV-LV}}$, impedance voltage from short-circuit test from MV winding to LV winding.
- $p_{k,\mathrm{HV-MV}}$, copper loss from short-circuit test from HV winding to MV winding.
- $p_{k,\mathrm{HV-LV}}$, copper loss from short-circuit test from HV winding to LV winding.
- $p_{k,\mathrm{MV-LV}}$, copper loss from short-circuit test from MV winding to LV winding.
- i_0, no-load current from open-circuit test.
- p_0, no-load power loss from open-circuit test.

1.4. Cable Section

A cable section is a branch component in a network.

1.4.1. Power-Flow Calculation

To perform a power-flow calculation, the minimum required parameters are

- a from-bus
- a to-bus
- length
- a cable genre

Here, the from-bus and to-bus are the two terminals of a cable section.

Unagi assumes a cable section to be longitudinally homogeneous. That means, along the section, all the parameters like cable genre and external environment are constant. If an actual connection has different parameters, you need to split the connection into different sections, where each section is longitudinally homogeneous. For example, if a connection has two different cable genres, you need to use two cable sections to model the connection, where each cable section has one cable genre.

Note the nominal voltage of a cable section is determined by the nominal voltage of the connected bus. The rated voltage of the involved cable genre can be equal to or higher than the nominal voltage.

1.5. 2-Winding Transformer

A 2-winding transformer is a branch component in a network.

1.5.1. Power-Flow Calculation

To perform a power-flow calculation, the minimum required parameters are

- a HV-bus
- a LV-bus
- a transformer genre

Note the nominal voltage of a winding of a transformer is determined by the nominal voltage of the connected bus. The rated voltage of the winding of the involved transformer genre can be equal to or higher than the nominal voltage.

Moreover, Unagi assumes the tap-changer of a transformer is fixed at its rated position.

1.6. 3-Winding Transformer

A 3-winding transformer is a branch component in a network.

1.6.1. Power-Flow Calculation

To perform a power-flow calculation, the minimum required parameters are

- a HV-bus
- a MV-bus
- a LV-bus

- a transformer genre

Note the nominal voltage of a winding of a transformer is determined by the nominal voltage of the connected bus. The rated voltage of the winding of the involved transformer genre can be equal to or higher than the nominal voltage.

Moreover, Unagi assumes the tap-changer of a transformer is fixed at its rated position.

1.7. External Grid

The actual power system much larger than the focused area of a study. It is commonly to model the focused area in detail and aggregate the rest network by an external grid component, which is widely used as a slack-node in the network. It is used only for power-flow calculation in Unagi.

1.7.1. Power-Flow Calculation

The parameters needed for power-flow calculation are as follows.

- Voltage magnitude
- Voltage phase angle
- RX ratio
- Short-circuit power

Note that, in Unagi the model presented in Fig. 55 is used. The external grid works as a slack-node in the network, and the parameters of RX ratio and Short-circuit power are used to determine the short-circuit impedance $\underline{Z}_{\mathrm{ext}}$ of the external grid. If the impedance is placed behind the slack-node, i.e. $\underline{Z}_{\mathrm{ext}}$ and external grid are on the same side of the slack-node, then the right-side shunt reactor is equivalent to be connected to the slack-node, whose voltage is fixed. And consequently the right-side shunt reactor does not work at all.

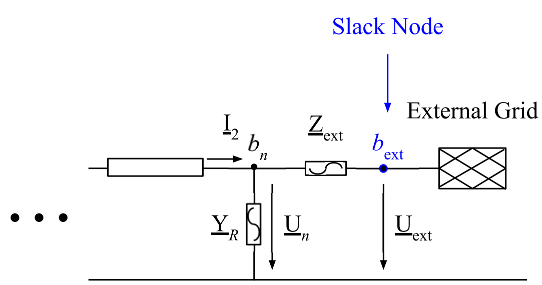

Figure 55: Model of external grid.

1.8. Shunt Reactor

A shunt reactor is used at a certain location along the export cable connection for reactive power compensation. It is modelled as a impedance with a resistive and an inductive part.

1.8.1. Power-Flow Calculation

Practically, the reactive power compensation is usually designed from a broader view other than just the component itself. It needs

- Compensation scheme. It specifies the necessity of the shunt and the location (`L`, `M`, `R`).
- Total compensation ratio. The base is the total reactive power from the cable connection. The total reactive power of the shunts are then determined by the product of the ratio and the base.
- Split. It gives the contribution of each shunt for reactive power compensation versus the total compensation ratio. The sum of the split of all shunts must be 1.
- RX ratio. For a shunt, it specifies the relative amount of the resistive part and the inductive part.

1.8.2. Parameters Derivation

A shunt reactor is modeled by its admittance, where a resistor (R) and reactor (X) are series connected. If the single-phase reactive power (Q_r [var]), r-x ratio, and rated phase voltage (Ur [V]) of a shunt reactor are known, the single-phase active power (P_r [W]) and admittance (Y [S]) of the shunt reactor can be calculated.

With known $\alpha = R/X$ and $U_r = |\underline{U}_r|$

$$
\begin{aligned}
Q_r = |\underline{I}_r|^2 \cdot X &= \frac{|\underline{U}_r^2|}{R^2 + X^2} \cdot X \\
&= \frac{U_r^2}{\alpha^2 \cdot X^2 + X^2} \cdot X \\
&= \frac{U_r^2}{(\alpha^2 + 1) \cdot X}
\end{aligned}
$$

Thus,

$$
\begin{aligned}
P_r &= |\underline{I}_r|^2 \cdot R = |\underline{I}_r|^2 \cdot X \cdot \frac{R}{X} = Q_r \cdot \alpha \\
X &= \frac{U_r^2}{(\alpha^2 + 1) \cdot Q_r} \\
R &= \alpha \cdot X \\
Y &= \frac{1}{R + jX}
\end{aligned}
$$

1.9. Static Generator

A static generator is commonly used to model wind-power generator for power-flow calculation. It is a generator with constant active and reactive power feed-in.

1.9.1. Power-Flow Calculation

- Active power.
- Power factor
- Mode. It can be `overexcited` or `underexcited`.

APPENDIX 2. Format Requirement

2.1. Operation Variants File

It is a CSV file that uses comma "," as column separator and dot "." as decimal separator. It can have many rows but only two columns. The first row is the header, which should be kept unchanged. The first column gives different values of voltage magnitude at the offshore substation (connected to the external grid). The unit is `[p.u.]` referring to the user-defined `IAC Nominal Voltage`. The second column gives different values of power factors of WTGs. The values should be in the range of `[-1, 1]`. Positive means the WTGs are in the `overexcited` mode, while negative means the WTGs are in the `underexcited` mode. The number of rows of two columns do no need to match. `Unagi` will make a combination between each pair of them.

Take the following file content as an example.

```
um_pu,power_factor
1,1
0.9,-0.95
,0.95
```

There are two values in the first column, `um_pu`, and three values in the second column `power_factor`. `Unagi` automatically builds six pairs:

$$
\begin{aligned}
&(\texttt{um\_pu} = 1, \quad \texttt{power\_factor} = 1)\\
&(\texttt{um\_pu} = 1, \quad \texttt{power\_factor} = -0.95)\\
&(\texttt{um\_pu} = 1, \quad \texttt{power\_factor} = 0.95)\\
&(\texttt{um\_pu} = 0.9, \quad \texttt{power\_factor} = 1)\\
&(\texttt{um\_pu} = 0.9, \quad \texttt{power\_factor} = -0.95)\\
&(\texttt{um\_pu} = 0.9, \quad \texttt{power\_factor} = 0.95)
\end{aligned}
$$

2.2. Duration Power File

It is a CSV file that uses comma "," as column separator and dot "." as decimal separator. It can have many rows and many columns. The first two rows are the header, and every profile contains two columns: one for `Duration` and the other for `Power`. The first row gives profiles' names, and the second row gives the each profile's `Duration` and `Power`. The user is free to use any profile name in the first row, but the second row of each profile should be kept unchanged. Note that each profile has one name but two columns. Thus, after each profile name, there should be an empty field marked by double commas, ",,", in the first row. There can be as many profiles as the user needs. For each profile, the duration and power must be in pairs, i.e., the number of durations and the number of power must be the same. While different profiles can have a different number of pairs. A value of `Duration` is a portion of a year, e.g., 0.5 means half year. Thus, it cannot be larger than 1, and the sum of all durations in one profile must be equal to 1. Note

`Unagi` assumes one year has 8760 hours. A value of `Power` is in the unit of [p.u.], referring to the user-defined `Rated Active Power` of a WTG.

Take the following file content as an example.

```
Profile_1,,Profile_2,,Profile_3,
Duration,Power,Duration,Power,Duration,Power
0.25,1,0.25,0.75,0.2,0.8
0.1,0.75,0.1,0.5,0.2,0.5
0.5,0.5,0.4,1,0.6,0.9
0.15,0.25,0.1,0.25,,
,,0.15,0.25,,
```

There are three profiles, thus six columns. `Profile_1` has four pairs, `Profile_2` five pairs, and `Profile_3` three pairs.

2.3. WTG Power File

It is a CSV file that uses comma "," as column separator and dot "." as decimal separator. It can have many rows and many columns. The first row is the header, which gives a name of each profile. The user is free to use any profile name. Each profile uses one column. It has time-series values of WTG active power in the unit of [p.u.], referring to the user-defined `Rated Active Power` of a WTG. A different profile can have a different length.

Note the timestamps should not be given in this file. Unagi uses the user-defined `Start Timestamp` and `Timestep` to construct all the timestamps. The timestamps should at least cover one calendar year to allow yearly-based analysis like yearly energy loss and yearly OPEX. Thus, if the `Start timestamp` is `2021-01-01 00:00:00` and the `Timestep` is 1 [h], then the user must provide at least 8761 values in a profile because there are 8760 hours in the year 2021 and at least one more value for the year 2022. Then, the yearly-based analysis will be performed for these two years. It is worth mentioning that the timestamps are based on calendar years, not relative years. Say with the `Timestep` of 1 [h], for the same length of values, say 17520, if the `Start timestamp` is `2021-01-01 00:00:00`, then time range covers two whole years of 2021 and 2022 (both these calendar years have 8760 hours). However, if the `Start timestamp` is `2021-07-01 00:00:00`, then the time range covers the second half-year in 2021, the whole year of 2022, and the first-half year in 2023. Moreover, the effect of a leap year is automatically considered. For example, the year 2020 is a leap year. Suppose the `Timestep` is 1 [h] and a profile's length is 8761. Then if the `Start timestamp` is `2021-01-01 00:00:00`, the end timestamp is in the year of 2022. However, if the `Start timestamp` is `2020-01-01 00:00:00`, the end timestamp is still in the year of 2020. Last, `Unagi` generates timestamps according to UTC (Coordinated Universal Time). So, issues like time-zone dependence and daylight saving shift are automatically excluded.

Take the following file content as an example. It is not the entire content but just a part of it. The actual file content can have many more rows.

```
profile_1,profile_2
0.62,0.2
0.7,0.13
1.0,0.4
```

```
0.99,0.6
0.8,
0.2,
```

2.4. WTG Power Curve File

It is a CSV file that uses comma "," as column separator and dot "." as decimal separator. It can have many rows but only two columns. The first row is the header, and it should be kept unchanged. The first column is for wind speed and the second column is for active power of WTG. They form a pattern describing the relationship between `power` and `windspeed`. Unagi assumes all WTGs use the same pattern. It will use interpolation to fit the function. Then the corresponding power can be obtained for any wind speed. Note that for wind speed values outside the range provided by this file, the resulting power is zero. This file is used in combination with the `Windspeed File`. Thus, the unit of wind speed is not important, but the two files, `WTG Power Curve File` and `Windspeed File`, must use the same unit. The values of `power` is not in [p.u.], but in a user-defined unit, e.g. [MW].

Take the following file content as an example. It is not the entire content but just a part of it. The actual file content can have many more rows.

```
windspeed,power
2.9,0
3,70.021377
3.1,111.639888540136
```

2.5. Windspeed File

It is a CSV file that uses comma "," as column separator and dot "." as decimal separator. It can have many rows and many columns. The first row is the header, which gives a name of each profile. The user is free to use any profile name. Each profile uses one column. It has time-series values of wind speed, which is in the same unit as that in the file of `WTG Power Curve File`. A different profile can have a different length.

Note the timestamps should not be given in this file. Unagi uses the user-defined `Start Timestamp` and `Timestep` to construct all the timestamps based on the same approach for the `WTG Power Curve File`, see appendix 2.3..

Take the following file content as an example. It is not the entire content but just a part of it. The actual file content can have many more rows.

```
ws_profile_1,ws_profile_2
7.617,6.1
7.244,6.2
6.717,6.3
6.097,6.4
6.016,6.5
```

```
5.774,6.6
5.813,6.7
5.656,
5.476,
```

2.6. IAC Layout File

It is a CSV file that uses comma “,” as column separator and dot “.” as decimal separator. It can have many rows but only three columns. Unagi uses this file to construct an IAC network. It consists of blocks; each block is for one string. The first row starts with “String #...”; and the last row starts with “,Total,...”. The first row is the header but not actually used by Unagi. The second row must always starts with “SS...”. The term of “SS” represents the bus at offshore substation to which the external grid is connected. From the third row on, each row starts with a name of WTG connecting point along a IAC string. The second column is a cable genre code. The code must use this format: <conductor area><conductor metal>. Only two metals are accepted: AL for aluminium and CU for copper. The third column is the length from the bus mentioned by the previous row. The length must be in the unit of [km]. Since this style is reserved for export connection. The last row is for the total length of the string. It must contains the word “Total”.

Note that the bus name can be any name with the following exceptions.

- The name of bus cannot use the style of bus_ex_<num>, where <num> is a place holder for an arbitrary number. For example, bus_ex_0, bus_ex_1, etc.
- It cannot starts with SS, like SS1, SSABC, etc. Because Unagi uses it to detect the start of every string.
- It cannot contain the word Total. Because Unagi uses it to detect the end of every string.

Take the following file content as an example. It is not the entire content but just a part of it. The actual file content can have many more rows.

```
1 String #1,Cable Type,Length (km)
2 SS1,-,0
3 B1,800AL,7.8
4 B2,300AL,2.91
5 ,Total,10.71
6 String #2,Cable Type,Length (km)
7 SS1,-,0
8 C1,800AL,3.6
9 C2,800AL,2.91
10 C3,300AL,2.01
11 C4,300AL,1.34
12 ,Total,9.86
13 String #3,Cable Type,Length (km)
14 SS1,-,0
15 D1,800AL,2.26
16 D2,300AL,2.48
```

String 1 is described by the block from row 1 to row 5, and string 2 by the block from row 6 to row 12. The third row shows that the bus name is B1, the IAC cable section connects from this bus to the bus in the offshore substation, which is indicated by the previous row (the second row). It uses the cable genre code of `800AL`. And the cable section is 7.8 [km] long. Likewise, the fourth row defines the bus name as `B2`. The cable section connects this bus to the bus `B1`. The cable genre code is `300AL`, and the length of the cable section is 2.91 [km].

2.7. Database Cable Genre File

It is a CSV file that uses comma "," as column separator and dot "." as decimal separator. It can have many rows but a fixed number of columns. The first row is the header and should be kept unchanged. See appendix 1.1. for details. `Unagi` provides both a template and an example.

2.8. Database Transformer2W Genre File

It is a CSV file that uses comma "," as column separator and dot "." as decimal separator. It can have many rows but a fixed number of columns. The first row is the header and should be kept unchanged. See appendix 1.2. for details. `Unagi` provides an example.

2.9. Database Transformer3W Genre File

It is a CSV file that uses comma "," as column separator and dot "." as decimal separator. It can have many rows but a fixed number of columns. The first row is the header and should be kept unchanged. See appendix 1.3. for details. `Unagi` provides an example.

APPENDIX 3. Accelerate

`Unagi` uses two approaches to accelerate the computation on a single computer: parallel computing and rounding decimals.

3.1. Parallel Computing

It is realized by the Python built-in package called `multiprocessing`, which provides process-based parallelism. A specific part of a study process is split into different batches. Each batch can run independently. If the user enables parallel computing, `Unagi` will use all the threads in the CPU to run those batches in parallel.

To find out the number of threads in the CPU on a computer, use this Python code:

```
import multiprocessing as mp

mp.cpu_count()
```

3.2. Rounding Decimals

Rounding decimals can cause a loss of accuracy but reduce computation time. For a specific iteration process, a different input value will have a different result, and the same input value will have the same result. Thus, rounding two different decimals both to a certain position can make them equal, and consequently `Unagi` needs to run the iteration once instead of twice.

For an MW-level WTG, its operating active power value is practically accurate enough if the precision is at the [kW] level. For example, two WTG power values 123456.789 [W] and 123123.123 [W] can be both rounded up to 123000 [W] ($= 123$ [kW]).

For the power loss calculation of an IAC network, the current in the cables can be accurately represented with the precision of 10 [A], and the cable temperature can be accurately represented with the precision of 1 [Celsius]. For example, the value of 123.456 [A] can be rounded up to 120 [A], and 123.456 [Celsius] can be rounded up to 123 [Celsius].

APPENDIX 4. Calculate U and I of Cable Section

The voltage and current at any terminal of any cable section can be calculated by power-flow calculation. The ABCD-matrix approach can then be used to calculate the voltage and current at any position on a cable section.

For a cable section shown in Fig. 56, suppose $\underline{U}_q$, $\underline{I}_q$, $\underline{U}_p$, and $\underline{I}_p$ are obtained from power-flow calculation. Then, the program creates n (e.g. $n = 99$) cable subsections with the same cable genre but different lengths. With the given values of $\underline{U}_q$ and $\underline{I}_q$, the ABCD-matrix approach is then used to obtain the voltage and current at positions p_1, p_2, p_3, ..., p_n.

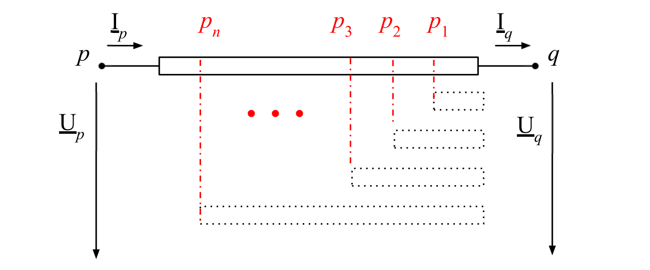

Figure 56: Calculation of voltage and current at any position on a cable section.

4.1. ABCD-Matrix Appraoch

The ABCD-matrix is used to described the relationship between the voltage and current from the two terminals of a cable section. The detailed explanation can be found in [12].

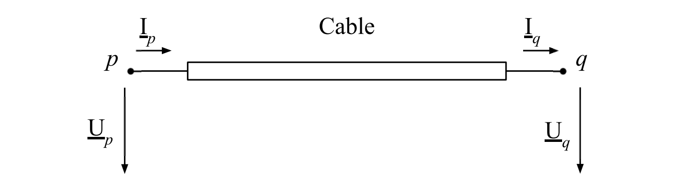

Figure 57: A cable section with two terminals p and q.

For a single phase cable section (see Fig. 57), the ABCD-matrix equation formulated as

$$\begin{bmatrix} \underline{U}_p \\ \underline{I}_p \end{bmatrix} = \begin{bmatrix} \underline{A} & \underline{B} \\ \underline{C} & \underline{D} \end{bmatrix} \begin{bmatrix} \underline{U}_q \\ \underline{I}_q \end{bmatrix} \tag{50}$$

where

$$\begin{aligned}
\underline{A} &= \cosh(\underline{\gamma} d)\\
\underline{B} &= \underline{Z}_{\mathrm{w}} \sinh(\underline{\gamma} d)\\
\underline{C} &= \frac{1}{\underline{Z}_{\mathrm{w}}} \sinh(\underline{\gamma} d)\\
\underline{D} &= \cosh(\underline{\gamma} d)\\
\underline{\gamma} &= \sqrt{(R + j\omega L)(j\omega C)}\\
\underline{Z}_{\mathrm{w}} &= \sqrt{\frac{R + j\omega L}{j\omega C}}
\end{aligned}$$

- R, L, C are respectively the resistance, inductance, and capacitance per unit length of the cable section.
- d is the length of the cable section.
- $\underline{U}_p$ and $\underline{U}_q$ are respectively the phase-to-ground voltage at two terminals of the cable section.
- $\underline{I}_p$ and $\underline{I}_q$ are respectively the current at two terminals of the cable section.

APPENDIX 5. Data Derivation

5.1. External Grid

To perform short-circuit calculation with Pandapower package, the `Short-Circuit Power` [MVA] and its `R/X ratio` are needed. This section presents an example of how to derive them. The data is also used in the examples provided by `Unagi`. It is derived from the data from Table 2.

Table 2

S_r [MVA]	400 / 226 / 226
U_r [kV]	230 / 66 / 66
$u_{k,HV-MV1}$ [% @ 226 MVA]	12
$P_{k,HV-MV1}$ [kW @ 226 MVA]	558.9

The resistance of r [p.u.] can be calculated as

$$Z_{base} = \frac{U_r}{\sqrt{3}I_r} = \frac{U_r^2}{S_r} \tag{51}$$

$$R = \frac{P_k}{3I_r^2} = \frac{P_k \times U_r^2}{S_r^2} \tag{52}$$

Therefore,

$$r = \frac{R}{Z_{base}} = \frac{P_k \times U_r^2}{S_r^2} \cdot \frac{S_r}{U_r^2} = \frac{P_k}{S_r} = \frac{558.9 \times 10^3 [W]}{226 \times 10^6 [VA]} = 0.002473\,[p.u.] \tag{53}$$

Then with

$$r^2 + x^2 = u_k^2 \quad \Rightarrow \quad x = \sqrt{u_k^2 - r^2} = \sqrt{0.12^2 - 0.002473^2} = 0.119975\,[p.u.] \tag{54}$$

Thus, the rx_ratio can be calculated

$$rx\_ratio = r/x = 0.002473/0.119975 = 0.020613 \tag{55}$$

The the short-circuit power of the external grid can be calculated by:

$$S_k = 3 \times \frac{\left(U_r/\sqrt{3}\right)^2}{Z_k} = \frac{U_r^2}{u_k \cdot Z_{base}} = \frac{U_r^2}{u_k} \cdot \frac{S_r}{U_r^2} = \frac{S_r}{u_k} = \frac{226[MVA]}{0.12} = 1883.333333\,[MVA] \tag{56}$$

APPENDIX 6. Model Validation

6.1. Power Flow

This app uses pandapower package for power flow calculation [11]. The package is validated by their developers. They are tested against DIgSILENT PowerFactory or PSS Sincal. Their website gives detailed information about the validation.

However, to ensure the correctness for the package and for this app, various standalone tests are performed with Shell.

BIBLIOGRAPHIC INFORMATION

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