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Wind
PRO

Chapter 10
eGRID

10 ELECTRICAL eGRID

10.0 eGRID – Introduction

10.0.1 Introduction to eGRID

The influences of WTGs on the electric grid of the utility as well as an optimised design of grid connection due to economic aspects play a more and more important role.

By using the module eGRID, the essential influences of WTG projects on the electric grid can be calculated and documented for unmeshed wind farm and grid cabling by load-flow and short-circuit calculations. Specifically, it is possible to calculate

- · Annual losses in cables, lines and transformers based on local wind climate,
- · voltages at the grid nodes and utilization check of the components (design check)
- · voltage variations at the grid nodes,
- · increase of short-circuit current,
- · long term flicker,
- · voltage variations due to switching effects.

Furthermore, the calculation results are checked against compliance of norms / standards or free-definable guidelines. Everyone, dealing with the electric grid connection of WTGs like planners, manufacturer, grid as well as wind farm operators get with WindPRO and the module eGRID an useful tool, which can be used to determine and to check the influences of planned WTG projects on the one hand and on the other hand to optimise grid connection of a wind farm in relation to energetic and economic terms.

10.0.2 Background of eGRID

The module eGRID have been developed within the frame of the EU-Project „DISPOWER" (www.dispower.org) in collaboration with University Kassel (Institut für Elektrische Energietechnik/Elektrische Energieversorgungs-systeme, Kassel) and ISET (Institut für Solare Energieversorgungstechnik, Kassel).

In order to work with eGRID, the WindPRO module BASIS is required. In BASIS, the project-, object- and map management is being arranged. Please read the corresponding chapter in the documentation for the BASIS module to get further information.

eGRID is used for the calculation and estimation of electric influences of single WTGs or wind farms to the electric grid based on load-flow and short-circuit calculations of radial grids. Hereby, a symmetric three-phase grid structure represents the basis of the load-flow calculations. The German norm VDE 0102 respectively the international norm IEC 60909 is the basis for the short-circuit calculations.

Further, the module provides you with the possibility to perform a calculation of the annual losses within the wind farm cabling based on given wind conditions. By using the results of this calculation, an optimised grid layout based on economic parameters can be designed.

Additionally, within the grid topology the used objects like transformers, WTGs as well as total cable lengths are documented and displayed in order to facilitate the generation of specification sheets. For these calculations, the digital contour lines, which have been created for other calculation purposes within WindPRO, are used to calculate the lengths of cables and overhead lines automatically.

10.0.3 Step by Step guide to the Electrical Calculations

☞ Establish the maps (if you want a graphical input on the maps) and the relevant project properties (please refer to chapter BASIS)

☞ To take advantage of the advanced calculation of cable/line lengths, taking the elevation into account, height contour data should be established in a line object. See chapter 2.8 BASIS for details.

Establish the relevant objects;

☞ WTGs – these can in WTG catalogue be extended with electric properties, e.g. build in transformer and cables for advanced calculations, but for most "traditional" analyses, the WTG can just be connected and handled based on the given Power. Cos(phi) can be added at calculation start.

☞ External Grid, for defining voltage levels and short circuit power at the grid connection point.

☞ Electrical cable/line object, which holds all grid line information's. The object work as a special variant of the WindPRO line object, which mean that it must be in edit mode to add/edit lines. Lines can be digitized on map background and "snapped" to objects, like WTGs or transformers, which mean that moving a WTG or transformer automatically moves the line. At right click when digitizing a line, an object, like a transformer can be created and "dropped" at the end of the line current being digitized. The dimensions and electric properties of the lines can be given as "generic" which means that the software automatically calculates the dimensions based on voltage, load etc. This is recommended to use in the preface of the grid design.

☞ Transformers, bus bars (for splitting a cable/line to go to more destinations), loads and WTGs can be inserted as "free objects", but must then be connected via the Electrical cable/line object later on to take part in the calculation.

Perform calculations;

☞ Start the calculation using the project manager and choose the desired calculations

☞ Especially for the loss calculation, the expected annual wind farm production must be entered OR the expected wind distribution, which then gives the rough energy calculation for use in the loss calculation. Note the loss calculation is based on a simulation of different feed-in situations of the WTGs.

☞ Preview/Print the results

10.1 Input of data for Electrical Calculation

10.1.1 The eGRID Objects

Please read chapter 2 "BASIS" for general information about the work with maps and objects in WindPRO.
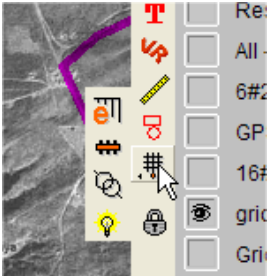
In the object bar to the right of the map, the eGRID objects are "collected" into one expandable object button. The External grid object, which always is the first to establish for designing an electrical grid system, is the "main object" – holding the cursor at this will show the other eGRID objects, from top: Electrical grid (for drawing the grid lines), the bus bar (for connecting more different cable/lines), the transformer and finally the load object.

10.1.1 Input of an External Grid (Grid connection point)

With the symbol *External Grid*, a new grid connection point is being placed on the map. The user interface for the entry of the relevant data (figure 1) appears.

Figure 1 User interface of an External Grid

The External Grid represents the basic component of the whole grid. Due to the fact that there will be only one External Grid object in most of the projects, this object is not only being used to enter the parameters of the connection point itself like e.g. short-circuit power and frequency. Additionally ALL voltage levels to be used in the later designed grid as well as a default 'increase factor' and a CosPhi-value for the WTGs have to be specified. Considering the 'increase factor' and the CosPhi-value, minimum cross sections of cables are proposed performing the cabling of the grid (Cable Cross Section Assistant).

Naturally, it is possible to enter several External Grid objects e.g. to describe alternative connection possibilities. Doing so, the External Grid object which shall be considered in a calculation has to be chosen in the calculation setup, defining the calculation itself.

For the parameter input, different input alternatives like the specification of the short-circuit power S_k or the sub-transient short-circuit power $S_k^{''}$ as well as the grid angle Y_k or the R/X-ratio are presented.

After data entry of all nominal voltage levels in the grid, which can be designated to an individual colour and displayed using this colour at the map, the nominal voltage for the External Grid as well as all other grid objects can be assigned using convenient drop-down menus.

Furthermore, it is also possible to designate the maximum allowed voltage variation to each voltage level. The compliance to this range is being checked for every single grid node after a calculation. The maximum allowed voltage levels can also be given at the time when the calculation is started.
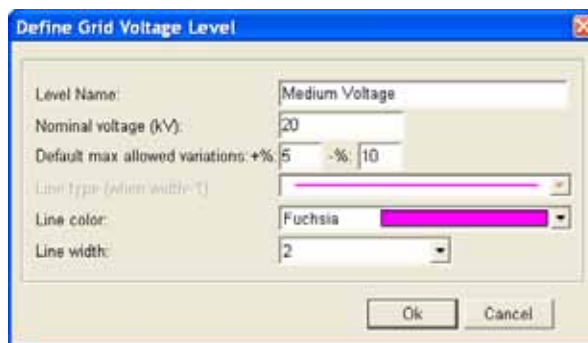
Figure 2 Definition of a voltage level. The name is free text, choosing e.g. "high", "medium" "low" or similar, allow the user to redefine voltage levels without having incompatible names related to the specified voltages.

10.1.2 Input of a Transformer

After placing a transformer, the user interface for the entry of the relevant data (figure 3) appears.

The electrical data of a transformer is subdivided into three tabs. Information about the data source as well as a description can be included in a fourth tab. The first contains more or less standard information like manufacturer, short name, type, rated power, nominal frequency and rated voltages. Based on this information, the file name of a transformer is being produced, when you have specified a new transformer.

Figure 3 User interface of a Transformer – Tab "Main specifications"

At the top of the user interface, a direct access to the transformer catalogue is given in order to choose a transformer. Under it, specifications of the nominal grid values have to be made. Due to the data input in the External Grid element, this is easily done. It is also possible to select the same voltage level for both sides to create an e.g. 20/20kV transformer in case of the utility demand to have a galvanic separation between the wind farm and the grid of the utility.

In main specifications the data giving the unique description of a transformer is given, like manufacturer, type etc. The main figure to enter here is the rated power (S_r) in MVA. For a wind farm of 10 MW with a cos(phi) of 0,9, the minimum needs will be 10/0,9 = 11,1 MVA. The rated voltages are the ones the transformer is designed for, but it can typically be used also for slightly different voltage levels.

The second tab includes data about the resistance of the transformer like short-circuit voltage and copper losses. Here, several input alternatives are presented.
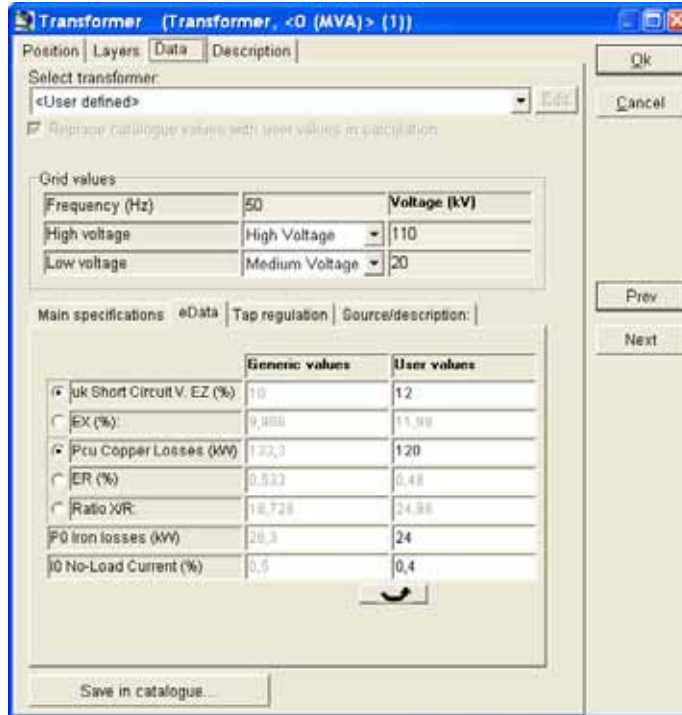
Figure 4 User interface of a Transformer – Tab "eData"

The electric specifications of a transformer basically consist of the reactance (X) the resistance (R) and the iron losses. The two first can be specified in different ways, see input form. Based on evaluation of the parameters for a number of transformers, formulas for calculation generic values have been developed and the software can calculate the values based on these automatically.

The third tab contains information about the transformer tap positions as well as the vector group.

Figure 5 User interface of a Transformer – Tab "Tap regulation"

Tap regulation
Tap regulation mean that a transformer can be set to different transformation levels. This is used in a grid to adjust voltage drops in the grid. In a traditional consumer grid, the transformers nearest the high voltage substation will typically be set to decrease the voltage level further to the nominal decrease, while the ones at a long distance from substation will be set to increase relative to the nominal decrease to compensate for the higher voltage drop of the high voltage line from the substation.
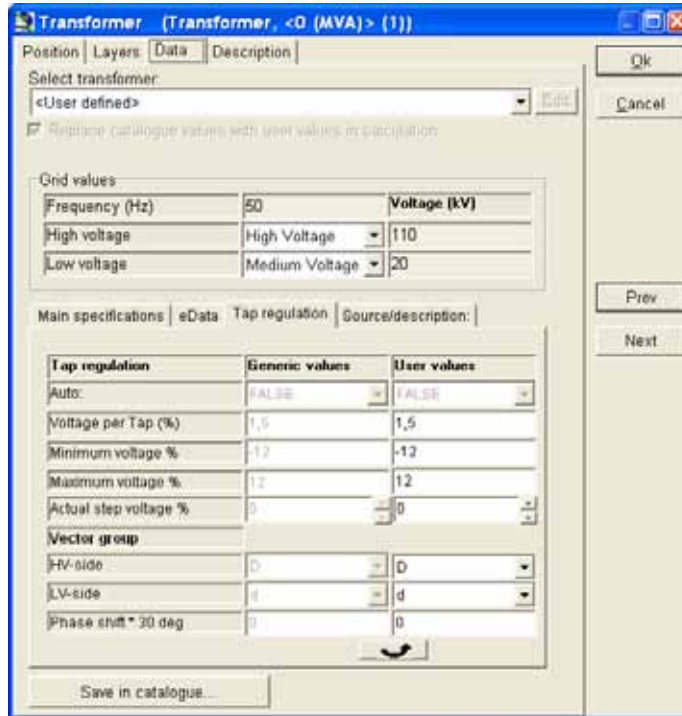
Transformers at higher voltage levels (sub stations) typically can auto adjust the transformation level based on the actual load. In the first eGRID version, the user has to set the tap regulation manually. At a later stage it is planned to let the software automatically calculate the tap setting for these types of transformers.

Vector group
The vector group describes the construction of the transformer, how the windings are established at the high and low voltage side. These can be found in the transformer manufacturer catalogue and often the transformers can be delivered based on user specifications.

Save in catalogue
Via this button, a direct access to the transformer catalogue is given. It is possible both to select a transformer, which is stored in the catalogue or to store a transformer, defined using the several registers of this window, directly in the catalogue. For this, simply click on the button "Save in catalogue". An individual input can also be done by selecting a transformer from the catalogue, and choose the option "Replace catalogue values with user values in calculation" and then modifying the necessary data.

10.1.3 The Transformer Catalogue

As default, the transformer catalogue browser appears like depicted.
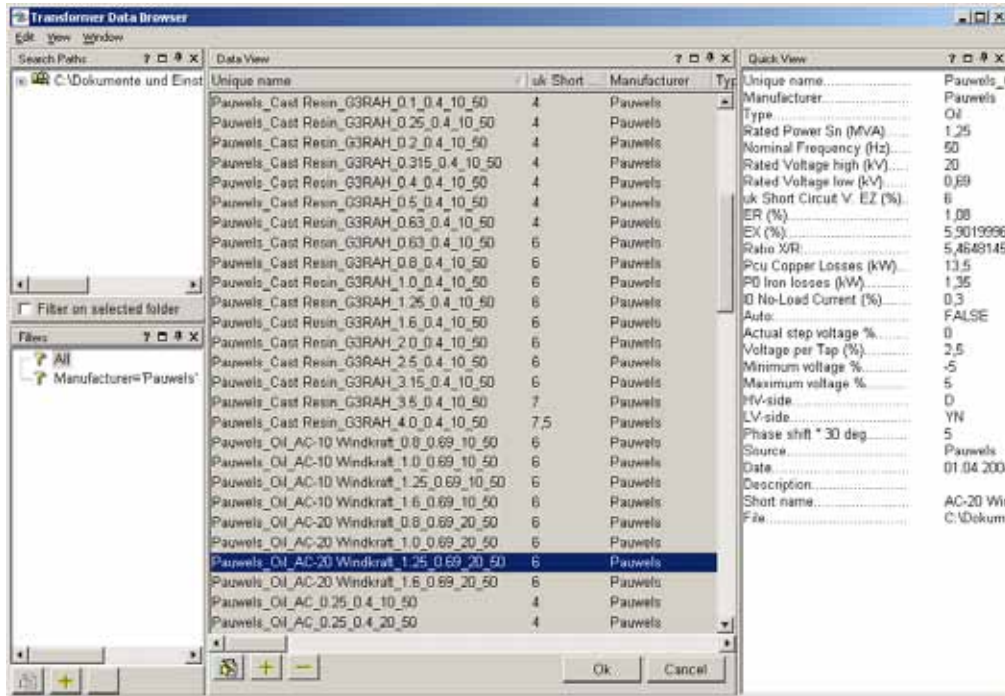
Figure 6 Browser of the Transformer Catalogue

At the upper left side, search paths can be defined. Within these paths, WindPRO is searching for relevant transformer data. Based on bad experiences with closed catalogues, the transformer data is located using individual files. Using the option "Filter on selected folder", solely the data sets which are located directly in this folder (without sub-folder data) is being depicted. At the lower left side, a search filter can be defined. A quick view of the selected transformer is presented at the right side. A transformer is chosen, by performing a double click at an entry. Using the right mouse button, you get access to the editor menu of the catalogue for editing and e.g. modifying the transformer data. As in the Windows-Explorer, the main information of the chosen transformer can be copied to the clipboard.

Figure 7 Search filter definition within the Transformer Catalogue. Double click at the parameter to get it into the filter expression and then add the expression.

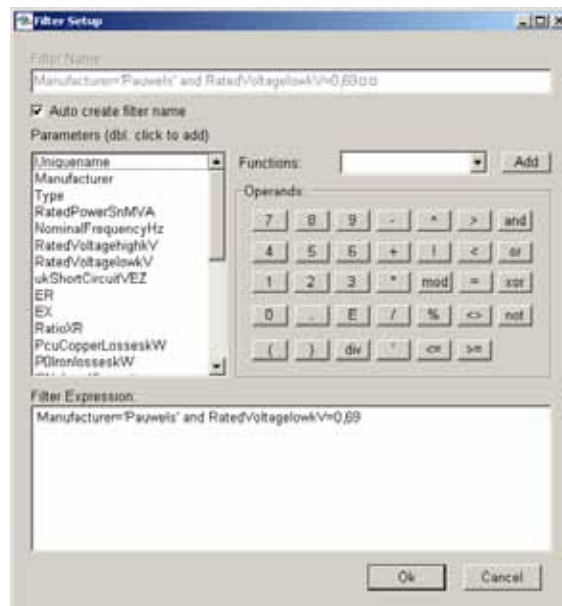Up to now, more than 1000 transformers are implemented in the catalogue. In order to find a specific transformer in the catalogue, free-defined search filters can be specified by using e.g. the type, material, name, short name, manufacturer, voltage levels, apparent power, etc.

The upper entry is being used for the name of the search filter. If selected, WindPRO will create this name automatically (Auto create filter names have to be activated). User defined names is optional. The search parameters for the definition of several search criteria are located in the left field. They are selected by a double click, e.g. on manufacturer. Now, you have to enter the condition of this parameter (e.g. = ´Pauwels´). After this, any other conditions e.g. a rated voltage at the low voltage side of 690V (RatedVoltageLowkV = 0,69) can be defined.

10.1.4 Input of a WTG, especially the WTG eGRID data

(Please read chapter 2 „BASIS", part 2.5.2 for input of WTGs in general). It must be pointed out that eGRID makes no differences between new and existing WTGs.

For simple grid configurations or rough survey calculations, e.g. if only one type of WTG is being used in a wind farm or all turbines feed-in with the same power factor, it is possible to make all inputs, which are required for the calculation directly within the calculation definition, neglecting internal WTG transformers or using automatically generated generic transformers (please have a look at chapter 10.2 Calculation and Input of Calculation Properties). Thus, the generation of the following described eGRID data category isn't necessary under these circumstances.

The wind turbine catalogue has been expanded by an information category eGRID within the detail data. The required electrical data can be taken out of measurement reports dealing with the electric measurement of the individual WTG. In practice there are three different measurement protocols: A protocol which bases on IEC 61400-21, a protocol which bases on MEASNET guidelines and a measurement protocol published by the German "Fördergesellschaft Windenergie e.V." called FGW. In meantime, the last protocol was updated to the IEC protocol, so that it can be handled like this. In contrast to the IEC protocol, the MEASNET protocol contains additional data about harmonics and interharmonics. Due to the fact, that eGRID doesn't calculate any harmonics, the actual protocols are handled identically. There is only a separation from the old FGW protocol.

The category eGRID implements five tabs. The first tab contains data of the generator type as well as the power peak factors of the wind turbine. In this connection, it has to mentioned that no differences between the real power factor λ and the power factor cosφ are being made for new WTG types. This factor is called cosφ (CosPhi) within the eGRID module in general.
Also the short-circuit contribution which is being set to the generic values at this tab. If you have detailed information about the short-circuit parameters of the WTG, you are free to enter your own data. Additionally, you have to select if the used measurement protocol bases on the old FGW or on the new FGW, IEC or MEASNET guideline. Please note that data input at tabs "Flicker" and "Switching" will be different based on this selection.
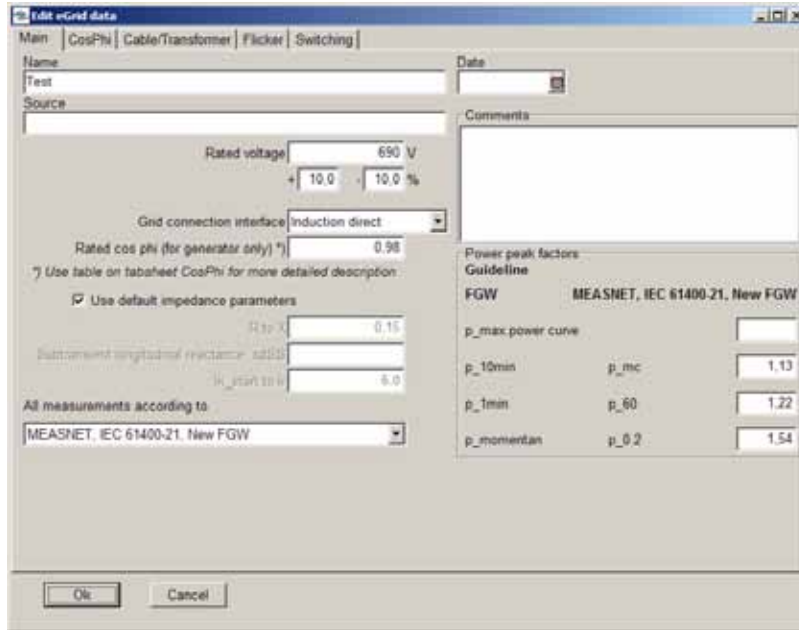
Figure 8 User interface of the WTG category eGRID – Tab "Main"

The second tab deals with the detailed information about the power factor in case the part-load operation as well as the operation of a WTG as a load shall be examined. For this purpose you have to uncheck the checkbox and select the way you want to enter the power data (active power, power factor, reactive power, apparent power).
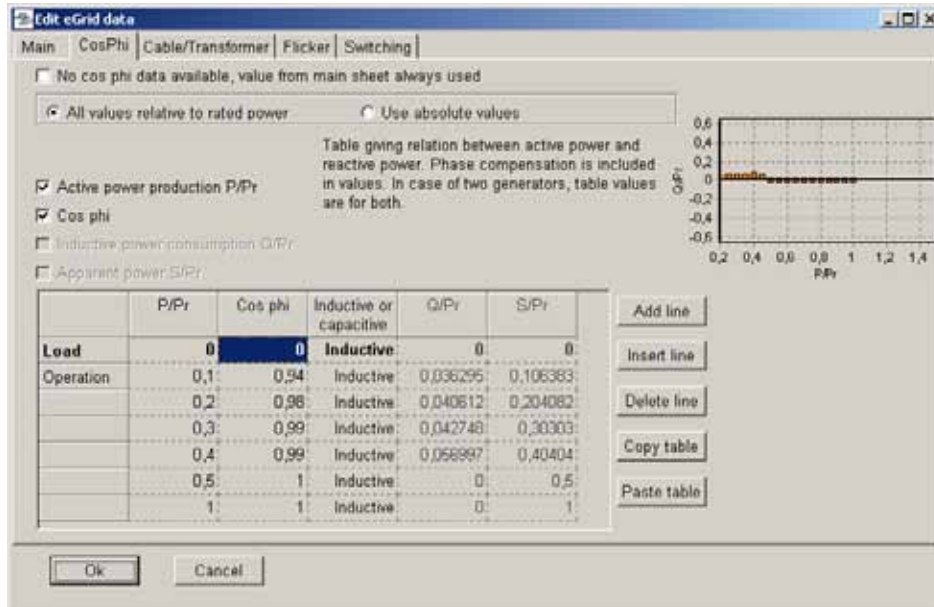

Figure 9 User interface of the WTG category eGRID – Tab "CosPhi"

The first row implements the WTG operation as a load. All other rows describe the trend of the CosPhi depending on the power. Necessary interim values, used for the calculation, are computed by linear interpolation.

Information about WTG internal objects; generator, cables and transformers can be entered by selection of the appropriate objects from the data libraries at the third register sheet. These data is only needed for calculation of internal voltages, losses etc. inside the WTG. This is normally not a requirement for documentation of the grid connection of a WTG, but it is an option for e.g. manufactures to help design the "inside" electric system of the WTG. Note that the electric power curve for a WTG normally gives the power output at the low voltage level at the WTG. Sometimes, the measurement protocols are based on the high voltage side of the transformer, e.g. 20kV. So, the power curve should include the losses in the build in transformer – this it might not always be so.
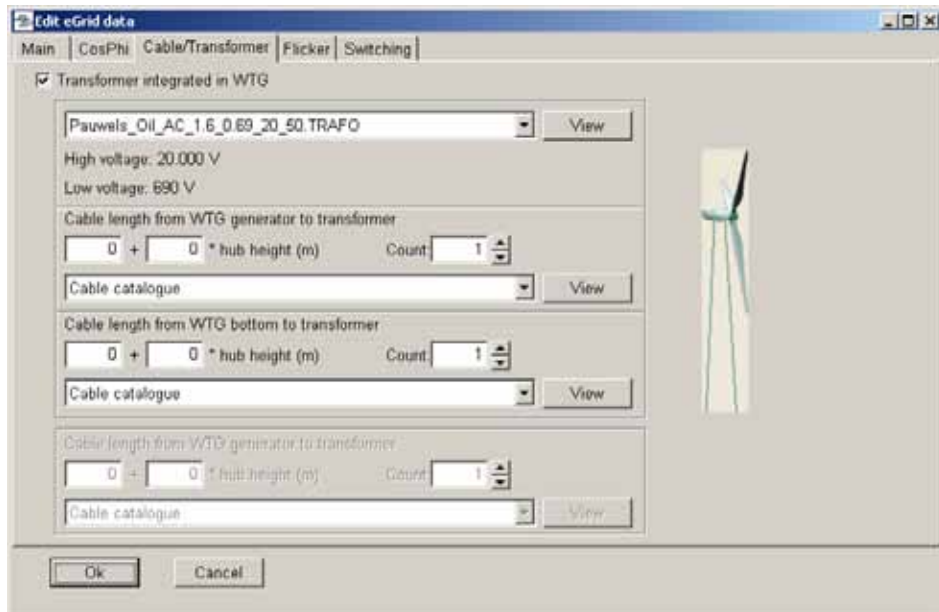
Figure 10 User interface of the WTG category eGRID – Tab "Cable/Transformer"

The fourth tab implements the flicker data. Please note that the user interface as well as the input data are different concerning the chosen measurement protocol (refer to the description of the Main tab). Using the old FGW measurement protocol, three kinds of flicker data specification can be handled:

- declaration of a flicker factor and a flicker angle
- flicker factor independent from the grid angle
- flicker table

Entering data based on the new FGW, MEASNET or IEC protocol, a data table dealing with the flicker factors at different mean wind speeds and several grid impedances has to be completed.

Figure 11 User interfaces of the WTG category eGRID – Tab "Flicker"

The data used for the calculation of voltage variations due to switching effects has to be entered in the fifth tab. Again, the input data are different concerning the chosen measurement protocol.
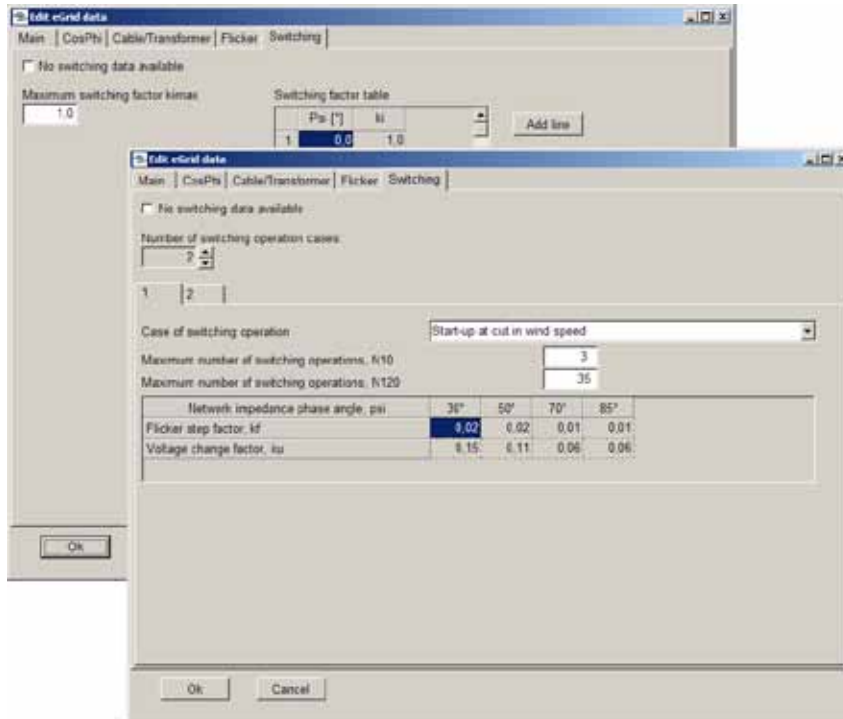
Figure 12 User interfaces of the WTG category eGRID – Tab "Switching"

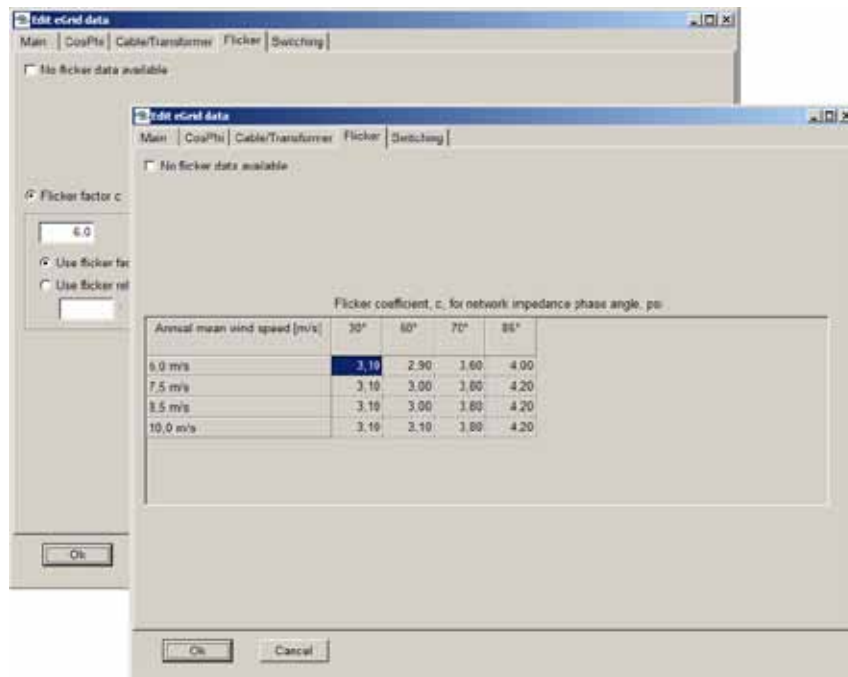Defining a corresponding "Flicker" or "Switching" calculation, no input – neither choosing an annual mean wind speed for the flicker calculation nor selecting a switching reason for the individual turbines – is necessary. Every single item is considered in the calculation automatically. As usual, generic values can be defined in the calculation setup for WTGs which don't have the corresponding data in their data sets.

10.1.5 Input of a Load

The electrical data of a load is subdivided into two tabs. The first contains the nominal data of the load. For this, several input possibilities are provided. Additionally, it is possible to consider this load in part within the calculations as free-definable percentage values of active and reactive power values by choosing 'Part load enabled'.
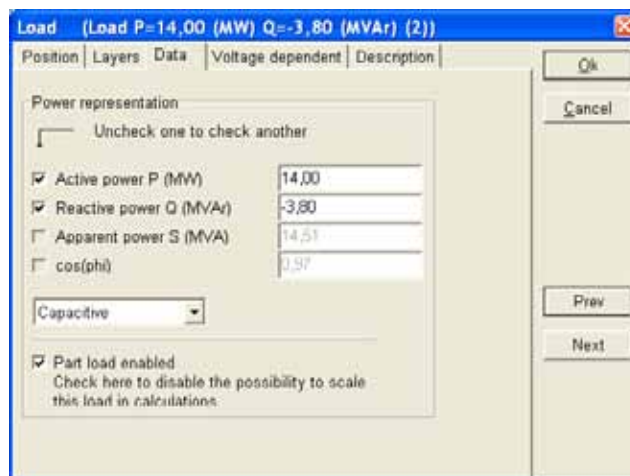
Figure 13 User Interface of a Load – Tab "Data"

You only have to enter parameters within the Data tab, if you want to define the load as voltage dependent - a load is defined as voltage independent as default. By doing so, the rated voltage and six parameters have to be entered in order to describe the load characteristic based on the equations:

$$P = P_R \times \left(K_{0P} + K_{1P} \times \left(\frac{U}{U_R} \right) + K_{2P} \times \left(\frac{U}{U_R} \right)^2 \right)$$

$$Q = Q_R \left(K_{0Q} + K_{1Q} \times \left(\frac{U}{U_R} \right) + K_{2Q} \times \left(\frac{U}{U_R} \right)^2 \right)$$
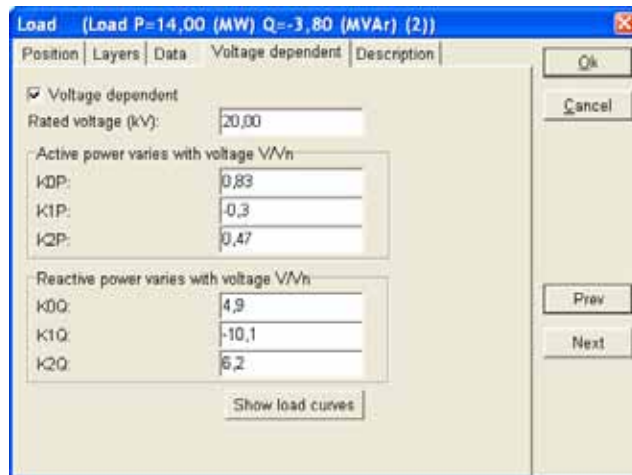
Figure 14 User Interface of a Load – Tab "Voltage dependent"

The defined load characteristic is pictured by selecting 'Show load curves'. You are free to zoom in or out within the range of 0.8 to 1.2 of the rated voltage as well as to modify the chart to your individual demands by changing the parameter values of the load characteristic or performing a double click at the chart.
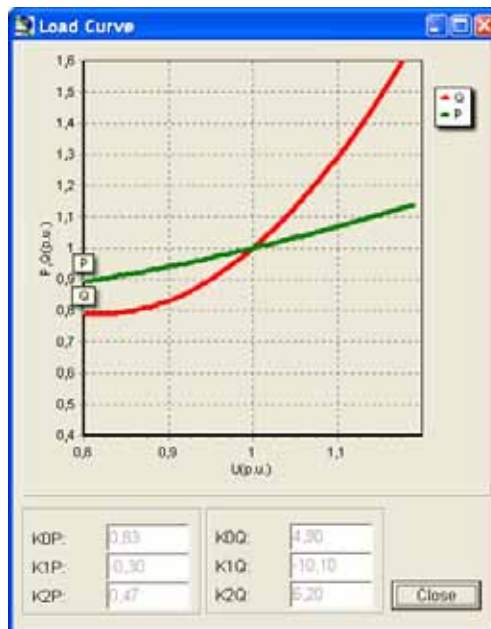
Figure 15 Presentation of voltage dependent Load Characteristic

10.1.6 Input of a Bus bar

After placing a bus bar, a separate window dealing with the position of this object appears. A bus bar doesn't contain any electric data. It is just a way to merge more electric cable/lines into one or make a star connection.

It should be mentioned that a bus bar is automatically generated when connecting one cable/line type with another.

10.1.7 Input of an Electric Grid

This object is the most "advanced" and the "centre" for designing the grid connection. The object works slightly similar to the line object in WindPRO (for height contour lines etc.). This mean that the object just is a "fixpoint", that can be placed anywhere on the map. When data (cables/lines) shall be entered or edited, the object must be in edit mode. When it is in edit mode, the data belonging to this object is the only ones that can be reached. So the object needs to be taken out of edit mode before other actions can be taken.
NOTE: An important difference to the line object with height contour lines to be aware of: Activating a line for changing properties do ONLY work on the line between two nearest points, not the full line. If you want to change properties for a "full line" select "Extend to whole cable line" in the right click menu.

 Electric grid object on map – right click on object to get MENU or select (by left click on object) and press <Ctrl> + <e> to activate EDIT mode

 Electric grid object on map in EDIT mode shown by a red dashed line around the object – the little black square in the middle show the object is selected. <Ctrl> + <e> deactivate always EDIT mode (no selection needed).

In general, the different connection possibilities (cable and overhead lines) are handled identically. In the automatically length calculation, taking end extension and "hanging lines" into consideration, different values can be defined for cables and overhead lines. Besides this current limiting factors for cables due to the surroundings (condition of ground) and e.g. isolation material in cable, can be given detailed, while overhead lines only can be limited by a power factor in the first version of the eGRID module.

In order to simplify the description, only the term cable is being used in the following.

After placing the object, the object properties appear. Here, you can select whether the connection of a WTG to a cable shall be checked or not on the basis of the rated voltage of the turbine. For this check, the WTG has to contain one eGRID data set. Turbines without electrical data can generally be contacted. Using slow computers or extensive grid structures, the check should be deactivated depending on the performance of the computer. Editing the properties of the Electric Grid object this is possible at any time.

After the placement, the Electric Grid object is in edit-mode, i.e. cables and overhead lines can be created for this object or previously created connections, belonging to this object, can be modified. Both happen predominantly by means of the context menu after clicking the right mouse button. Another possibility to create or handle connections is the connecting table, which will be described at the end of this chapter.

The right click menu
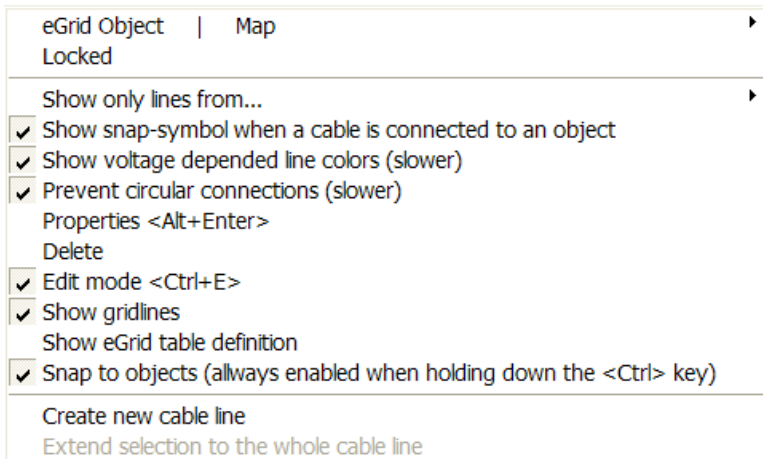
There are many options in the right click menu. Note that the menu depends on the situation, from which the menu is activated. Here shown from "scratch", where no cables yet are established.

First time use will be to place cursor where a new line should be created, then right click and chose menu "Create new cable line". As a result, the user interface for the input of the cable parameters is being opened (see later). If the cable was generated at an object, this object is registered automatically as starting point of the connection.

After the parameterization of the cable is finished (explained later), simply mark the cable route by clicking on your map on the screen. If the option "Snap to objects" is activated in the context menu or by pressing <Ctrl>, the unconnected end of the cable jumps to the nearest object, which can be connected based on the voltage level and the grid topology – the input of meshes is prevented. The connection to an object does not finish the digitizing process in order to accelerate the wiring of several objects with the same type of cable. A semi-circle around the connected object visualizes the connection of this object to the cable. In order to finalize the wiring process, the item instruction "End" has to be chosen within the context menu.
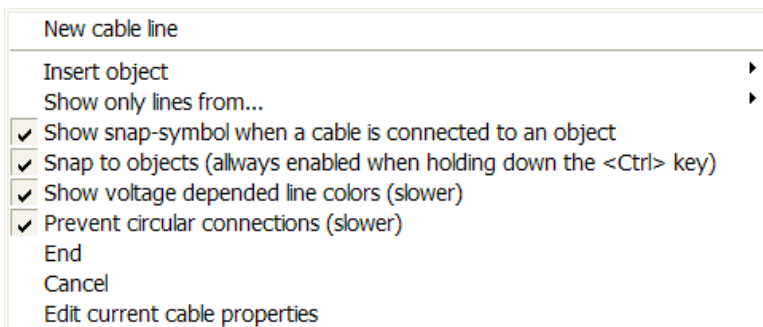
Right click when digitizing to get this menu. "End" will just stop digitizing, while "insert object" will give you the option to e.g. establish a transformer or WTG at the end of the cable – and afterwards continue with a new cable.

Selecting an existing connection by one mouse-click on the cable, the cable itself is being set into edit mode.

```
eGrid Object    |    Map                               ▸
Locked

Show only lines from...                                 ▸
✔ Show snap-symbol when a cable is connected to an object
✔ Show voltage depended line colors (slower)
✔ Prevent circular connections (slower)
Properties <Alt+Enter>
Delete
✔ Edit mode <Ctrl+E>
✔ Show gridlines
Show eGrid table definition
✔ Snap to objects (allways enabled when holding down the <Ctrl> key)

Insert point
Create new cable line
Continue cable line
Edit cable line properties
Remove cable line
Extend selection to the whole cable line
```

The menu at right click at a cable after activating this – clicking at a point will include the menu: "Remove point" instead of "Insert point". Choosing "Edit cable line properties" give access to the cable input form explained after next figure. You also can perform a double click at the activated cable to open the cable line properties.

All points of the cable are represented and can be dragged with the mouse for more accurate positioning of the cable.
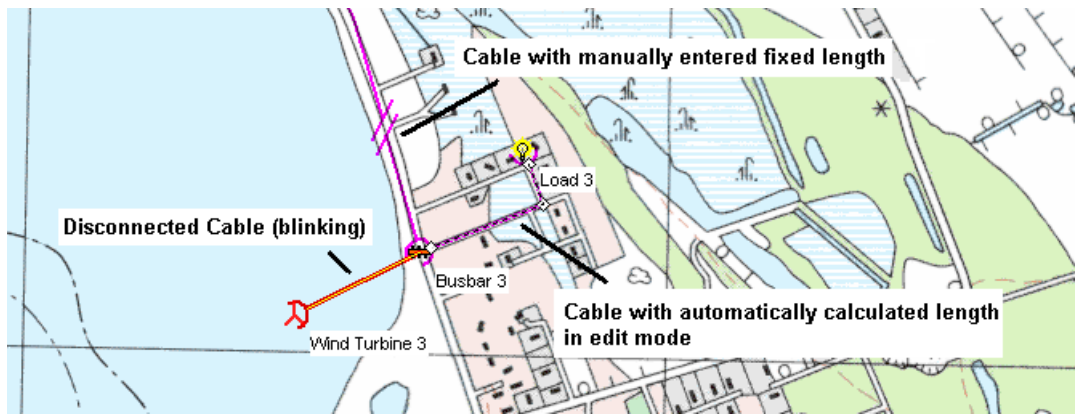

Figure 16 Different cable modes

10.1.7.1 Cable parameters

The cable parameters are differenced between laying and electrical data. The laying parameters like the terminator points of the cable, length, current limiting factors and the number of parallel layed cable systems ("number of parallel cores per phase) appear on the left side of the window.

Based on the electric data of typically used cables (systems of three single core cables in trefoil formation; type N2XS(F)2Y or NA2XS(F)2Y), you have access to "cable size calculator", which is located in the left side of the window. It is explained in a separate section following this.

The right side contains data about the cable itself like e.g. name, structure and electrical data. Please note that the item "number of cores" deals about the cable design itself whereas the electrical data are given about a three-phase system. This can be one three-core cable as well as a system of three single-core cables in trefoil or flat formation. The laying mode of a system of three single-core cables (trefoil or flat) is being described at the tab "Source/description".
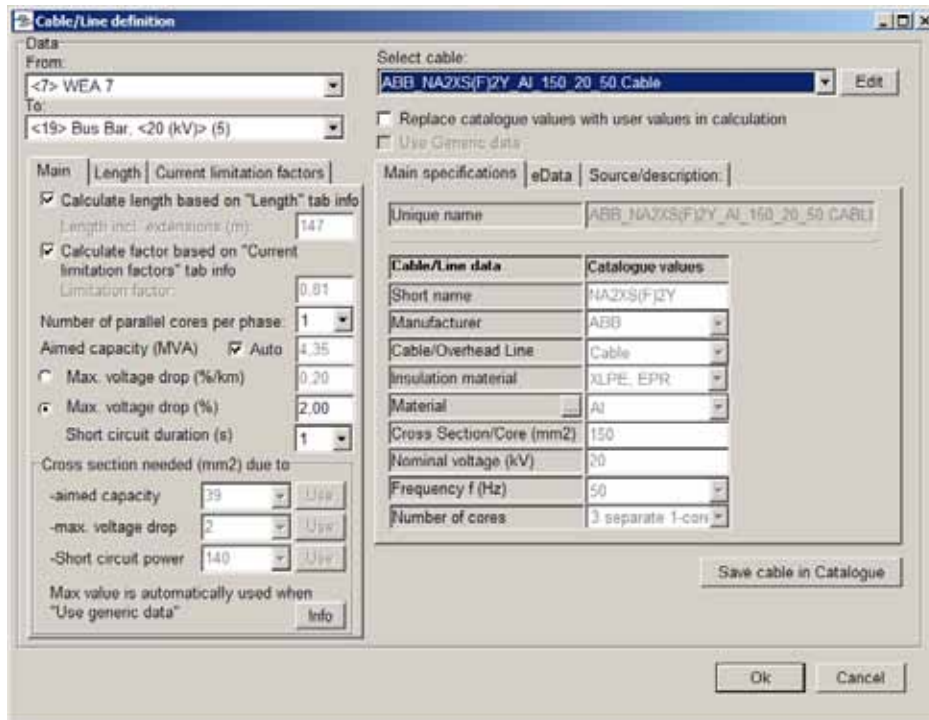
Figure 17 User interface of a Cable – left site the laying data, right side the cable properties. Note: when checking "use Generic data", cable – lien data will be calculated automatic and updated automatic when a calculation is started so just the needed size is used.

As in the transformer menu, direct access to the cable catalogue is also provided. Again, it's possible to select a cable available in the database or to store a cable entered within this window directly into the catalogue. Also, an individual input can be made by selecting a similar cable from the database and choose the option "Replace catalogue values with user values in calculation" and then modify the necessary data.

Like for the transformers, based on an evaluation of the parameters for a number of cables and overhead lines, equations for calculation generic values have been developed and the software can calculate the values based on these automatically. Nevertheless, deactivating "Use generic data", you can enter your own values.

The length can be calculated automatically based on the digitised cable on the map, which is recommended. But if a connection to a substation far from site is required, which is outside the map, the length can simply be entered and the end of the cable can just be put on an arbitrary spot at the map.

The length calculation gives different options for extensions of cables and lines. The elevation of the individually digitizing points is included in the length calculation if a digital height model (DHM) is established in a line object. But the contours between two digitizing points are NOT taken into consideration, so an exact calculation requires that enough digitizing points are established. Furthermore, a percentage offset can be entered at the tab "Length" (based on the fact that it is not possible to lay a cable as a straight line like drawing it on the map) as well as an absolute offset can be specified e.g. in order to take care about connecting the cable in a transformer cabinet.
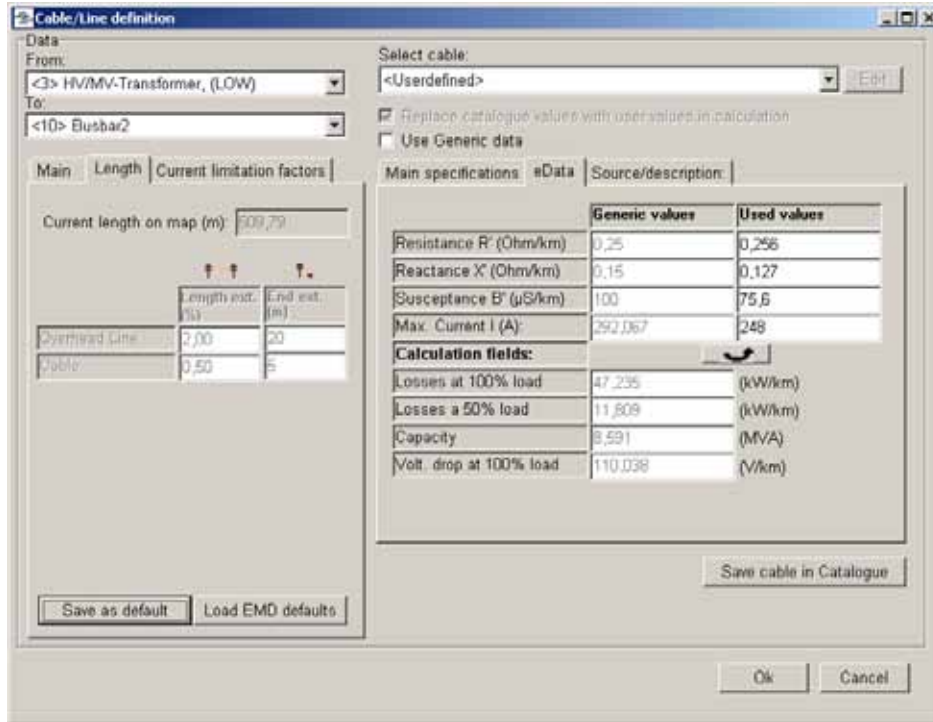
Figure 18 User interface of a Cable – left Tab "length", right tab "eData"

At the tab "Current limitation factors", several factors are combined. These factors should be considered in order to prevent cable overload which can lead to an accelerated aging of the cable or – in extreme case – heating-up resulting in melting the isolation material. The reduction factors are based on;

Ambient temperature in 0,7 m depth, see choices below:
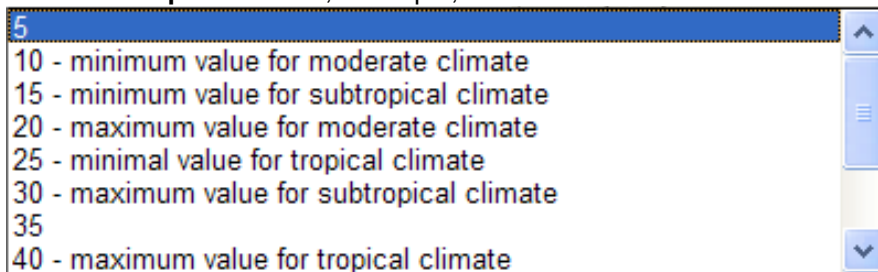
Number of parallel 3-phase systems
Based on the data of several manufacturers, a fixed distance of 7 cm distance has been chosen concerning laying the cable directly in ground; if the distance differs from 7 cm, the user may try to be a little creative finding a suitable value, and at the final dimensioning consult the handbooks from the cable manufacturer. Note: the number of parallel 3 phase systems might differ from the number specified at main tab sheet, while there might be other cables, not included in this calculation, OR there might be more parallel 3-phase systems, but buried in separate channels or at a distance so large, that the influence shall not be taken into consideration.
In case the cable is being laid in a duct, the limitation factor also depends on the system sizes
The k-factor based on more parallel systems laid together is influenced by the laying – if it is in the ground or in a duct, and if the cables are of similar size.

Soil thermal resistance – here some different defaults are available. Input is divided in moist area, the "remote surroundings" and the dry area, the near cable surroundings, that is dry due to that the cable heat up this part of the soil. The last mentioned often differ from the original surroundings due to that the cable in laid in a bed of sand or other material that gives the cable better conditions.
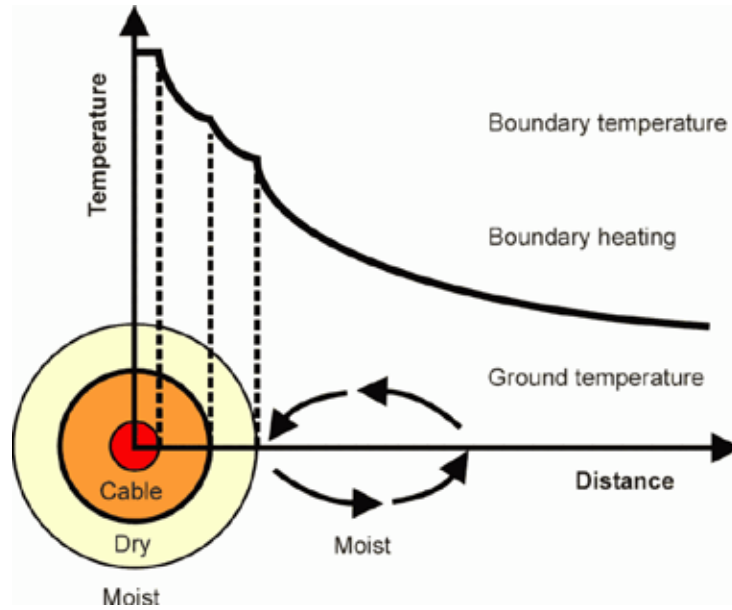
Figure 19 The cables heat up the near surroundings making this a dry area, which influences the transportation of heat from the cable.

Load factor might be the most important one. Hereby, it have to be mentioned that the maximum current values of a cable is presented by the manufacturers based on a so-called utility load, a special load condition with a medium power value of 0.7 times the maximum power value. It relates to a traditional consumer system, where full load only will be in peaks of maybe a few minutes. Due to the fact that a maximum power output has to be assumed for WTGs based on the fact that WTGs are able to feed-in maximum power over a long time period. This maximum load forces a current limitation factor of 0.81 which is automatically being used for all cables.
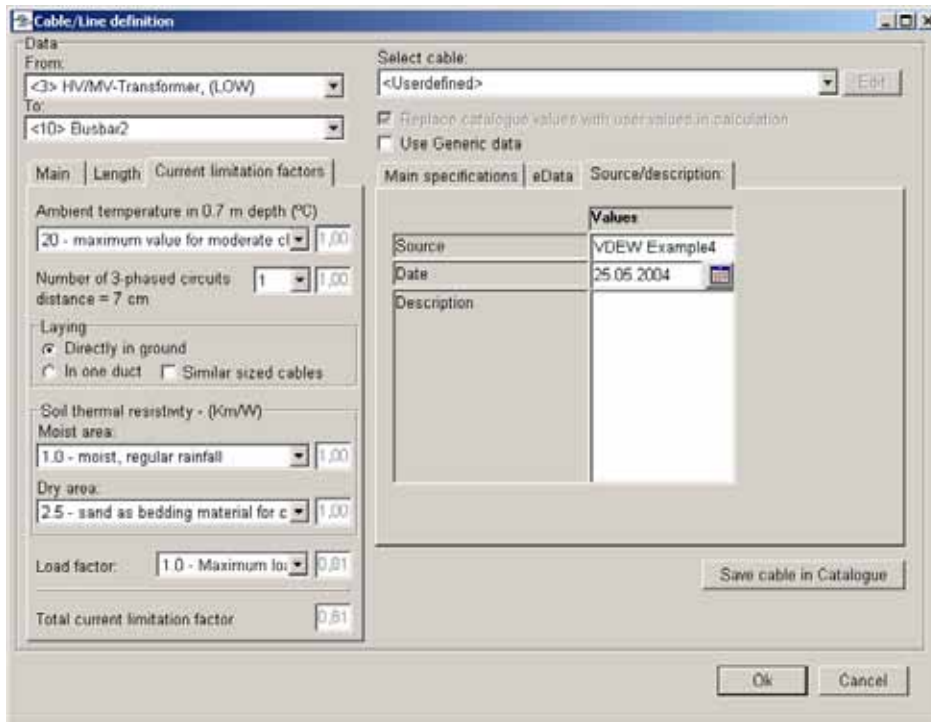
Figure 20 User interface of a Cable – left Tab "current limit factors", right tab "Source/description"

Note: The current limitation factor is only be calculated for cables. You can enter a value at the main tab sheet for overhead lines – consult the line manufacturer to get this value. Additionally, the calculation of the total current limitation factor doesn't relate to a special norm in detail. Several limitation factors given by different manufacturers are taken in order to provide a good reference value. Unfortunately, every single manufacturer provides only some and not all limitation factors. Furthermore, there is an interaction between several limitation

factors in reality, which is not being considered by the software. Due to this, the presented total limitation factor might not be the exact one but it offers definitely a good reference value.

10.1.7.2 Cable size calculator

An important feature at the left side of the cable input form is the cable size calculator. The calculator automates or gives assistance for dimensioning the size of a cable. Based on selected conductor material (copper or aluminium), the aimed capacity, which can be calculated automatically or set by the user, the maximum aimed voltage drop and the short-circuit current in case of a fault, the necessary cable size (cross section in mm^2) is being calculated by the program based on the following cable properties:

- System of three single-core cables in trefoil formation
- Maximum cable temperature: 90°C
- Medium voltage level (10-70kV)
- Grounded at both ends
- Ground temperature: 20°C
- Buried directly in ground
- Laying deep: 0,7m (1m)
- Thermal resistivity of soil (moist area): 1,0Km/W
- Thermal resistivity of soil (dry area): 2,5Km/W
- Load Factor: 0,7 (utility load)
- Total current limitation factor as defined in the corresponding tab sheet taking into account the variations from the manufacturer data listed before

In general, the cross sections of cables which carry the energy of several WTGs are determined on the basis of the current values under normal operation condition. Based on the low current values of cables which are connected to a single turbine or only a few WTGs, the dimensioning of these cables would be too small. Here, the short-circuit operation has to be taken into account. Additionally, the voltage drop will be a dominating item for long cables. Using "generic values" (in the preliminary design phase), the tool will automatically update the values before calculation, when the cable layout is changed. This makes the assistant very efficient. The user do not need to care about cable dimensions before the final layout is decided, and "real" cables might be selected from the catalogue or entered for the final calculation.

When not using generic data, but "user defined", the user can decide which of the calculated values (based on capacity or voltage drop) shall be used, or enter a value manually. Choosing from cable catalogue, the cross section of the corresponding data set is being used. Nevertheless, the assistant still nominates a size which should be taken from the catalogue. So, this information can be used to check your choice.

In general, using the cable size calculator the whole cabling can be performed only selecting e.g. the properties "type=cable" and "material=aluminium" after placing the WTGs in order to provide basic values for the capacity calculation of the cables.

Please note that the assistant considers only the normal load-flow operation and not a short circuit situation if the short-circuit power of the External Grid is set to infinite, i.e. only the normal feed-in of all WTGs to the External Grid object is being used for the cross-section calculation. This leads to very small cross-sections for cables which are connected to stand-alone WTGs. Additionally, the assistant presents just calculated cross sections – not normed values. Also, the power value of the WTGs which is specified in the properties of the External Grid is used to estimate the cross sections. In general, the 10-minute mean maximum power output of the WTGs should be used based on standard guidelines. If a WTG data set contains electrical data, the specified data are used (incl. the CosPhi-value). Otherwise the factors which are specified in the External Grid are taken.

10.1.8 Cable/line catalogue

The structure of the cable/line catalogue follows the one for the transformers, see section 10.1.3.

10.1.9 Cabling Table

As an alternative (or supplement) way to design the grid, the cabling table can be used. The table is activated by the corresponding button in the LEFT menu bar. In case of several existing Electric Grid objects in one project, you have to choose the object, which shall be shown.

Figure 21 Cabling Table

After checking one or several cables (Multi Edit function) and selecting "Edit Checked Cable(s)", the already described user-interface of a cable appears with the exception that using several cables the start and end points are deactivated. Please take care about the fact that all – not only the modified – settings in this window will be allocated to the selected cables after pressing "OK".

In order to generate a new connection, after selection of "Create new cable", the start and end point can be indicated in the appearing parameterisation window.

Apart from the cabling options and the possibility to edit or delete objects, the cabling table contains another important characteristic: Elements can be generated, which do not appear on the map. This characteristic has been introduced for objects where no information is available, e.g. just having the information: "The wind park can be connected via a 4.5 km cable to a grid with the following parameters … ". A connection of such objects is only possible by using the connecting table.

10.2 Calculation and Input of Calculation Properties

10.2.0 Introduction to calculations

After designing the grid and connecting to the relevant objects, go to the calculation menu. Here click on the green arrow at "eGRID" (if it is yellow, it means that you do not have licence for this module installed.)

Limiting values and calculation guidelines valid for the calculation have to be defined mainly at the tab sheet "Main". Each calculation, selected within this tab sheet, leads to a further tab sheet at which the respective settings relating to the calculation properties as well as limit values for this calculation can be seen and changed, if necessary. A final decision about the grid, which shall be calculated (if more alternatives established), has to be made in the tab sheet "Grid objects". Here it is also possible to chose between alternative wind farms if more alternatives, or to deselect one or more WTGs in the relevant calculation. In the tab sheet "Description" a detailed description can be entered e.g. the background for the calculation.

10.2.1 Tab sheet 'Main'
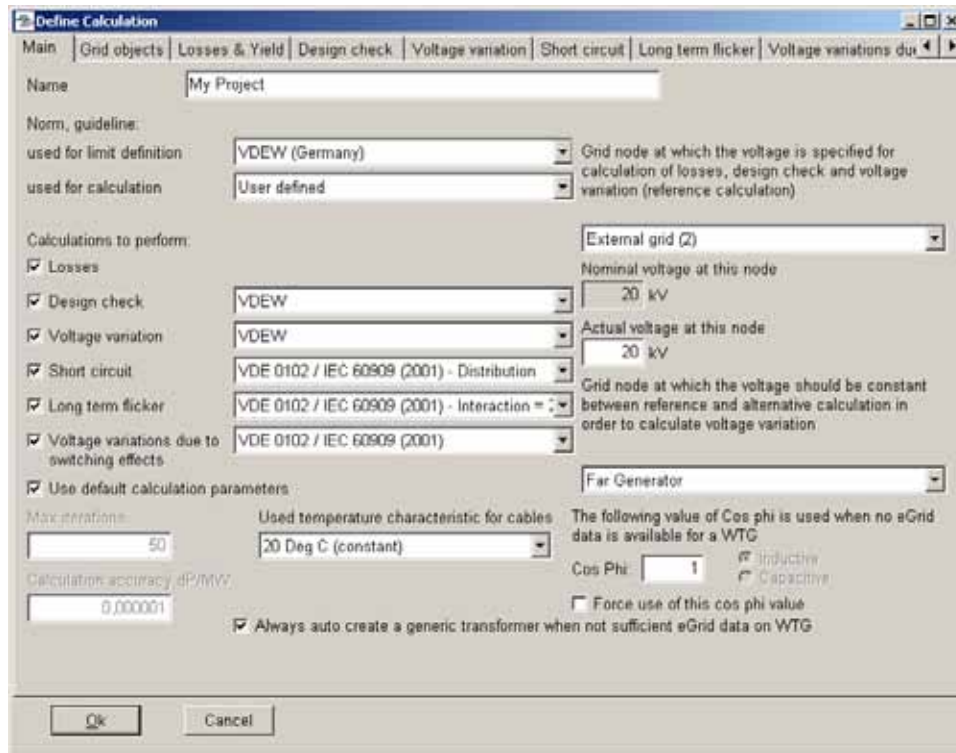
Figure 22 Calculation menu "Main" – Selection of the calculations to be performed

In addition to the possibility to name the calculation, the tab sheet "Main" is primarily used to decide which calculations shall be performed. Predefined settings for limits as well as for calculations to perform can be chosen. These are mainly related to German requirements in the first version. At the moment, either the German VDEW or the norm IEC 61000 can be selected in order to specify limit values. Naturally, it is also possible to define own values. Concerning the calculation properties, in addition to the possibility of a self-defined calculation, a calculation based on the German norm VDE 0102 respectively the IEC 60909, both in the variant of 1990 or 2001, can be selected for a calculation, which bases on a short-circuit calculation.

Regarding the VDEW guideline, the Design Check calculation corresponds to a dimensioning calculation. All settings, necessary for this calculation as well as for the calculation of the voltage variations are made automatically. The choice of a pre-defined calculation leads - with exception of the loss calculation - generally to the selection of all calculations.

Each calculation, selected in this tab sheet, leads to a further tab sheet, in which the respective settings can be viewed concerning the calculation properties and the limit values for this calculation and changed, if necessary.

The calculation accuracy as well as the maximum number of iteration steps can also be adapted.

The right side of this tab sheet contains additional information, necessary for the calculation. So, one voltage value at one grid node has to be defined for a loss, design check or voltage variation calculation. This voltage at this node is the basis for the calculation (for a voltage variation calculation, which bases of two load-flow calculations, it is the basis for the first calculation). Typically, this is the node at the next bigger transformer station or the Common Coupling Point. In the practical use, it is mainly the node of the External Grid.

Additionally, the grid node has to be noted at which no voltage variation should be occur for the calculation of voltage variations. That mean at this node the voltage is fixed. Typically, this is at the Far Generator.

In order to enable the possibility to perform basic load-flow calculations without a lot of entries, it's also possible to define an overall CosPhi value used for all WTGs. For this type of calculation, it is not necessary to define several eGRID data entries within the WTGs prior to the calculation. It is also possible to use the defined CosPhi value for all WTGs (including WTGs with a eGRID data set), selecting "Force CosPhi value.

Additionally, selecting "Always auto create a generic transformer when no eGRID data on WTG", automatically generated transformers are used for WTGs which are connected to e.g. the medium voltage grid level without transformers, on the basis of generic transformer data.

Furthermore, a temperature dependency of the cable resistance can be chosen. In general, the electrical data of a cable are used like specified in the cable catalogue. These are the cable properties at a temperature of 20°C. Due to the fact that any current flow results in losses, the cable will become warmer which leads to an increased cable resistance. Here, a corresponding consideration can be chosen, respectively the grid can be inspected using the maximum cable parameters at 90°C:

- ☛ 20 Deg C (constant)
- ☛ Linear current dependency
- ☛ Quadratic current dependency
- ☛ 90 Deg C (constant)

Due to the fact that the losses, which cause the heating, increase with the square of the current value, the quadratic current dependency should be the most realistic one.

In order to calculate the actual cable resistance, which is being done individually for every single cable in the grid, a cable temperature of 20°C is assessed in case of no current flow and a temperature of 90°C is determined for the maximum current carrying capacity which is being calculated taking into account the given maximum current value for each cable (e.g. manufacturer data) AND the specified individual current limitation factors. Based on these two points, the cable temperature is being calculated for a linear or quadratic current dependency and the corresponding resistance value is specified via the equation

$$R_T^{'} = R_{20}^{'}(1 + 0{,}004\,(T - 20))\,.$$

(T is the cable temperature in Deg Celsius).
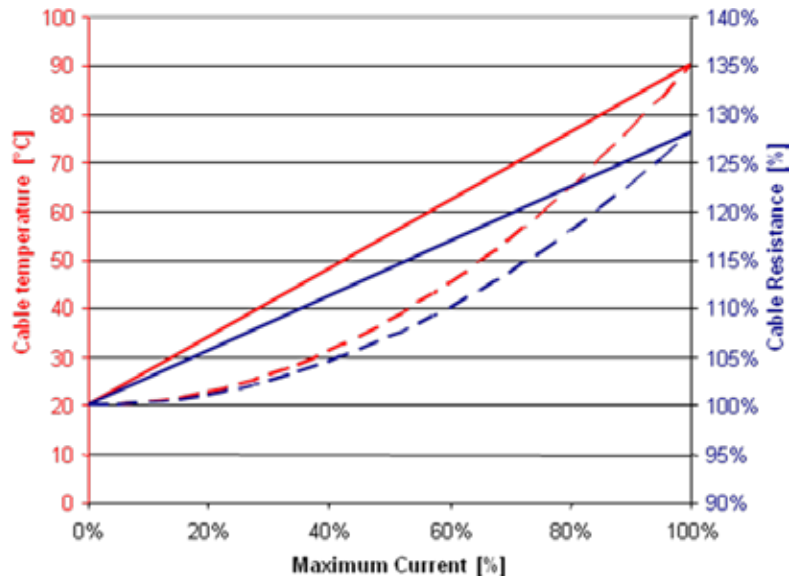
Figure 23 Current-Temperature dependency of the cable resistance

10.2.2 Tab sheet 'Grid objects'
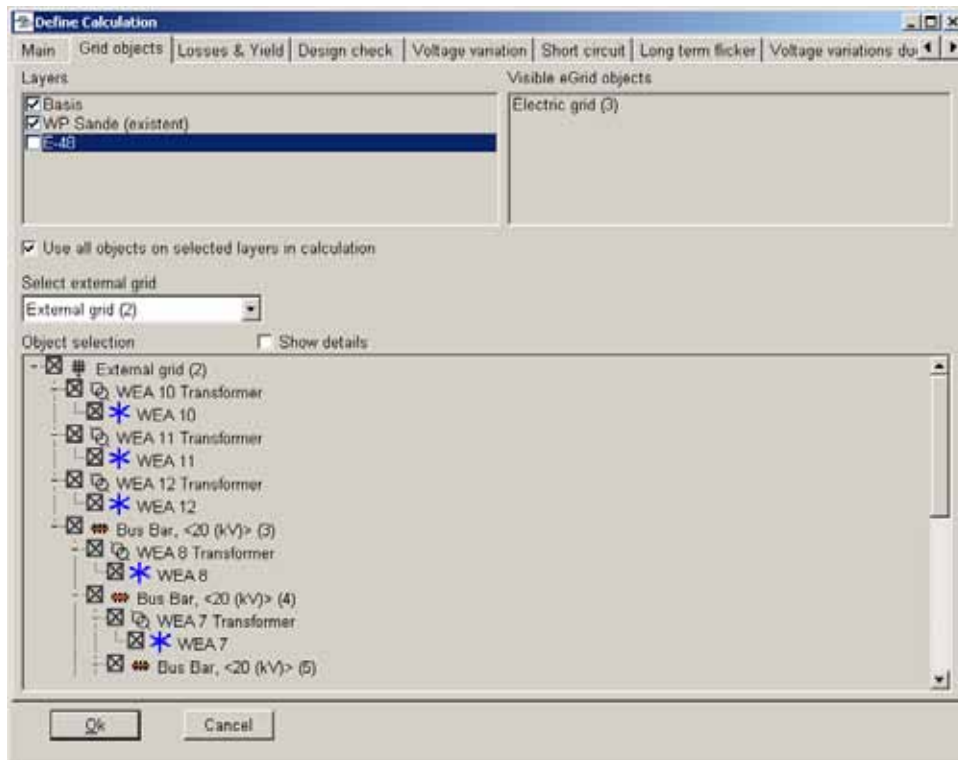
Figure 24 Calculation menu "Grid Objects" – Defining the final grid structure

Within this tab sheet, the grid structure (based on one or several Electric Grid object(s)) and grid objects (WTGs, etc.), which shall be considered in the calculation, have to be chosen. Mainly, this belongs to grids which include several Electric Grid and / or External Grid objects. This is typically done by choosing the layers on which the relevant grid objects are located. As default, all objects which belong to the visible layers at calculation start are chosen. Likewise, it is possible to deactivate specific objects for a calculation.

Due to the fact that the calculation algorithm implemented in the eGRID module cannot compute meshes, the arranged grid is being examined relating this item. A recognized mesh is announced.

10.2.3 Tab sheet 'Losses'

Figure 25 Calculation menu "Losses" – Defining a wind distribution

Within the tab sheet "Losses", the calculation conditions for the calculation of the annual losses within the cables and transformers have to be defined. The calculation de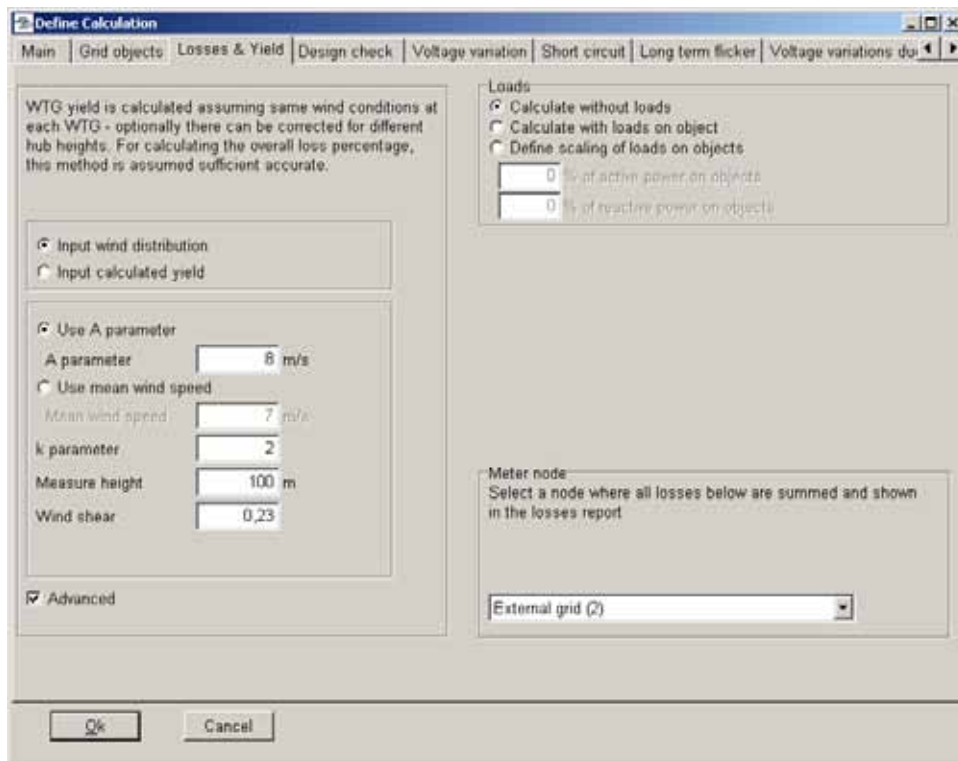termines the annual losses based on the wind frequency distribution. For this purpose, the rated power output of the WTGs is divided into 12 classes. For these classes, the frequency (hours per year) is calculated for each power class. Either the Weibull distribution with an A-parameter and/or a mean wind speed and the k-factor in hub height or the annual yield of the whole wind park can be selected as basis for the frequency distribution. When working with the Weibull distribution and selecting "advanced" (settings), even different hub heights between the WTGs and the distribution can be included. By using the calculation based on the annual yield, with the help of a standard k-factor, an A-parameter is determined. These values are the basis for the frequency distribution. If you additionally select the "advanced" settings, you get the possibility to change the k-parameter and to define the reference hub height as well as the wind shear (Hellman exponent) (see chapter Energy 3.2.2).
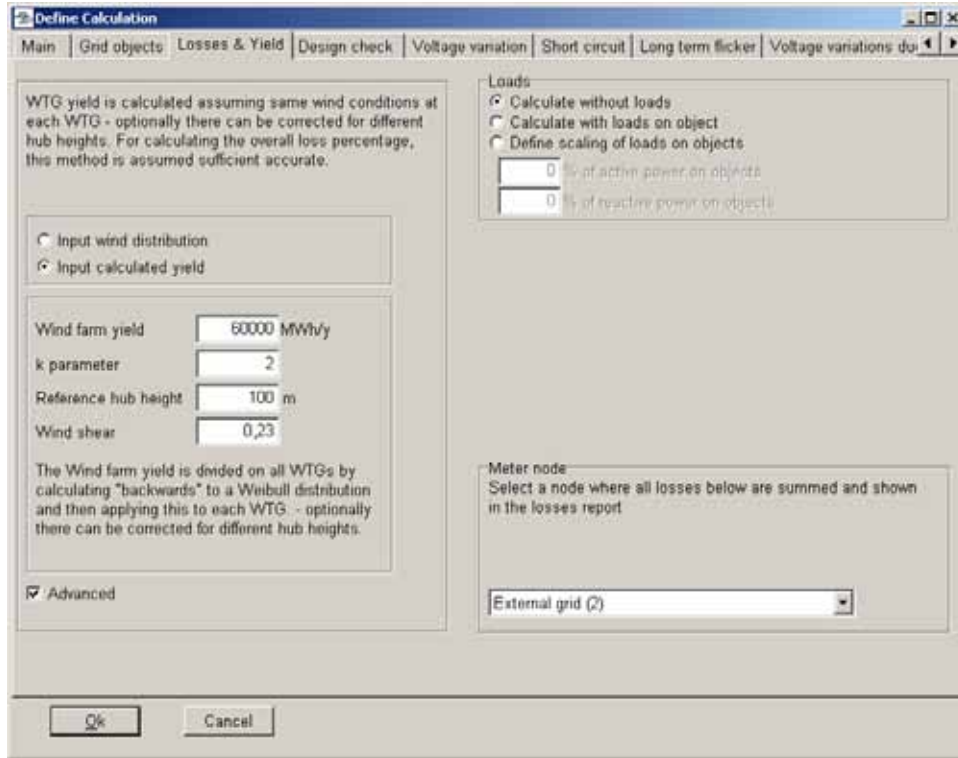
Figure 26 Calculation menu "Losses" – Input of a calculated yield

10.2.4 Tab sheet 'Design check'
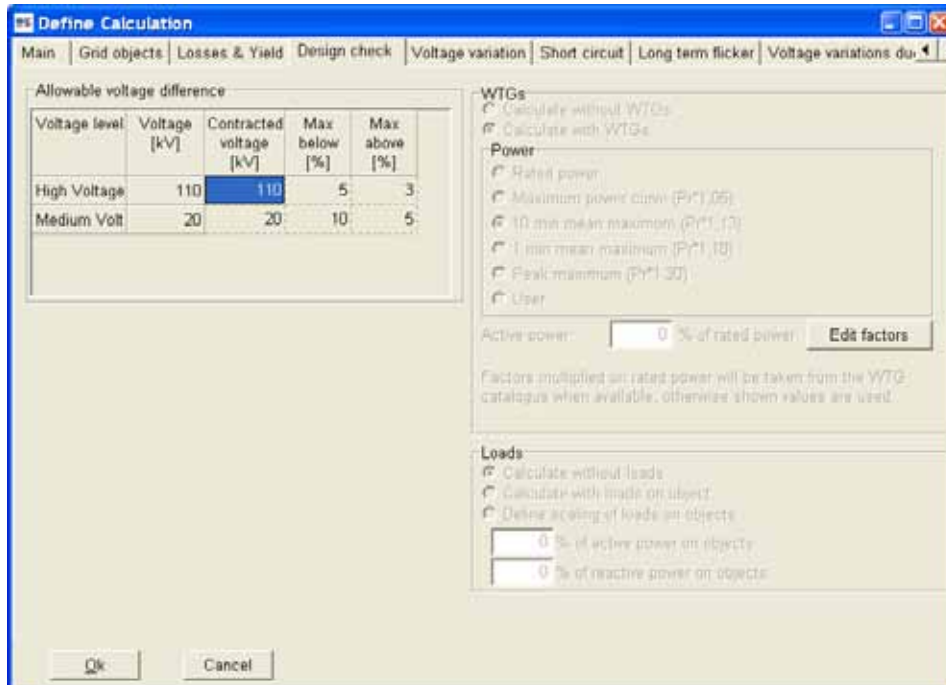
Figure 27 Calculation menu "Design check"

An individual load flow calculation can be defined within the tab sheet "Design check". If in the tab sheet "Main" a pre-defined calculation method is being selected, modifications of the settings at the right side of the tab sheet are not possible. Otherwise, the feed-in power of the WTGs can be defined up to the treatment as consumers (the data for this operation have to be indicated in the eGRID data of the turbines). Additionally, there's the possibility to define default values according to WTGs, no eGRID data have been entered, or those WTGs, the selected

entry is missing (e.g. the 10-minute maximum power value of the WTG). Concerning the loads a calculation without, with and with proportional presence of the consumers can be defined.

At the left side, permissible voltage variation values can be entered, which normally refer to the nominal voltage entered in the external grid. If a deviating reference voltage is agreed with the utility, this value has to be specified in the column "Contracted voltage". Then, the permissible proportional voltage deviations refer to these voltages. If pre-defined limit values were selected in tab sheet "Main", no changes are possible in this table relating the limit values.

10.2.5 Tab sheet 'Voltage Variation'
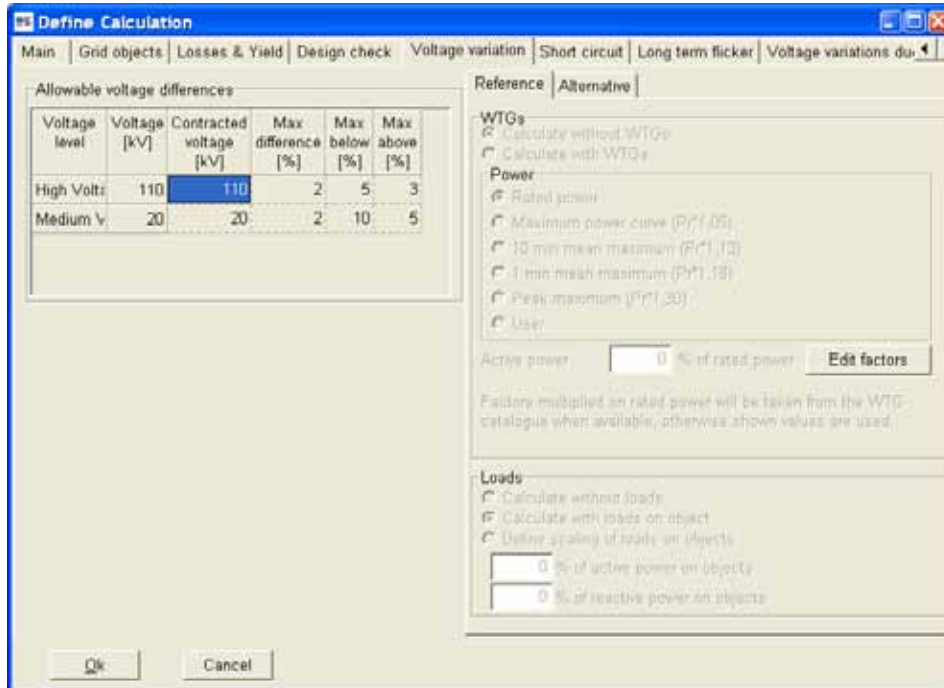
Figure 28 Calculation menu "Voltage variation" – reference calculation

The tab sheet "Voltage variation" offers the possibility to compare the grid voltages of two different operating conditions of the grid. Here, the voltage variation at each grid node is calculated, based on both operating conditions, and examined on the basis of the allowable limits, which are defined in the table at the left side. Otherwise, all settings are identical to the possibilities described in the tab sheet "Design check".
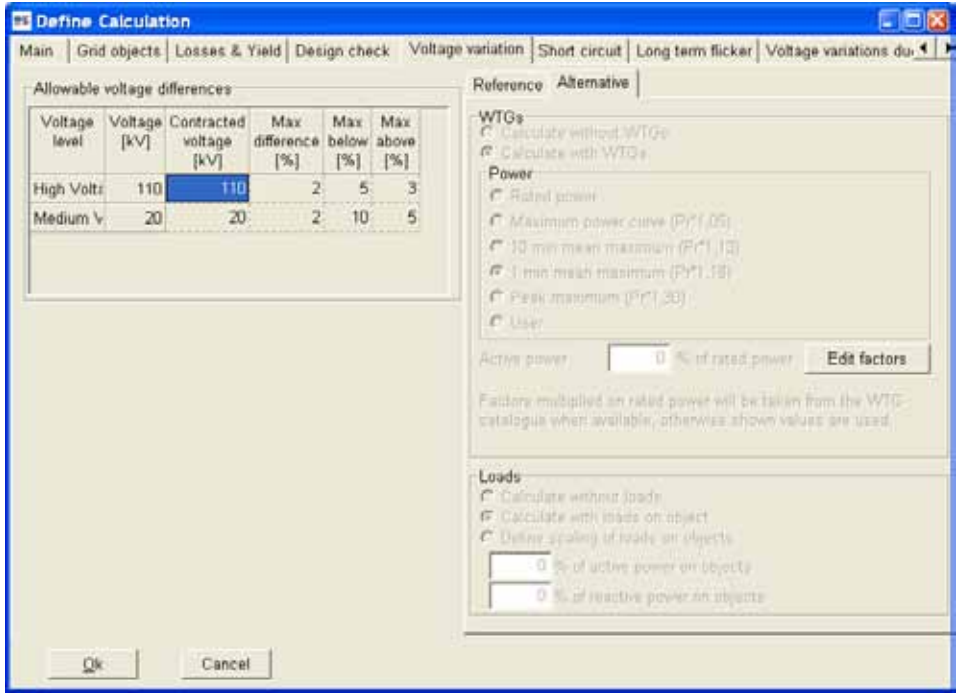
Figure 29 Calculation menu "Voltage variation" – alternative calculation

10.2.6 Tab sheet 'Short Circuit'
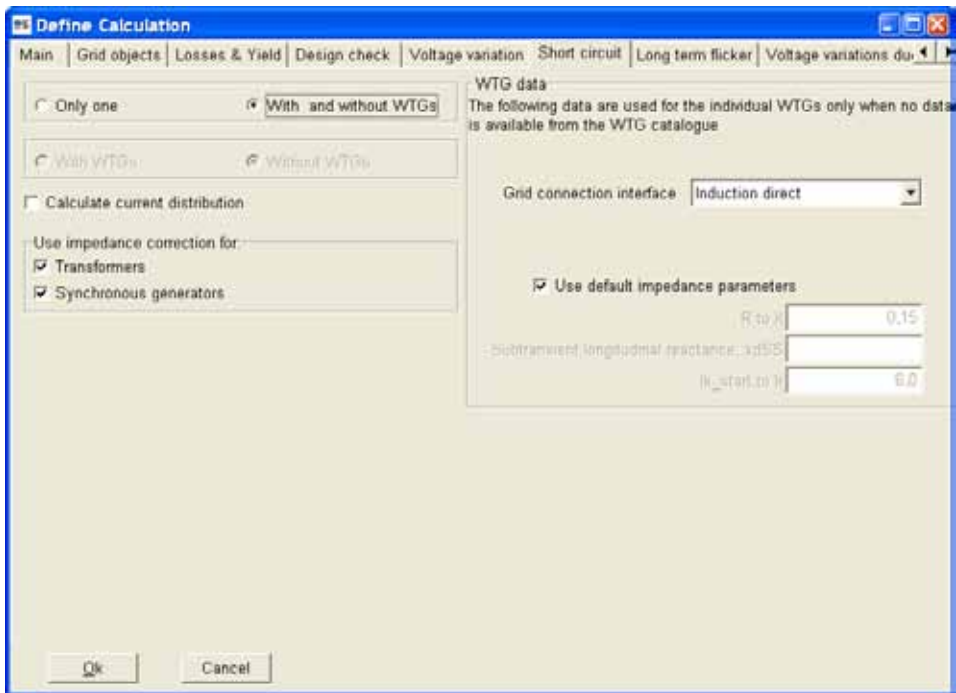
Figure 30 Calculation menu "Short circuit"

While the first three tab sheets "Losses", "Design check" and "Voltage variation" are based on load flow calculations, the other tab sheets are based on short-circuit calculations.

If a user-defined calculation is adjusted in the main tab sheet, you can select if one (without or with WTGs) or two (without and with WTGs) calculations shall be performed and further if the current distribution of the short-circuit current should also be calculated. Additionally, the use of impedance correction factors for transformers and/or synchronous generators can be activated. These factors, which are defined in the standard VDEW 0102 and/or IEC 60909 (versions of 2001), lead to a decrease of the impedances of these components and thus to a higher short-circuit current.

10.2.7 Tab sheet 'Long term flicker'
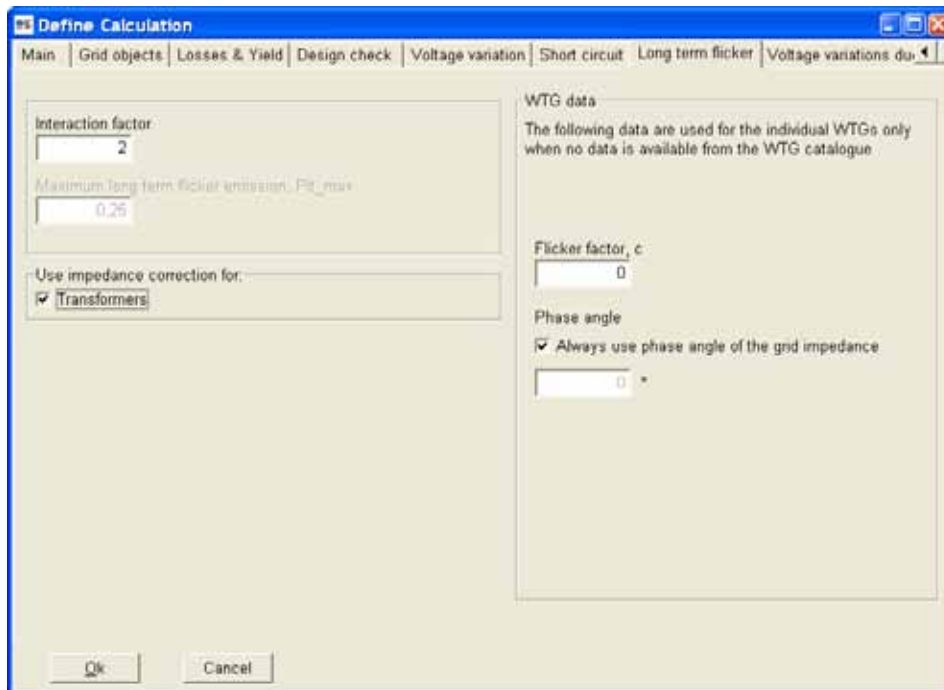
Figure 31 Calculation menu "Long term flicker"

At the left side of the tab sheet "Long term flicker", the interaction factor relating the flicker contribution of single WTGs, which is normally given to '2', and the maximum permissible total flicker value (P_{lt} or A_{lt}) have to be indicated. Additionally, equivalent to the tab sheet "Short circuit" you have to define if an impedance correction according to the standards of 2001 shall be used for transformers. Due to the fact that the flicker calculation bases on a calculation of the short-circuit power without generators, this indication is only necessary for transformers – in contrast to the tab sheet "Short circuit".

At the right side, you can indicate default flicker data. These values are used, if no eGRID data have been entered for a WTG or no flicker data are defined for a turbine.

10.2.8 Tab sheet 'Voltage variations due to switching effects'
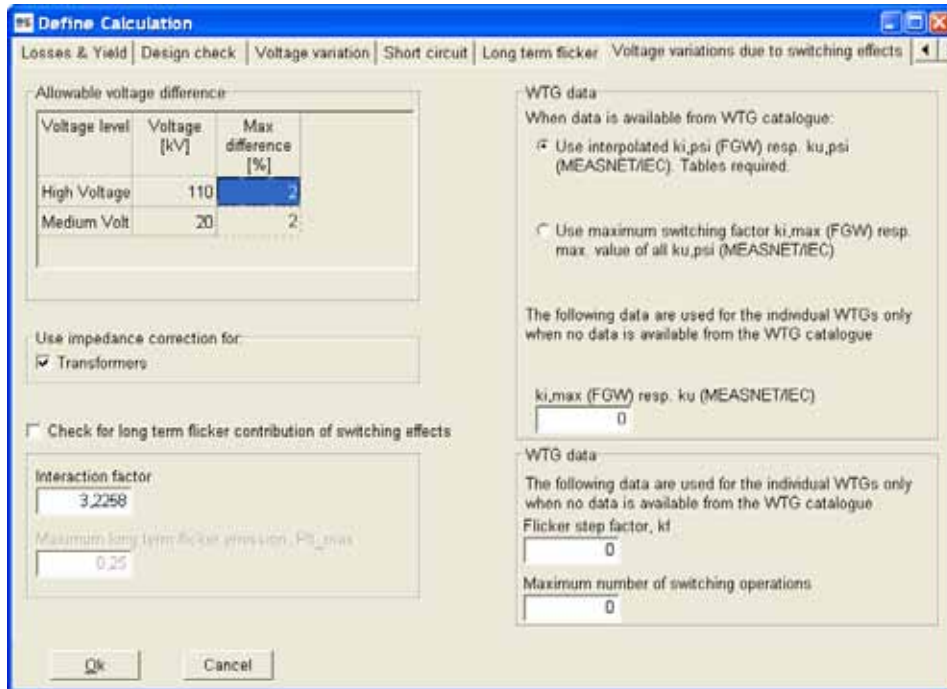
Figure 32 Calculation menu "Voltage variations due to switching effects"

The tab sheet "Voltage variations due to switching effects" equals the tab sheet "Long term flicker". Beside the data for the maximum permissible voltage variation and whether an impedance correction for transformers shall be used, at the right side, an indication whether the maximum or an interpolated switching factor (if several switching factors were entered in tabular form) should be used for the calculation. Additionally, there's the possibility to define a default switching factor, if no eGRID data have been entered or no switching factor has been defined for a WTG.

If the flicker contribution of the switching process should be calculated, the corresponding option has to be checked. As in the definition of a flicker calculation, the interaction factor of the WTG individual flicker contributions has to be defined at the lower left side as well as the maximum value. At the lower right side of the window, flicker data can be defined which is being used for WTGs without any corresponding electrical data.

10.3 The Results – Printouts/reports

Figure 33 After calculation the results appears on the window of the calculation manager.

In the tree structure, usual for Windows, the individual reports and results can be pre-viewed and/or printed. Each kind of calculation produces its own report in which the respective conditions for calculation and results are contained. Within the results, first the main results and afterwards additional results are designated. Further it is informed whether the entered limit values are fulfilled or exceeded.
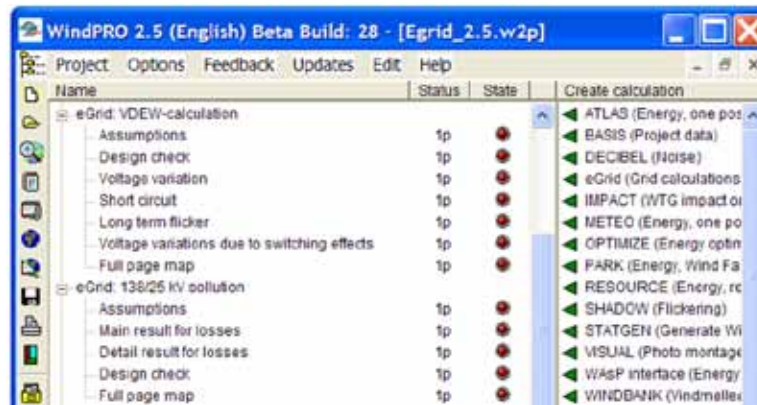
Losses: This report is divided into 'Main results' and 'Detail results'. The annual active and reactive power losses in the transformers and cables are calculated on the basis of the entered wind distribution and wind profile. The loss is also given as a percentage of the wind farm production.

Design Check: The calculated grid voltages are presented as the main result, followed by the utilization as well as the active and reactive power losses of the transformers and cables.

Voltage variations: The main result of this calculation, which is based on two individual calculations (reference and alternative calculation), is the proportional voltage variation at each node. Subsequently, the result of each individual calculation is specified as with the calculation of the design check.

Short Circuit: In dependence of the selected calculation variant (calculation with and/or without WTGs; calculation of short-circuit current distribution within the grid) the contents of this report varies. First the short-circuit power, the grid angles and the short-circuit currents of all nodes, possibly for both calculations, are shown. If demanded, additionally the current distribution for each object is being presented.

Long term flicker: As in a losses calculation, the report of this calculation is divided into a main and a detailed report. In the main report of a flicker calculation, only the total long term flicker values at any grid node are presented, followed by an assessment which bases on the defined limit value. Also, the short-circuit values which are very important for the calculation are shown. Within the detailed report, the contribution of each WTG as well as the used flicker factor in order to calculate the contribution is indicated for each grid node.

Voltage variations due to switching effects: This calculation is divided into a main and a detailed report also. In the main report of a switching effect calculation, the maximum voltage variation at any grid node is presented as well as the WTG and switching reason which are responsible for it. In case there identical results for other turbines, only one is being presented. Additionally, the maximum long term flicker values are shown, followed by an explanation which switching process leads to the maximum value. If "Worst case" is being presented, the maximum value is the result of different switching processes for different WTGs. Both values are checked regarding their limit values, which results into a combined assessment. Again, the short-circuit values which are also very important for the calculation are shown. Within the detailed report, the used switching factor and the contribution of each WTG are presented equivalent for the presentation of the long term flicker values for each grid node.

Map: The actual calculated grid with all used objects is presented on the map.

10.4 eGrid – Theory behind the calculations

Medium voltage distribution grids, to which most of the decentralized power supply structures are connected, have nominal voltages of 20 or 30 kV in accordance to DIN IEC 38. In order to have a high reliability of power supply, medium voltage grids are normally built up as ring grids, ring grids with cross connections or meshed grids. Under normal conditions, often they are operated as radial networks. In the case of repair and/or disturbance, individual parts of the grid can be switched off or switched over by existing grid interfaces.
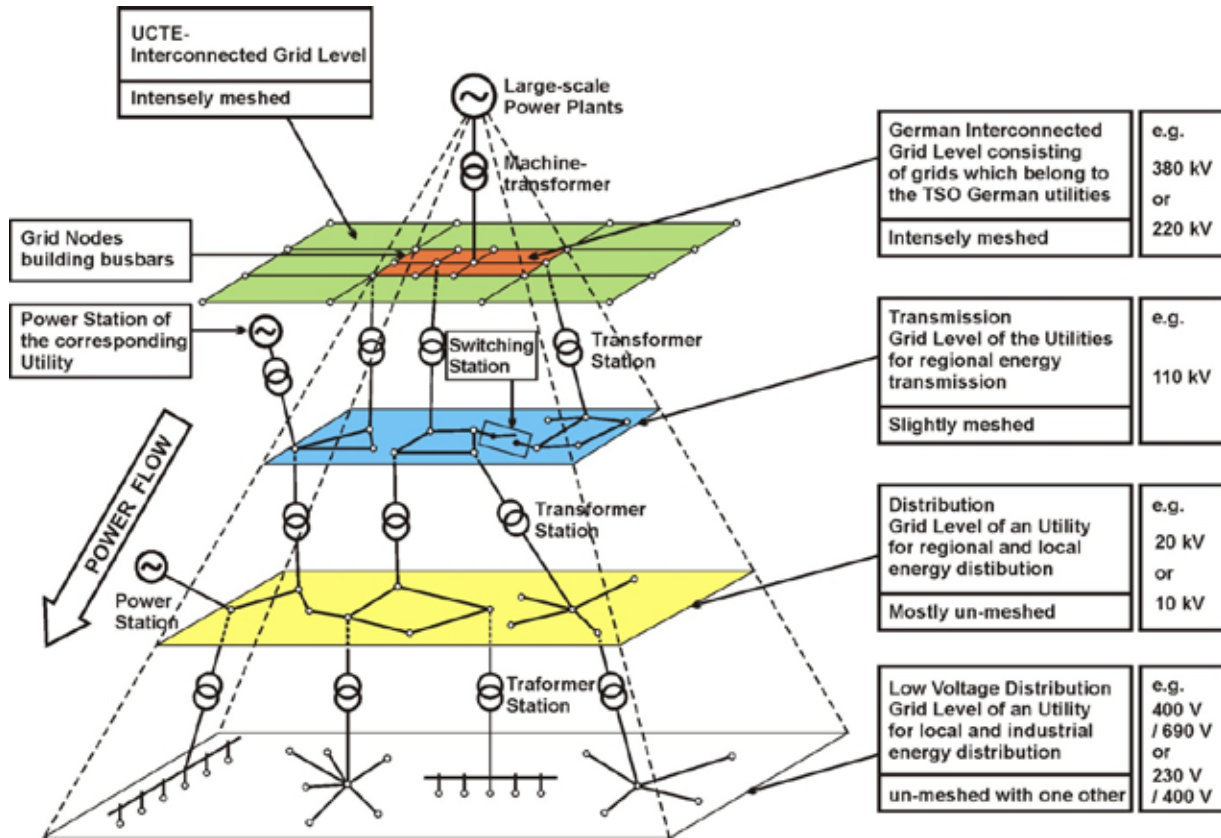
Figure 34 Different voltage levels and grid structures of the electrical grid in Germany

Usually, also a wind park has a radial grid, because one or more wind turbine generators are connected to one grid node. Due to this, the calculation algorithm was adapted to this grid configuration (radial grid). Meshed grids will not be calculated.

10.4.1 eGrid – Component Modeling

In order to simplify the electrical grid input, only components which are primarily important for the electrical grid calculation are implemented. Ancillary equipment like protection devices is not implemented. The components, relevant for the grid calculation, are:

- · External Grid
- · Transformers
- · Electrical Grid (Cables / Overhead Lines)
- · Busbars
- · Loads / Compensation Devices
- · WTGs

10.4.1.1 External Grid

Differently to other grid calculation programs, in the load-flow calculation the External Grid is implemented as an RX-serial connection – in the same manner as in the short-circuit calculation. Thus, this component also contains power losses and a voltage drop. This has the advantage that the voltage at the grid connection point (input voltage of the External Grid) is not constant every time. It can rise or fall in the case that there is no regulation about the connection point of this component.
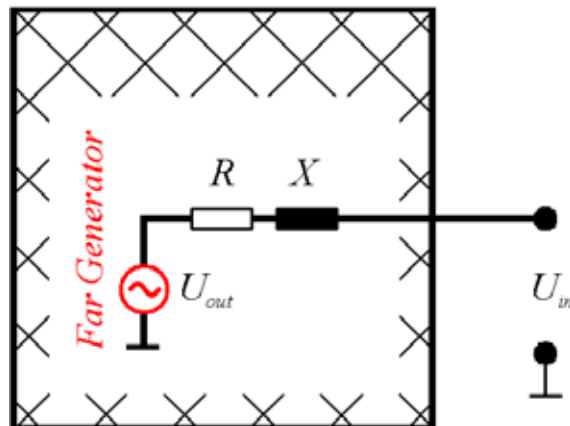
Figure 35 Circuit diagram of the ´External Grid´ component

Certainly, this approach can be confusing for utilities which have all-embracing grid models. But, – normally – a non involved person gets only the characteristics (S_K'', Ψ_K and the rated voltage U_R) of a possible connection point. The voltage of this grid node must not be constant in practice, in opposite to e.g. a large transformer station at which the voltage is regulated.

At the end of the total load-flow calculation, all angles are modified based on the angle of the output voltage of the ´External Grid´ element – the Far Generator - which is set to ´0´.

10.4.1.2 Two-Winding-Transformers

A Two-winding-transformer is integrated by its equivalent T-circuit diagram. Therefore, the impedance of a transformer has to be split into two equal portions.

Figure 36 Circuit diagram of a two-winding-transformer

All calculations are performed at the high voltage level. So, there must be a voltage conversion from the lower- to the higher voltage level of the transformer. Due to the fact, that – depending on the polarity of the transformer –

this conversion has to be done at the input or output side of the transformer using the transformation factor, the transformation is not pictured in the circuit diagram.
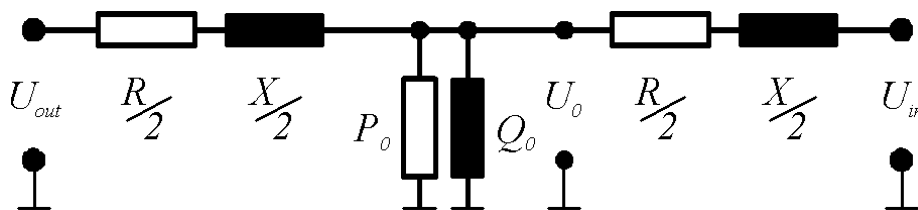
10.4.1.3 Electrical Grid

In the medium voltage level, the cross sections of the overhead lines and cables lie in a limited range, which is determined by the mechanical and electrical characteristics of the lines. The maximally permissible cross section of overhead lines is limited by the mechanical stability of the supporting masts of the overhead line and may not exceed 120 mm^2 [12, 13]. The minimum cross section does not amount less than 16 mm^2 in consideration of the permissible mechanical wire stresses [12]. However, in practice no cross sections for overhead lines and cables under 35 mm^2 are used due to economic reasons.

For the simulation of the cables or overhead lines, the equivalent Π-circuit diagram is used in the calculation algorithm.
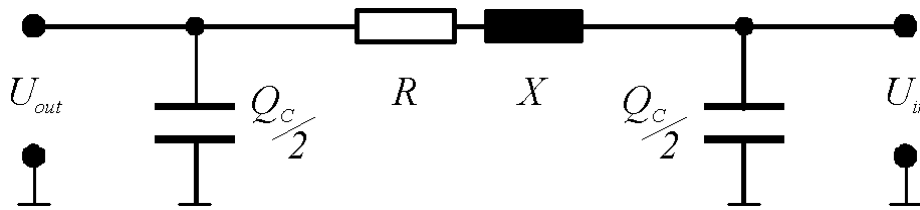

Figure 37 Circuit diagram of a cable or overhead line

While the voltages are calculated in the same manner as by the External Grid, by the calculation of the power values the reactive power production of the capacities have to be considered.

10.4.1.4 Loads / Compensation Devices

The loads are regarded as passive grid elements with an active power demand.
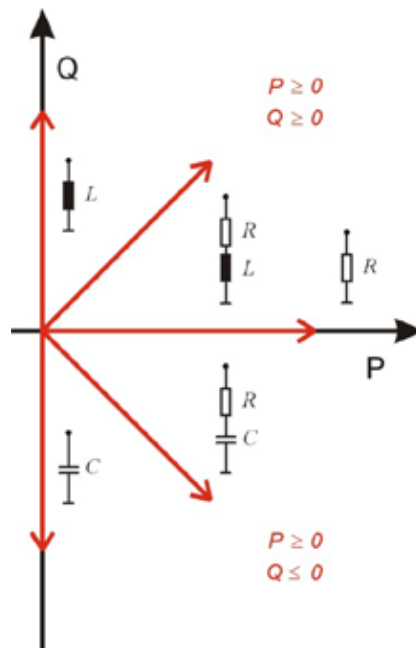
Figure 38 Different load classes

Normally, the power demand of the loads depends on the actual voltages. This dependency is not linear. The accuracy of the mathematical description of this relationship, the so called load-characteristics, mainly defines the calculation accuracy of all parameters of the operating condition of the grid like the voltages of the nodes, power losses and voltage drops. In practice, the consumer characteristics are very various. So, assumptions are inevitable. The literature [7, 8, 9] gives some theoretical recommendations, which are only conditionally applicable in practice. The available programs solve this problem differently. Each program developer uses his own "tricks" in order to reach a solution (convergence) of the mathematical grid model.

In the educational books as well as in the available grid calculation programs, the power dependency (active and reactive power) referenced to the actual voltages is integrated via a power function. The value of the exponent varies among the different sources from ´2´ down to ´0´.

$$P = P_R \times \left(\frac{U}{U_R}\right)^n \quad ; \quad Q = Q_R \times \left(\frac{U}{U_R}\right)^m$$

The dependency is pictured in the following figure for several exponents.

Figure 39 Common load characteristic

This description of the dependency has the advantage that – if the grid calculation leads to no result (does not converge) – the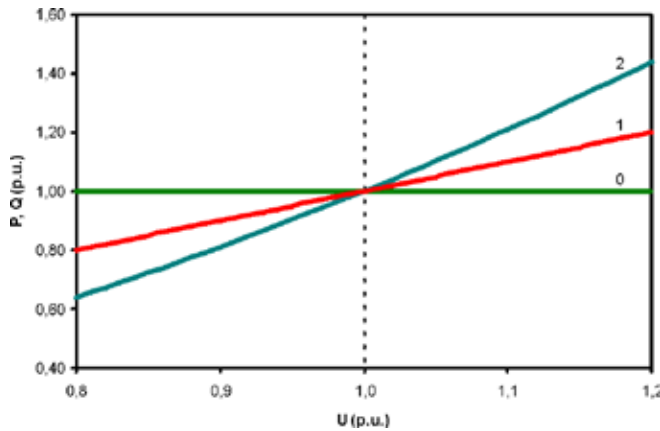 convergence of the calculation can be forced by changing the exponent towards ´0´. Unfortunately the user is not informed about this adjustment.

In our calculation algorithm, this dependency is integrated via the average load characteristics based on [10, 11],

$$P = P_R \times \left(K_{0P} + K_{1P} \times \left(\frac{U}{U_R}\right) + K_{2P} \times \left(\frac{U}{U_R}\right)^2\right); \quad Q = Q_R \times \left(K_{0Q} + K_{1Q} \times \left(\frac{U}{U_R}\right) + K_{2Q} \times \left(\frac{U}{U_R}\right)^2\right)$$

which correspond to the load conditions within the medium voltage level at best in our experience. On the basis of the parameters K_{0P}, K_{1P}, K_{2P}, K_{0Q}, K_{1Q}, K_{2Q}, it is possible to adapt the characteristics to the real load conditions without much effort. A variation of these characteristics, which are represented in figure 40 with realistic values ($K_{0P} = 0.83$; $K_{1P} = -0.3$; $K_{2P} = 0.47$; $K_{0Q} = 4.9$; $K_{1Q} = -10.1$; $K_{2Q} = 6.2$), does not take place in the calculation program. However, the user is informed in the case that the calculation did not converge.
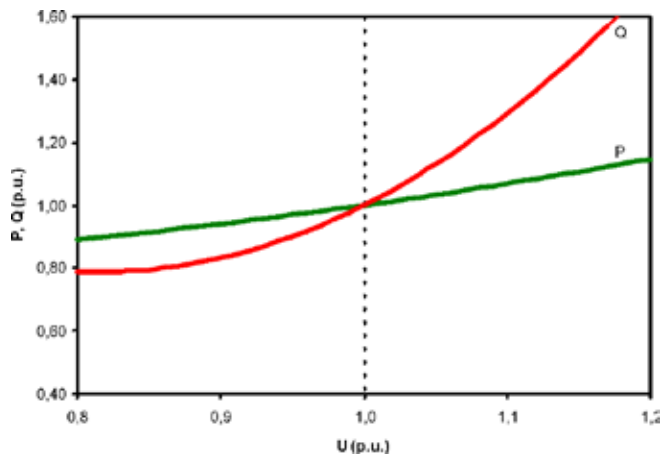
Figure 40 Average load characteristic based on [10, 11]

10.4.1.5 Generators / Wind Turbine Generators

All generators – including wind turbine generators – which are available on the market can be divided into four main classes:

· Synchronous generators

· Induction generators

· Double-fed induction generators

· Generators which are connected to the grid via a power electronic converter, so that the generator itself is not important for the behavior of the total generator system any more.

Each of them can be specified by similar parameters in static operation. Hereby, it is assessed that the feed-in power does not depend on the actual voltage at the connection node of the generator.

It is obvious, that the feed-in power of wind turbine generators depends on the wind speed. The dependency between wind speed and the active power output was already implemented in WindPRO for many marketable wind turbines.
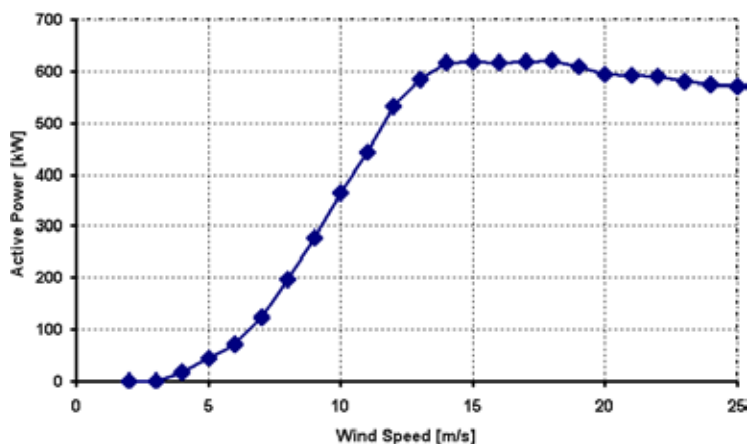
Figure 41 Dependency between wind speed and active output power by a Nordex 43 wind turbine [5]

Regarding the reactive power, the relationship between the active power and the power factor, which is not constant, had to be included in the dataset. Actually the calculation of the reactive power is performed by linear interpolation on the basis on few sampling points, which are taken out of measurement reports, made by international acting measurement institutes.
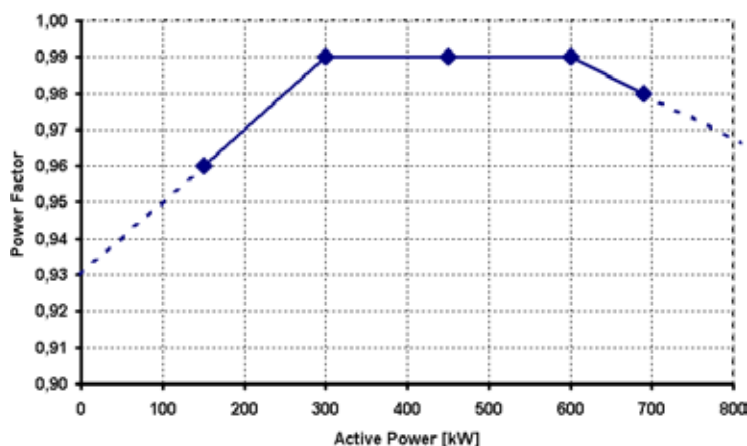
Figure 42 Implemented power factor characteristic of a Nordex 43 wind turbine [4]

Due to the way, that the calculation of the power factor via few sampling points contains a loss of accuracy, this calculation has to be replaced by another algorithm. But the fact, that for a normal user there are many unknown parameter settings in a wind turbine which have directly effects to the power factor, like the switching points of compensation capacities, an exact characterization seems to be impossible.

10.4.2 eGrid – Calculation Methods

The purpose and the scale of grid calculations are determined by a concrete and individual task, which can be very different in each case. For example, the existing connection capacity has to be evaluated in order to decide about the connection of a further wind turbine generator to the grid, which is described via technical criteria. In accordance with the guidelines for parallel operation of own generation plants with the grid of the utility [2, 3], these criteria refer with:

· Voltage variations also by flickers

· Variations of the short-circuit current

· Power factors

· Harmonics

These criteria can be affected by the normal operation of a wind turbine generator. Using modern wind turbines, in which IGBT inverter technology is implemented, the last two items can be neglected. Thus, the first two criteria represent the characteristics, which are to be considered as the main topics for the grid calculation.
The grid, at which the connection of wind turbine generators is to be examined, is regarded as an energy distribution system with two areas: the infinite bus and the affected grid area, as presented in the following picture.

Figure 43 Typical example of a wind turbine connection to the grid

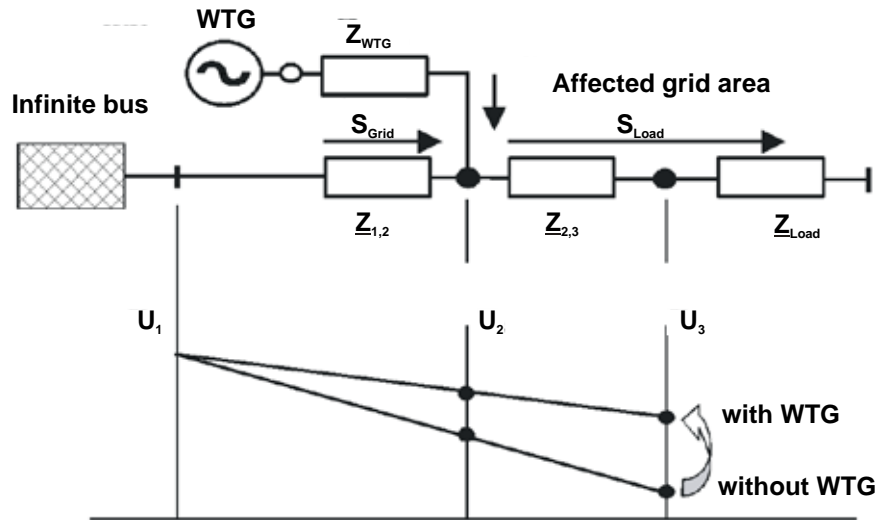Due to the problem definition specified above, only two calculations are selected from the large scale of the grid calculation tasks: the load-flow calculation and the short-circuit calculation. The voltages of the grid nodes could be obtained by load-flow calculations. So, on the basis of two calculations (calculation with/without wind turbine generators), voltage variations can be determined. The short-circuit calculation specifies the available short-circuit power of a grid node, which can be used for the estimation of flicker effects.

As already mentioned, the electrical calculation implements two independent calculations: the load-flow and short-circuit calculation. Differently to other calculation programs, which have to handle large matrices in order to calculate a meshed grid, due to the concentration on radial grids, the calculation algorithm of the eGRID module bases on recursion, a very powerful calculation method. Doing so, several simplifications or neglections, necessary to handle large matrices can be avoided.

10.4.2.1 Load-Flow Calculation / Calculation of Voltage Variations

The voltages of the grid nodes are worked out by the load-flow calculation. This happens by setting the individual nominal voltage value for each grid node in a first calculation step. On the basis of the active and reactive power of the generators and loads, which are known due to the voltage set before, now the power losses in the components are calculated. The calculation is made through the entire grid toward the ´External Grid´ component, by which it is presumed that it can absorb or provide any power rates. On the basis of the – in such a way determined – load-flow, a specifying of the voltages takes place in a next step. Based on a fixed voltage of one grid node, given by the user, the voltages of all grid nodes are calculated again.
Due to these new voltages and an eventually voltage dependency of the loads, a new calculation of the load-flow can be necessary (next iteration step). After calculating the power values, new voltage values are calculated again and so on.
This calculation (iteration) is broken off, if the difference between two calculation steps achieves the given calculation accuracy. In [14] it is shown that under the multiplicity of all possible abort criteria the active power difference represents a reliable criterion.

$$\max(abs(P_i - P_{i+1})) < e$$

The calculation accuracy can be given by the user. The default value is 1e-6 kW. However, a fundamental characteristic of the iteration calculation is that the calculation leads to no result, i.e. that it does not converge. Therefore, a maximum number of iteration steps is specified, which can be also set by the user. Here, the default value is 50.
Due to the nature of a load-flow calculation, all voltages in the grid are calculated based on one grid node (the voltage is regulated at this node), i.e. there has to be a specified voltage value at a specified node. So, the parameters for a single load-flow calculation are

· the grid node for which the voltage is given

· the voltage of that node

Also it is possible, that there is no voltage regulation within the examined grid, this means the regulation is implemented within the Far Generator. In this case, the internal voltage of the ´External Grid´ is kept on the specified voltage (see also chapter 10.4.1).

The calculation of the voltage variations includes two load-flow calculations, the calculation of the grid e.g.

· without generators and

· with generators.

Thereby, a grid node can be assigned, at which no voltage variation takes place, i.e. the voltage is constant. So, for the calculation of voltage variations, there must be another parameter:

· the grid node for which the voltage is constant.

Naturally, this can be the same node with the given voltage value.

10.4.2.2 Short-Circuit Calculation

In all practical cases it is possible to determine the short circuit current at fault location via the method of the equivalent voltage source at the short-circuit location. During the short-circuit calculation, this source is the only existing voltage source within the grid [15, 16].

In principle, the calculation of the currents during a short circuit is a calculation of transient processes which requires the solution of differential equations. However, in practice frequently only a quasi-stationary calculation of the sub-transient current $I_K´´$ and the sub-transit short-circuit power $S_K´´$ is performed.

The computation is based on the determination of the impedance of the entire grid related to the fault location. Hereby, all components which feed-in into the grid i.e. the ´External Grid´ and all types of generators are replaced by their internal impedance's. Further, the capacities of the cables and overhead-lines, the parallel admittance's of the no-rotating loads, the impact by the static loads, the tap position and the no-load losses of the transformers can be neglected. So, the ´External Grid´, the cable and overhead-lines, the transformers as well as the generators are only described by their individual R-X serial impedance, whereas loads are ignored.
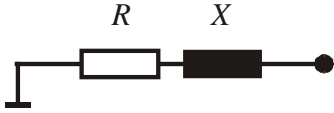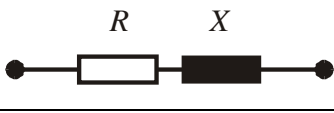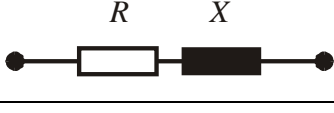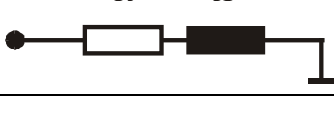
External Grid	R X
Cable / Overhead Line	R X
Transformer	R X
Generator	R X
Load	ignored

Figure 44 Equivalent short-circuit diagrams

Normally the short-circuit currents and the short-circuit power are determined for all grid nodes. Hereby, in each case only one fault location is chosen and analyzed.

Concerning the tasks of the project it is necessary to calculate only the symmetrical short-circuit in all grid nodes.

10.4.2.3 Flicker calculation

The flicker calculation bases on the results of the short-circuit calculation. Hereby, the short-circuit power and the grid angle of an inspected grid node is used, calculated by a short-circuit calculation without generators.

Basics

Based on the calculation algorithm of different wind turbines in the grid, the flicker contribution of each wind turbine can be estimated by the equation

$$P_{lt\,WT} = 1.1 \times \frac{c \times S_{R\,WT}}{S_k^{''}} = \frac{c \times P_{R\,WT}}{I_{R\,WT} \times S_k}$$

concerning the medium voltage level.

Hereby, the phase angles of the wind turbine and of the grid impedance are assumed as worst case. Within this formula, factor c is the flicker factor of the wind turbine, normally given by the manufacturer. $S_{R,\,WT}$ represents the rated apparent power of the wind turbine and $S_k^{''}$ is the initial short-circuit power of one grid node, a single wind turbine affects to.

Normally, the inspected grid node is the point of common coupling (PCC), the connection node of a whole wind farm, due to the fact that this node is affected most of all. Relating the grid nodes within a single wind farm or by the calculation of a grid with several wind farms (several PCC), different calculation algorithms exist in order to calculate the resulting flicker values in these nodes. The implemented algorithm bases on a publication of DEWI (Deutsches Windenergie-Institut GmbH).

In this algorithm, it is possible that the initial short circuit power of a grid node has to be taken into account in order to calculate the flicker contribution of one wind turbine, although this node is neither the grid node, at which the turbine is connected, nor the node, for which the long term flicker is being calculated. The allocation of the node will not be presented within this manual.

The interaction of each single flicker value to the total flicker is described by the equation

$$P_{lt\,res} = \sqrt[m]{\sum_{i=1}^{n} P_{lt\,WTi}^{m}}$$

whereas factor n represents the number of wind turbines and factor m represents an interaction factor normally set to 2. If all wind turbines are of the same type, i.e. they have the same apparent power and the same c-value, the combination of these equations leads to the popular formula for the flicker calculation concerning the PCC node or superordinated grid nodes.

$$P_{lt\,res} = 1.1 \times \frac{\sqrt{n} \times c \times S_{R\,WT}}{S_k^{''}}$$

In case of additional flicker sources in the grid, basing on different energy sources like wind or water, the factor m can be set up to 3, which corresponds to

$$P_{lt\,res} = 1.1 \times \frac{\sqrt[3]{n} \times c \times S_{R\,WT}}{S_k^{''}}$$

As already mentioned, within the equations above the phase angles of the wind turbine and of the grid impedance are assumed as worst case. For an exact flicker calculation, the angles have to be considered using a second flicker factor, the flicker relevant phase angle.

$$c_{exact} = c_{worst\,case} \times \left| \cos(\Psi_k + j_f) \right| .$$

Due to several reasons, which should not be represented within this manual, the term $\cos(\Psi_k + j_f)$ cannot be ´0´. If the value is lower than ´0.1´, the result of this term is set to ´0.1´.

Different methods providing flicker data

Due to the fact, that there are three different ways to present the relevant flicker data of a wind turbine, the implementation of the flicker calculation has to consider these methods.

Method A: Flicker factor and the individual flicker relevant phase angle

Here, the provided data are the flicker factor and the individual flicker relevant phase angle. The contribution of one wind turbine to the total long term flicker is being calculated via the equations described before.

Method B: Flicker factor and a dependent flicker relevant phase angle (j f = -Ψ k)

The available data are the flicker factor and the flicker relevant phase angle $j_f = -Y_k$, e. g. by an Enercon E40 (500 kW).

Y_k	0°	15°	30°	45°	60°	75°	90°
c	6	6	6	6	6	6	6

Table1 Flicker data of an E40 (500 kW)

Using this phase angle – due to the fact that the cos-term always is set to ´1.0´ – for the flicker contribution of the wind turbine always the worst case is considered.

Method C: Various flicker factors subjected to the grid angle Y_k

Here, the provided data are various flicker factors subjected to the grid angle Y_k, e. g. an AN Bonus 1.3 MW.

Y_k	0°	15°	30°	45°	60°	75°	90°
c	14	12	10	7	3	3	6

Table 2 Flicker data of an AN-Bonus 1.3 MW

Due to the fact that the calculation of the long term flicker requires the flicker factors of all grid angles, interim values are calculated using linear interpolation.

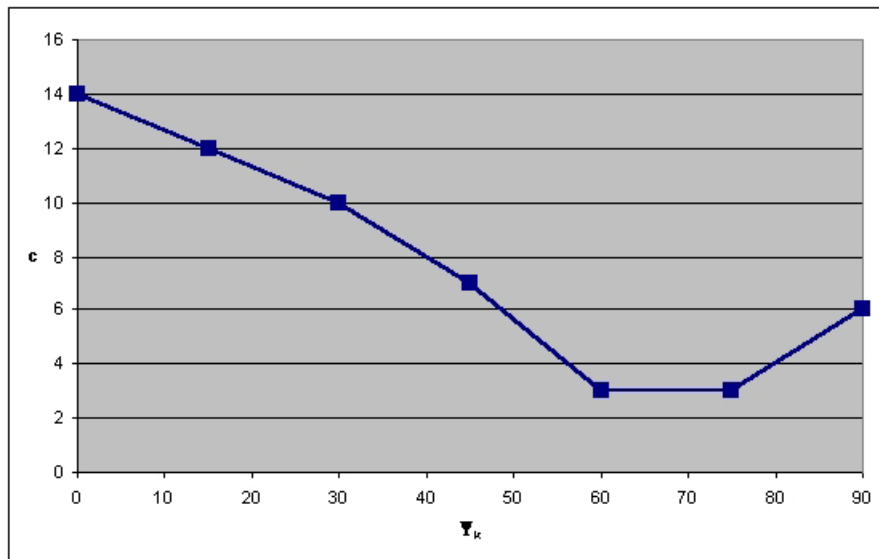*Figure 45 Interpolation of the AN-Bonus data*

If the flicker data should not be given within the range of 0°-90°, e. g. a turbine by Vergnet (300 kW),

Y_k	30°	50°	70°	85°
c	12.6	11.4	9.0	6.3

Table 3 Flicker data of a Vergnet turbine (300 kW)

the values at the border areas are calculated again by linear interpolation, using two adjacent values.
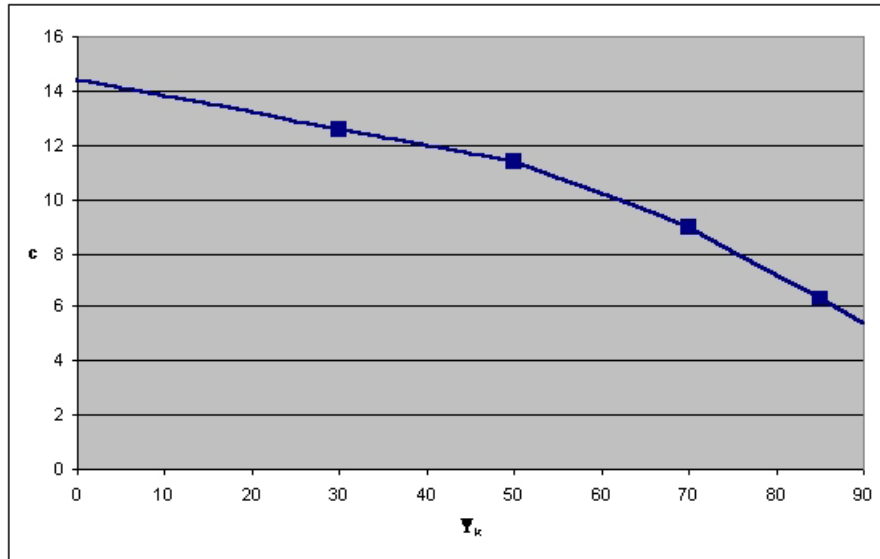
Figure 46 Interpolation of the Vergnet data

Due to the fact, that the angles at such border areas are not realistic anyway, for those areas a major tolerance to the real value seems to be acceptable.

10.4.2.4 Voltage Variations due to Switching Effects

Concerning the medium voltage level, the height of the voltage variations due to switching effects of each wind turbine can be calculated by the equation

$$\mathrm{D}u_{max} = 1.1 \times \frac{k_{i\,max} \times S_{R,WT}}{S_k^{''}} = \frac{k_{i\,max} \times P_{R,WT}}{I_R \times S_k}.$$

The calculation process is very similar to the flicker calculation. Here, factor $k_{i\,max}$ represents the maximum contribution of one wind turbine. Again, the height of this contribution depends on the grid angle. Equal to the flicker calculation, factor $k_{i\,max}$ can be replaced by a factor k_{iY} which represents the contribution at the specified grid angle Y_k.

Normally, the k_{iY} values are given as a table incrementing in 5°-steps.

Y_k	0°	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°	55°	60°	65°	70°	75°	80°	85°	90
k_{iY}	1.3	1.3	1.2	1.2	1.2	1.2	1.1	1.0	1.0	0.9	0.8	0.7	0.8	0.8	0.9	0.9	0.9	1.0	1.0

Table 4 Switching factors of an AN-Bonus 1.3 MW ($k_{i\,max}$ = 1.2)

Again, interim values are calculated using linear interpolation.

10.4.2.5 Interaction of the flicker contributions of switching processes

Based on the IEC Guideline as well as the actual BDEW Guideline (Germany), the long term flicker which is being created by a switching process of a WTG has to be calculated using:

$$P_{lt,E} = 8 \cdot N_{120,i}^{0,31} \cdot k_{f,i(\Psi)} \cdot \frac{S_{rE}}{S_{KV}} = \frac{8}{S_{KV}} \cdot N_{120,i}^{0,31} \cdot k_{f,i(\Psi)} \cdot S_{rE}$$

Due to the fact that there shouldn't be a difference whether a single turbine has e. g. 30 switching processes in a time frame of two hours (N_{120}) or each turbine of a group of ten WTGs switches only three times in the same time frame, a grouping is being performed within WindPRO: same type of WTG, same apparent power value S_{rE}, same value for the ´Flicker Step Factor´ k_f and same grid connection point respectively short-circuit power value of the grid connection point S_{KV} (this node can be different based on the inspected grid node). The total flicker contribution effect of the grouped WTGs is being calculated using:

$$P_{lt,E} = 8 \cdot (n \cdot N_{120,i})^{0,31} \cdot k_{f,i(\Psi)} \cdot \frac{S_{rE}}{S_{KV}}$$

Here, factor n is the number of the grouped turbines.

Unfortunately there isn't a calculation instruction in the IEC guideline or the old German guideline how to calculate the total flicker contribution based on an interaction of the contributions of different turbines or same kind of turbines with different grid connection points. Thus, so far (incl. WindPRO 2.6) a quadratic interaction factor has been used in WindPRO:

$$P_{lt} = \sqrt[2]{\sum_{i=1}^{N_E} P_{lt,i}^2}$$

Now, there is a calculation instruction in the German BDEW guideline:

$$P_{lt} = \frac{8}{S_{KV}} \cdot \left(\sum_{i=1}^{N_E} N_{120,i} \cdot \left(k_{f,i(\Psi)} \cdot S_{rE} \right)^{3,2} \right)^{0,31}$$

Regrettably this equation only relates to the grid connection point of a whole wind farm because there is only one short-circuit power of a single grid node which is being assessed for all turbines to calculate their contribution.

In order to get a general equation the equation hast o be modified.

$$P_{lt} = \frac{8}{S_{KV}} \cdot \left(\sum_{i=1}^{N_E} N_{120,i} \cdot \left(k_{f,i(\Psi)} \cdot S_{rE} \right)^{3,2} \right)^{0,31}$$

$$= \frac{8^{\frac{0,31}{0,31}}}{S_{KV}^{\frac{0,31}{0,31}}} \cdot \left(\sum_{i=1}^{N_E} N_{120,i}^{\frac{0,31}{0,31}} \cdot \left(k_{f,i(\Psi)} \cdot S_{rE} \right)^{3,2 \cdot \frac{0,31}{0,31}} \right)^{0,31} \quad ; \ 3,2 \cdot 0,31 = 0,992 \simeq 1$$

$$= \left(\sum_{i=1}^{N_E} \frac{8^{\frac{1}{0,31}}}{S_{KV}^{\frac{1}{0,31}}} \cdot N_{120,i}^{\frac{0,31}{0,31}} \cdot \left(k_{f,i(\Psi)} \cdot S_{rE} \right)^{\frac{1}{0,31}} \right)^{0,31}$$

$$= \left(\sum_{i=1}^{N_E} \left(\frac{8}{S_{KV}} \cdot N_{120,i}^{0,31} \cdot k_{f,i(\Psi)} \cdot S_{rE} \right)^{\frac{1}{0,31}} \right)^{0,31}$$

using

$$P_{lt,E} = \frac{8}{S_{KV}} \cdot N_{120,i}^{0,31} \cdot k_{f,i(\Psi)} \cdot S_{rE}$$

result to

$$P_{lt} = \left(\sum_{i=1}^{N_E} P_{lt,i}^{\frac{1}{0,31}} \right)^{0,31}$$

or in another way of writing:

$$P_{lt} = \sqrt[\frac{1}{0,31}]{\sum_{i=1}^{N_E} P_{lt,i}^{\frac{1}{0,31}}}$$

Thus, the same equation like before can be used in case an interaction factor of

$$\frac{1}{0,31} = 3,2258$$

is being taken into account.

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