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Bornholm Power System Model: Load-flow and State Estimation using DIgSILENT PowerFactory

Client User Manual, July 2009

DTU Electrical Engineering
Department of Electrical Engineering

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Client User Manual

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Udgivelsesdato: 09. juli 2009

Klasse:

Udgave: 1. udgave / 1. edition

Bemærkninger:

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1. Introduction

The power system of the Danish island of Bornholm, which in the following is termed the Bornholm system, is owned and operated by the Distributed System Operator (DSO) of Bornholm, the Oestkraft Company. The Bornholm system comprises a meshed 60 kV system and radial 10 kV and 0.4 kV systems. Through a 135/60 kV transformer and a 60 kV submarine cable the Bornholm system is connected to the 135 kV transmission system of Sweden. Power generation in the Bornholm system contains thermal generation units, such as diesel and steam turbines, and a large share electricity-producing wind turbines; the share of wind turbines exceeds 30% of the electric energy consumption and will increase in the future. The ability to go into planned island operation distinguishes the Bornholm system from the main Danish transmission system.

This document presents the Bornholm system model developed at the Centre for Electric Technology (CET), Technical University of Denmark (DTU), with focus on the load-flow solution and mapping of operation regimes, e.g. voltage, current, active and reactive power flow within the 60 kV system, submarine cable to Sweden and 60/10 kV substations. Under the 60/10 kV substations, the active and reactive power contributions are separated into generation and load, e.g. consumption and losses, and shunts.

The developed model comprises also a state-estimation algorithm of the wind turbine generators, thermal power plant generators (as a lumped representation so far), load, 60 kV lines, 60/10 kV transformers and shunts, converting the available measurements of voltage and current magnitudes, power-factor absolute values as well as the grid frequency measurement under the Hasle 60 kV station and the active and reactive power measurements on the 10 kV feeder levels under the Åkirkeby 60/10 kV substation, into the voltage (magnitude and angle), current (magnitude, angle and direction), active and reactive power (with direction) etc. of the mentioned grid components.

2. Application Note

The Bornholm system model comprises:

1/ an electric system part with representation of the grid components such as stations and substations, lines and cables, transformers, generators, load and shunts, and

2/ a state-estimation part comprising a DIgSILENT Programming Language (DPL) script reading available measurements, finding a suitable load-flow solution of the Bornholm system model and writing the results into user-specified text files for further comparison to the measurements.

The state-estimation part relies on the quality of the available measurements. Some measurements are found suspect or incomplete, for instance some of the power-factor measurements in the 60/10 kV substations. Establishment of more measurements, for instance those of the active and reactive power with direction at each 10 kV feeder, is also found necessary for getting better state-estimation. Since such a weakness regarding the available measurements is recognized and enhancement of the measurements is expected to take place, the state-estimation algorithm should be updated if and when better and more measurements become available for the CET, DTU.

2.1. Recommended Version and Build

The Bornholm system model is implemented into and tested using the commercially available DIgSILENT PowerFactory simulation program, ver. 13.2 build 343. The use of ver.13.2 build 343 has been agreed with the project manager.

2.2. Model File

The Bornholm system model file is “Project Bornholm 60kV Net v11.dz”. The latest and tested, official model file version is dated 2009-07-07.

The official model file is owned by the project manager with all exclusive rights to access, use and introducing changes.

Please be careful with altering the official model file and avoid overwriting the official model file with your own file versions without prior (written) accept from the project manager.

2.3. Newer Program Versions and Builds

The Bornholm system model is readable into newer program versions and builds of the DIgSILENT PowerFactory simulation program. The electric system part is considered compatible with newer versions and builds of the DIgSILENT PowerFactory simulation program, whereas the state-estimation part might not be fully compatible with newer program versions or builds. When a newer program version or build is to be applied, but the state-estimation part is not updated to this newer version or build, the following steps are recommended:

1/ the Bornholm system model should be imported into, the DIgSILENT PowerFactory ver. 13.2 build 343,
2/ the state-estimation part, finding the load-flow solution of the system, should be executed from the program ver. 13.2 build 343,
3/ the Bornholm system model should then be exported from ver.13.2 build 343 and imported into the preferred newer program version and build, where the work is to be continued.

Exporting and importing activities are in accordance to the common practice of the DIgSILENT PowerFactory simulation program.

3. Data Structure and Access

The data are owned by the project manager. The project manager grants the data access and allows changes and updates of the data. The model data are divided into the data of the electrical grid components and the measurements.

3.1. Electrical Grid Component Data

The electrical grid component data comprises the electric constants of the lines (overhead lines and cables), transformers, shunts, and to certain extend the data of thermal power plant generators, loads and wind turbine generators and their types/manufacturers. The electrical grid component data are extracted from the files provided by the project manager and applied for the model set-up.

Ref. [1], [2], [3] provide comprehensive overviews of the 60 kV power system topology and essential data of the electrical grid components with notification of all the 60 kV stations [1], cable connection and transformer to Sweden [2], 60 kV lines [1] and 60/10 kV substation transformers [3].

It must be kept in mind that the applied data represent the best approach and most recent knowledge about the Bornholm system at the moment where the Bornholm system model set-up took place. The electrical grid component data should be periodically verified and updated when deviation or need is discovered.

3.2. Measurements

Fig. 3.1 reproduces an overview of the available measurements in the 60 kV power system, which is given in Ref. [1].

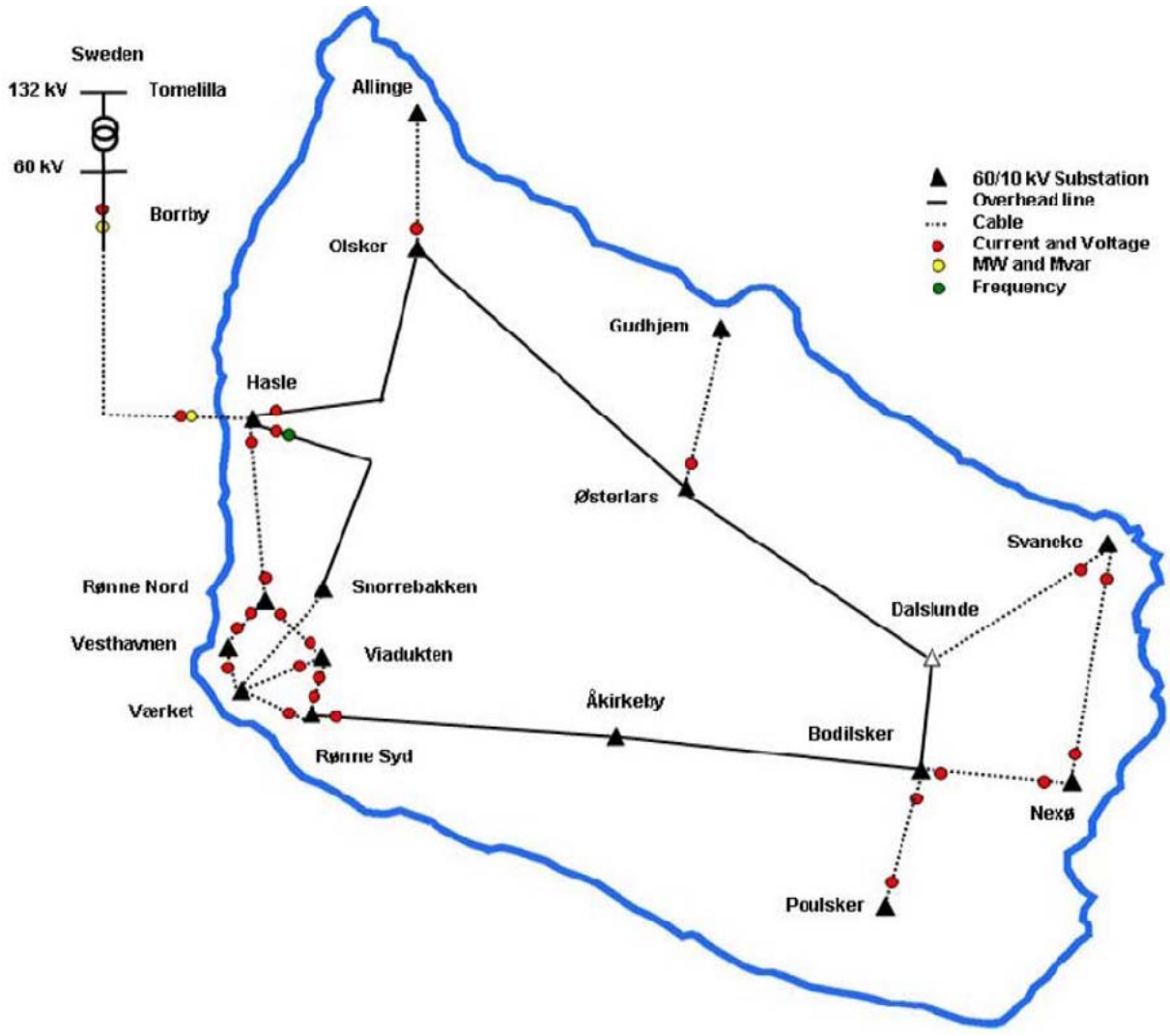

Fig. 3.1: Measurements in the 60 kV system.

When available and shown in Fig. 3.1, the measurements in the 60 kV system are:

1/ Voltage magnitude at the shown 60 kV line end,
2/ Current magnitude (no direction) at the shown 60 kV line end,
3/ Active and reactive power with direction at the Bornholm end of the cable connection to Sweden,
4/ It is noticed that the measurements in the Borrby end of the cable connection to Sweden are not found in the available measurement files,
5/ Frequency in the shown 60 kV line end (at the Hasle station).

The structure of the available measurements under the 60/10 kV substations is found in Ref. [3]. Typically the available measurements under the 60/10 kV substations comprise:

1/ Voltage magnitude at 10 kV side,
2/ Current magnitude through the 10 kV distribution transformer terminals,
3/ Current magnitudes at the 10 kV feeders, including wind turbine feeders, consumption feeders, and shunt feeders,
4/ Power-factor absolute values through the 10 kV distribution transformer terminals,
5/ Under the Åkirkeby 60/10 kV substation, the active and reactive power with direction measurements are available in each 10 kV feeder,

It must be noticed that the main generation station, the Værket 60/10 kV substation, does not have any available measurements of the 60 kV voltage or current. The thermal power plant units do not have any available active and reactive power measurements or other types of measurements which could be applicable for direct evaluation of the operation of (in-service or out-of-service) and power generation from these thermal power plant units.

4. Model Application

Please follow the instructions to start using the Bornholm system model in the DIgSILENT PowerFactory simulation program:

1/ Start the DIgSILENT PowerFactory simulation program. In this case, ver. 13.2 build 343.

2/ Start the Data Manager of the DIgSILENT PowerFactory, in accordance to the common practice of the simulation program.

3/ If the Bornholm system model is present in the Data Manager, then proceed to the next step. If not present in the Data Manager, then import the Bornholm system model (from the model file, for example “Project Bornholm 60kV Net v11.dz” into the Data Manager using the Import activity in accordance to the common practice of the DIgSILENT PowerFactory simulation program. See Fig. 4.1.

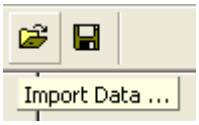

Fig. 4.1: Use of the Import activity.

4/ When the Bornholm system model is found in the Data Manager, then activate the Project containing the model. See Fig. 4.2.

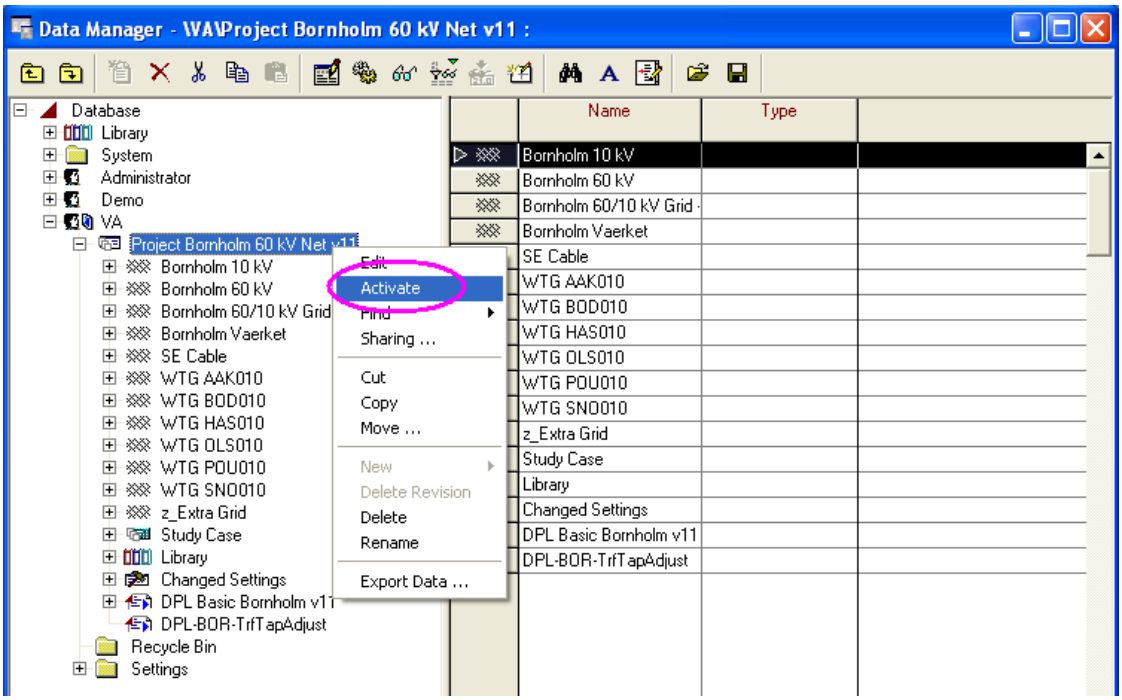

Fig. 4.2: Activate the Bornholm system model.

When the Bornholm system model has been activated, it is ready to run. The following working steps can be:

1/ Execution of the “Calculate Load-Flow” command in accordance to the common practice of the DIgSILENT PowerFactory simulation program. See Fig. 4.3. This activity requires that the user manually defines all the state variables and input parameters of the Bornholm system model, or

Fig. 4.3: Use of the Calculate Load-Flow activity.

2/ Execution of the DPL script “DPL Basic Bornholm v11” for the state estimation algorithm. See Section 4.2.

4.1. Electric System Part

The electric system part represents the network topology and the electric data of all implemented grid components of the Bornholm system model. The 60 kV network topology is shown in Fig. 4.4. The buses and lines of the 60 kV system are all arranged in accordance to the common practice of the DIgSILENT PowerFactory simulation program.

The sub-grid topologies representing the 60/10 kV substations with generation units such as thermal power plant units as well as wind turbines are shown as Composite Nodes, see marking in Fig. 4.4. By double clicking on the Composite Nodes, the sub-grid topologies are shown in separate graphical windows of the simulation program.

Fig. 4.5 shows the result of the double clicking on the Composite Node belonging to the Hasle 60/10 kV substation.

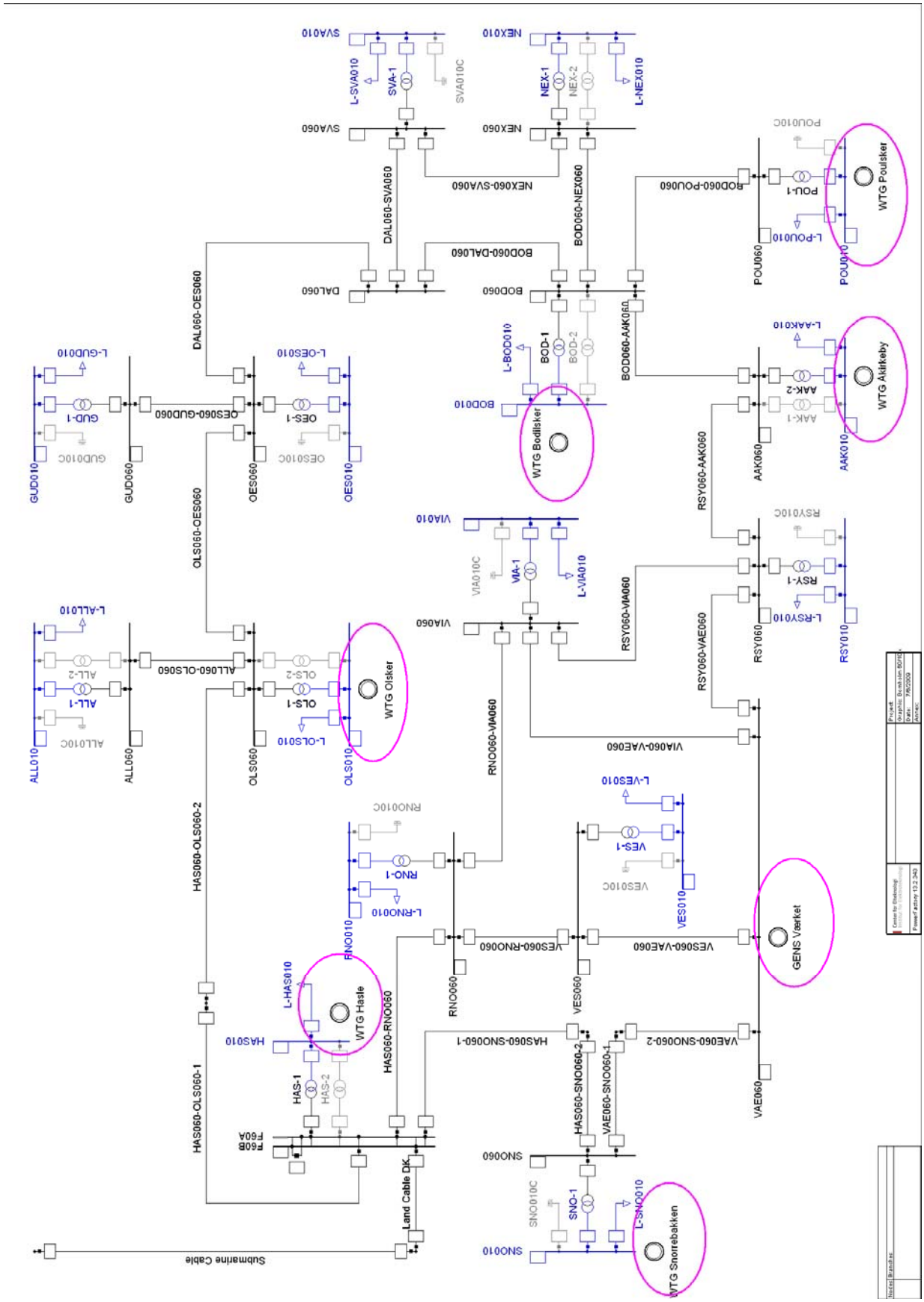

Fig. 4.4: Network topology of the 60 kV system of the Bornholm system model with marking Composite Nodes.

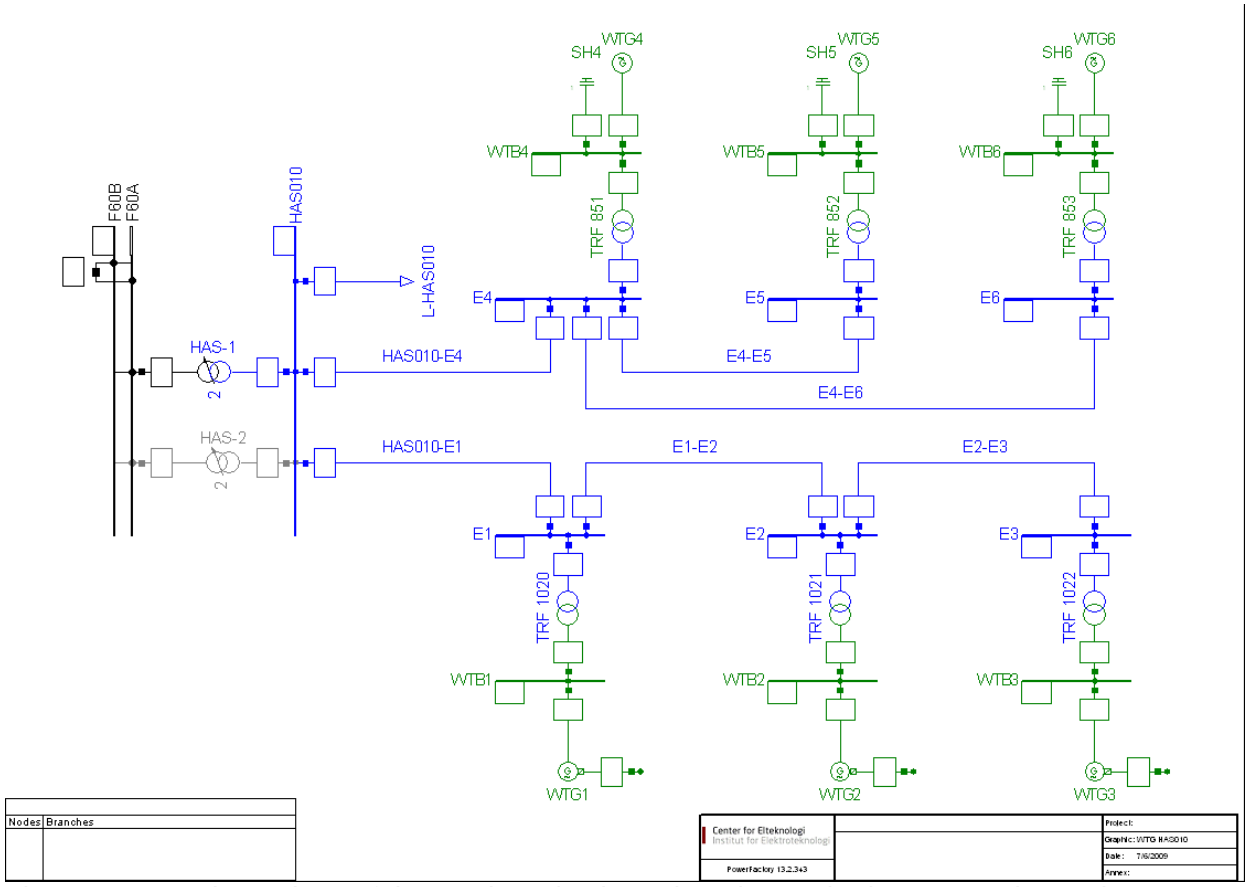

Fig. 4.5: Network topology of the Hasle 60/10 kV substation under its Composite Node.

The substations with no generation units do not have such graphical features.

It must be noticed that each substation contains, under the 60 kV voltage level:

1/ A 10 kV terminal representing the 10 kV terminal of the 60/10 kV substation,
2/ 60/10 kV distribution transformers, except of the coupling stations,
3/ A reactive compensation shunt, if any present under the given substation,
4/ A lumped load representing all the consumption feeders and losses in these feeders.

Additionally, under the 60/10 kV substations comprising thermal power plant units and wind turbines:

5/ Each wind turbine model is set up individually, i.e. representing a single wind turbine unit with its MVA rating and type (fixed-speed, induction generator based and shunt or variable-speed, doubly-fed induction generator based), wind turbine transformer and its cable connection to the 10 kV terminal. See Fig. 4.5 in example of the wind turbines under the Hasle 60/10 kV substation.
6/ Each thermal power plant unit is set-up individually, i.e. with representations of the synchronous generators and their transformers. See Fig. 4.6 as example of the Værket 60/10 kV substation.

Please notice that the above mentioned synchronous generators under the Værket substation are all disabled when applying the state-estimation algorithm and the entire substation is assigned to be a swing bus of the Bornholm system model. The swing bus generator is “Sym_VAE060”.

This assumption has been applied so far due to a lack of measurements for these thermal power plant units (and hence it is not possible to assign any active and reactive power delivery from these generators to the grid using historical record).

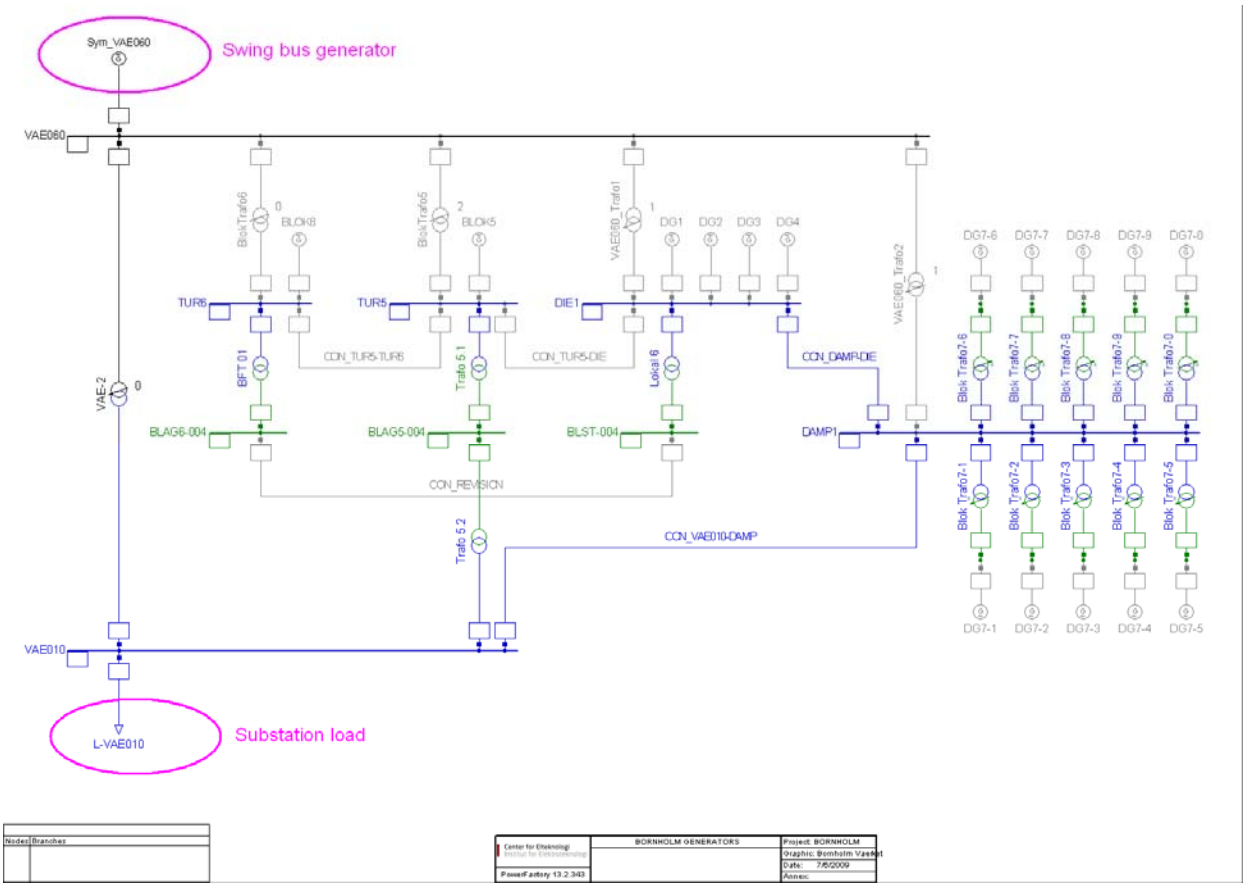

Fig. 4.6: Network topology of the Værket 60/10 kV substation under its Composite Node.

Nevertheless, the Værket 60/10 kV substation is prepared for individual to simulate each thermal power plant unit – then the operation point of each unit can be set up manually by the user. When the operation points of the thermal power plant units have been assigned manually by the user, the swing bus generator “Sym_VAE060” must be disabled, the substation load assigned by the user and a load-flow solution found executing the “Calculate Load-Flow” command, see Fig. 4.3.

4.2. State Estimation Part

The state-estimation part comprises the DPL script “DPL Basic Bornholm v11”. It reads the available measurements from text files, performs load-flow computations adjusting the model states to fit with the measurements, and delivers the computation results into text files. In this way, the load-flow computation results can be directly compared to the available measurements for each applied time instant.

4.2.1. Input text files

The input text files read by the DPL script are produced from the Excel files containing the available measurements. The format of the input files corresponds to the notification applied by the project manager in the four Excel files:

Oek_dag_1min_BEL_Målinger_YYYYMMDD_000000.xls
Oek_dag_1min_FEL_Målinger_YYYYMMDD_000000.xls
Oek_dag_1min_TRF_Målinger_YYYYMMDD_000000.xls
Oek_dag_1min_UDV_Målinger_YYYYMMDD_000000.xls

where “YYYYMMDD” stays for the year, month and day of the measurements. For instance, “YYYYMMDD” = ”20080901” stays for the measurements from Sept. 1st 2008. Please make sure that the measurements are not corrupted and fully applicable for the whole computation period by consulting the project manager.

The transformation from the Excel files into the input text files is arranged by simply inserting the measurements from the Excel files into the respective text files without headers and replacing “,” by “.”. The columns in the input text files are tabulator-separated. See Fig. 4.7 for example.

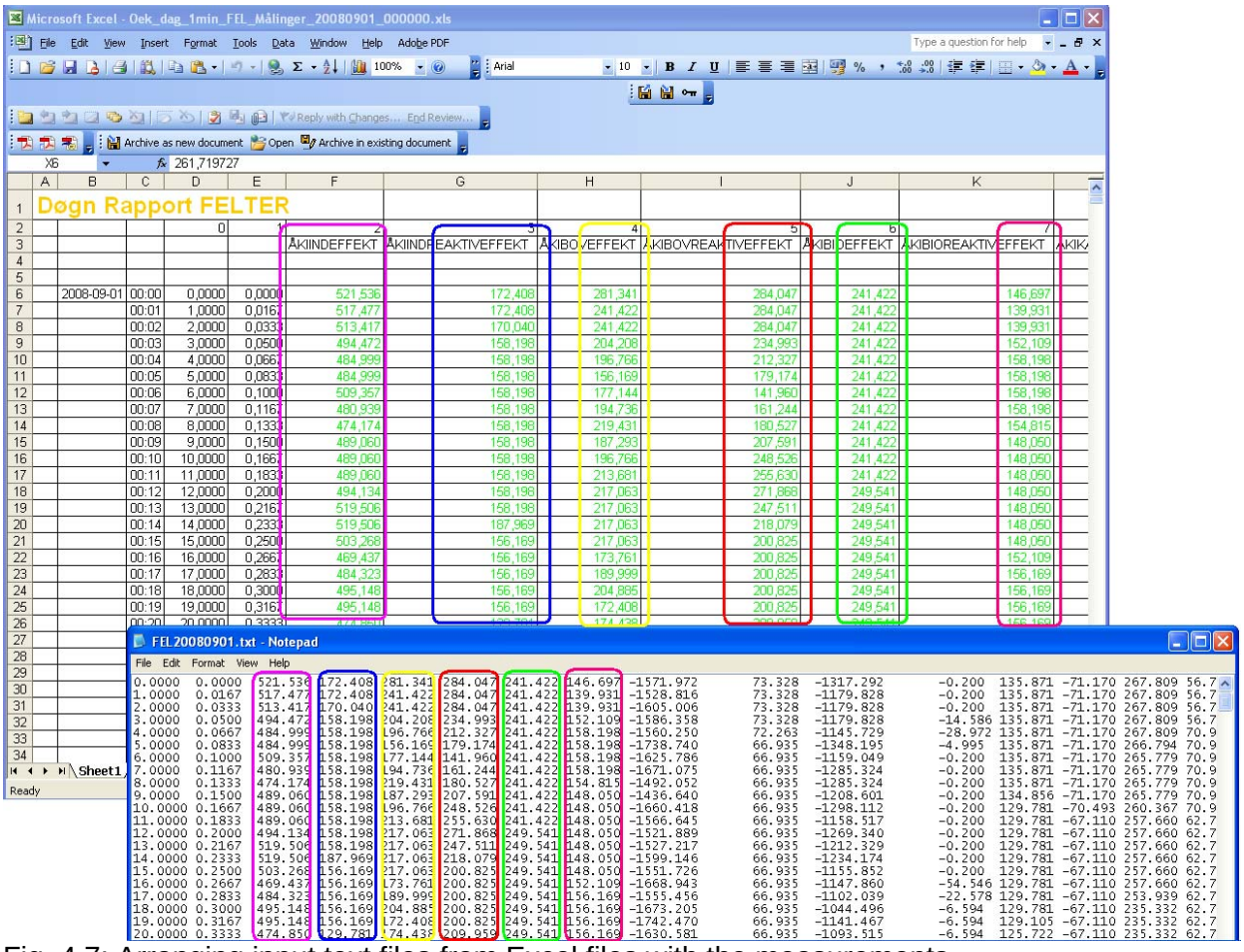

Fig. 4.7: Arranging input text files from Excel files with the measurements.

When longer than a-single-day measured sequences are required, the measurements of the following day are added at the end of the measurements from the previous day. Please take the maximum allowed file length into consideration.

4.2.2. Access to measurements

The access to the measurements from the DPL script in the DIgSILENT PowerFactory simulation program is arranged using the structures as exampled in Fig. 4.8 in the case of the FEL-file. The following procedure is implemented:

1/ Select the library “Library”,
2/ Select the library “Library MeaData”,
3/ From the last mentioned library select the structures (double clicking) and then assign a required input text file to the “Filename”. Please do this for all four shown structures. Please notice that the names of the implemented structures follow the names of the applied Excel files – to help the user with assignment of the right input files.

4/ Please do not alter any other parameter of the structure without prior (written) accept from the project manager.

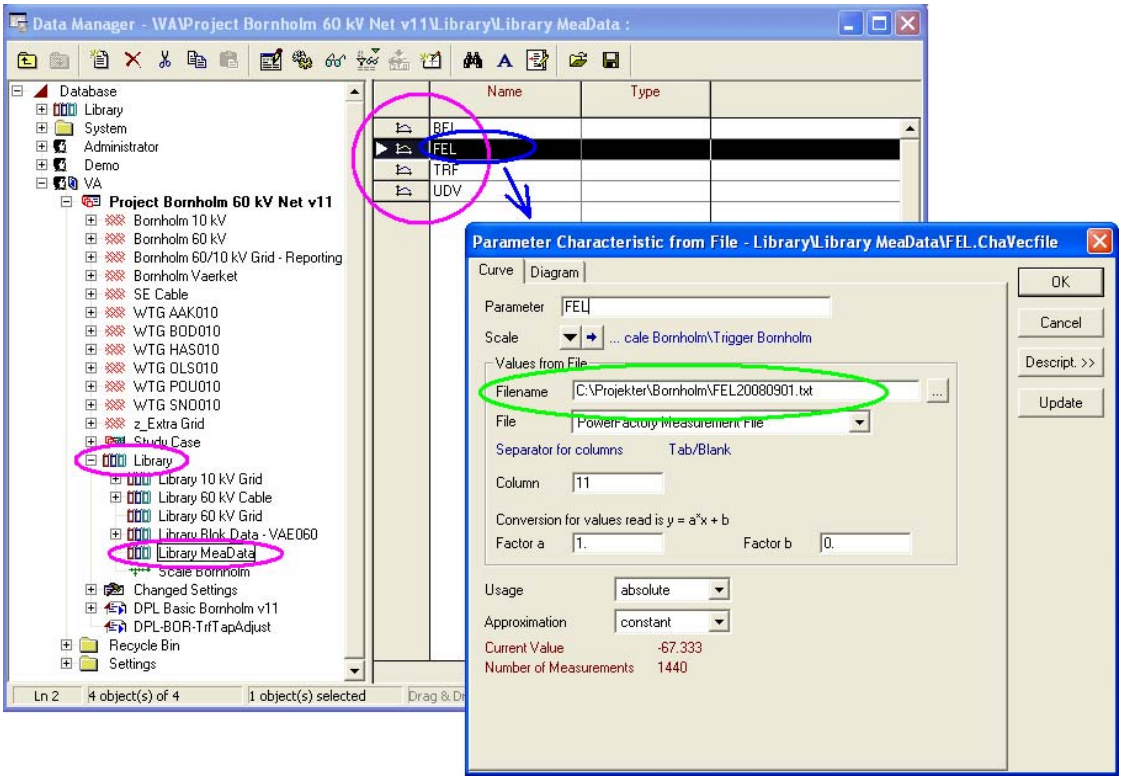

Fig. 4.8: Accessing measurements from the DPL script using structures. Enter a required input file name within the “Filename”.

Please notice that the structures, in the Bornholm system model using the DIgSILENT PowerFactory simulation program, must be assigned the measurements, as collected in the Excel files, accordingly to:

Measurements in Excel files:	→	Structures:
Oek_dag_1min_BEL_Målinger_YYYYMMDD_000000.xls	→	BEL
Oek_dag_1min_FEL_Målinger_YYYYMMDD_000000.xls	→	FEL
Oek_dag_1min_TRF_Målinger_YYYYMMDD_000000.xls	→	TRF
Oek_dag_1min_UDV_Målinger_YYYYMMDD_000000.xls	→	UDV

4.2.3. DPL script execution

When the structures BEL, FEL, TRF and UDV accessing the measurements have been assigned the input text files, the work with the DPL script can be started. The work is to be started with defining the output text files, e.g. the files containing the simulation results.

Please apply the following procedure:

1/ In the Data Manager of the active project with the Bornholm system model, select the “DPL Basic Bornholm v11” DPL script. Then select “Edit”, see Fig. 4.9.

2/ From the DPL script editing menu, assign the names and directories of the output text files as exampled in Fig. 4.10. In this example, the file “tm60test2” will comprise the measurements in the 60 kV system, “tm10test2” measurements in the 60/10 kV substations, “ts60test2” simulations in the 60kV system, and “ts10test2” simulations in the 60/10 kV substations. Please do not introduce other changes.

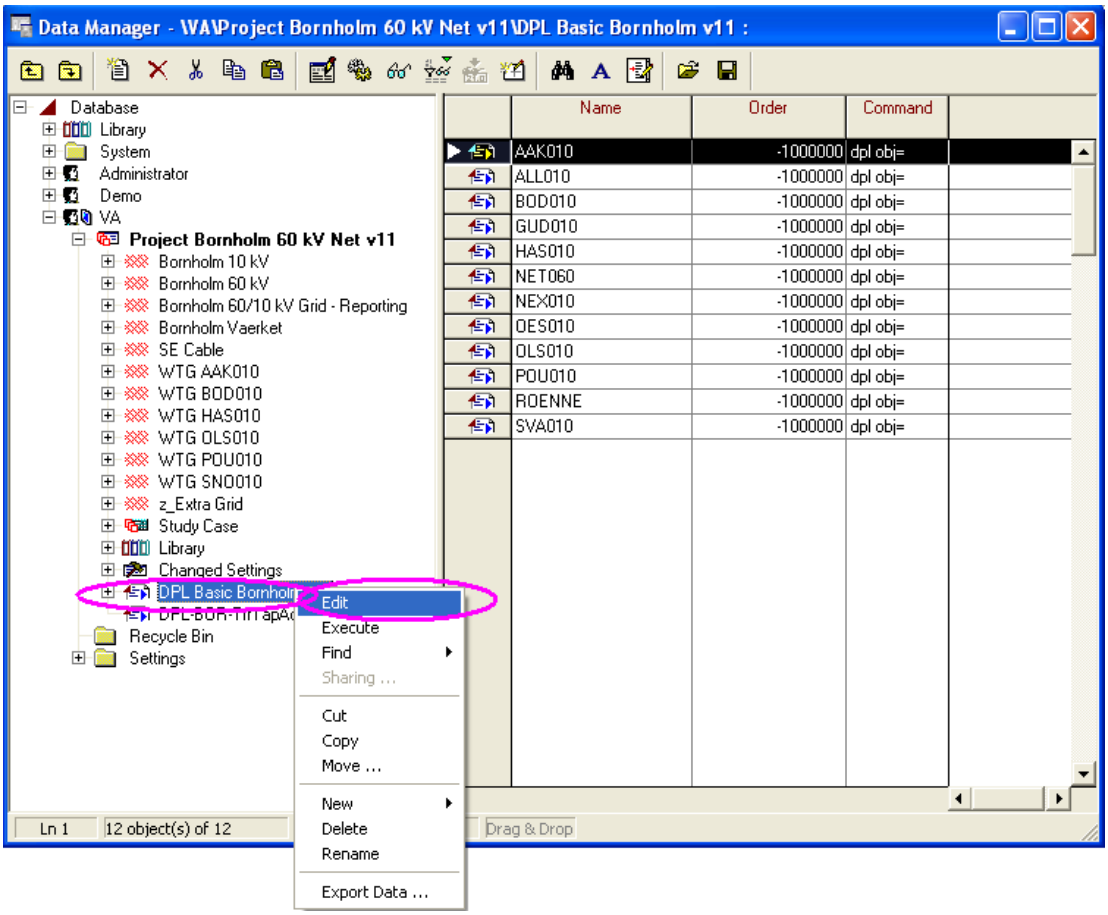

Fig. 4.9: Selecting Edit the DPL script prior to execution.

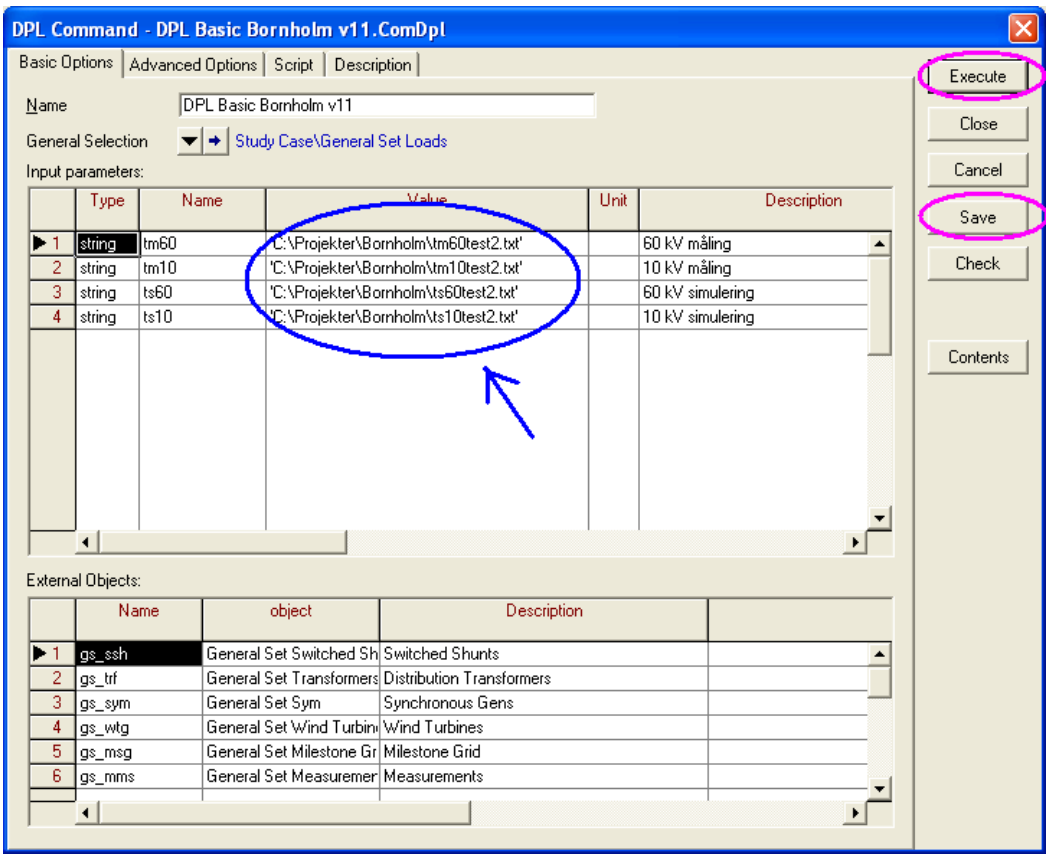

Fig. 4.10: Assigning the output text files.

3/ Select “Save” and “Execute”. See Fig. 4.10.

4/ In the popup window, please enter the start time in minutes, e.g. the time instant in the input text file containing the measurements wherefrom the state-estimation shall begin, followed by OK. See Fig. 4.11.

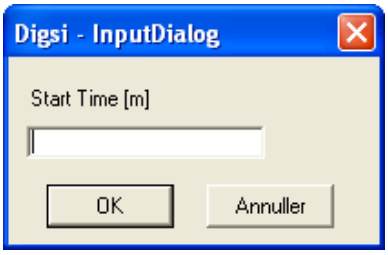

Fig. 4.11: Enter start time in minutes.

5/ In the next popup window, please enter the end time in minutes, e.g. the time instant in the input text file containing the measurements whereat the state-estimation shall end, followed by OK. See Fig. 4.12.

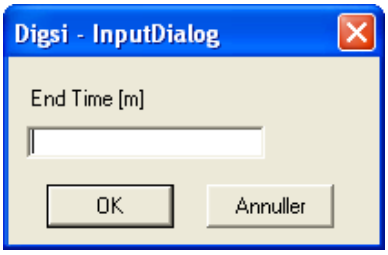

Fig. 4.12: Enter end time in minutes.

6/ In the next popup window, please enter the time step in minutes followed by OK. See Fig. 4.13. The time step shall be in whole minutes and not smaller than the time step in the input text files containing the measurements.

Fig. 4.13: Enter time step in minutes.

The DPL script starts executing, i.e. the state-estimation algorithm has started. Please notice that:

1/ When the entered start time is the same as the entered end time, the DPL script results in a load-flow solution of the entered time instant.

2/ When the entered end time is larger than the entered start time, the DPL script results in a series of load-flow solutions corresponding to the entered period with the resolution as the entered time step.

If the measured data are not corrupted and everything has been entered and assigned in a right way, the DPL script will be successfully executed. In a case of problems, please contact the project manager.

4.2.4. Output text files

The output text files comprises the simulation results for the 60 kV system including the cable connection to Sweden and for the 60/10 kV substations. The output text files are prepared and structured to easy direct comparison between the simulations and measurements. The first rows of the output text files are headers with the parameter names and units, for instance voltages in kV etc. The two first columns of the output text files are time in minutes and hours which are followed by the columns with the results accordingly to the header specifications.

The output text files comprising the measurements are with all available measurements of 60 kV system voltage magnitudes, 60 kV system current magnitudes, active and reactive power exchange in the cable connection to Sweden, 60 kV system frequency, 10 kV system distribution transformer voltage magnitudes, 10 kV system distribution transformer current magnitudes, 10 kV system distribution transformer power-factors, 10 kV system shunt feeder current magnitudes, 10 kV system wind turbine feeder current magnitudes as well as the active and reactive power of the wind turbine feeders and consumption feeders under the Åkirkeby 60/10 kV substation.

The output text files comprising the simulations are with the results, for each station and line, of 60 kV system voltage magnitudes, 60 kV system current magnitudes, active and reactive power exchange in the cable connection to Sweden, 60 kV system frequency, 10 kV system distribution transformer voltage magnitudes, 10 kV system distribution transformer current magnitudes, 10 kV system distribution transformer power-factor absolute values, 10 kV system shunt feeder current magnitudes, 10 kV system wind turbine feeder current magnitudes as well as the active and reactive power of the 10 kV system distribution transformers, wind turbine feeders and consumption feeders under each 60/10 kV substation.

The output text files are accompanied with a master Excel file "Master_Excel_File_Bornholm_va20090707.xls" prepared to easy direct graphical comparison between the simulations and measurements. The last four sheets of this file correspond to:

1/ Sheet "Måling_60kV" = Measurements in the 60 kV system from the corresponding output text file.
2/ Sheet "Måling_10kV" = Measurements under the 60/10 kV substations from the corresponding output text file.
3/ Sheet "Simulerling_60kV" = Simulations in the 60 kV system from the corresponding output text file.
4/ Sheet "Simulering_10kV" = Simulations under the 60/10 kV substations from the corresponding output text file.

Other sheets are the graphical plots comparing measurements to simulations.

Please do not change the master Excel file without prior (written) accept from the project manager.

4.3. Remarks

The Bornholm system model described in this document shall be treated carefully. Please do not introduce unauthorized changes to this document, the dz-file or other accompanying files.

Changes and updates shall be authorized, e.g. accepted prior to changes, by the project manager.

There is a restriction on updating the state-estimation part of the Bornholm system model, such as that the present DPL script has reached the maximum allowed length of approximately 65,500 characters. This implies that additional lines, characters or comments cannot just be added without careful rearranging of the DPL script code.

The electric system part can be updated without this restriction, but again only with prior accept of the project manager.

Since measurements from the thermal power plant units were not available at the time of the Bornholm system model preparation, the entire Værket 60 kV station is set as a swing bus of the Bornholm system model. Individual active and reactive power assignments of the thermal power plant generators shall be done manually by the user, in terms of the present DPL script. This part should, however, be easily updated in future versions of the DPL script when such measurements become available.

In islanded operation or isolation of 60/10 kV substations, the breakers are not open, but the currents through the breakers are assigned to zero by the DPL script. This simplification does not introduce any conflict to load-flow solutions. In cases of post-following short-circuit computations or dynamic simulations, the user shall open relevant breakers manually, in terms of the present DPL script.

The state-estimation algorithm, applied in the DPL script, is shortly described in Ref. [4-5] which are added as accompanying documents. The algorithm can be subject to adjustments and improvements when better and more measurements become available and when the authorization is granted.

5. References

[1] John Eli Nielsen, “The Bornholm Power System. The 60 kV Network”, Internal Report, CET, DTU, 2008-04-17, 5 p.

[2] John Eli Nielsen, “The Bornholm Power System. The connection between Sweden and Bornholm”, Internal Report, CET, DTU, 2008-04-17, 9 p.

[3] John Eli Nielsen, “ABB Network Manager at Bornholm Power System”, CET, DTU, 2008-04-19, 34 p.

[4] Vladislav Akhmatov, John Eli Nielsen, Jacob Østergaard, Arne Hejde Nielsen, “State-estimation of wind power system of the Danish island of Bornholm”, Nordic Wind Power Conference NWPC-2009, Bornholm, Denmark, Sept. 7-11, 2009, 6 p. (accepted)

[5] Vladislav Akhmatov, John Eli Nielsen, Jacob Østergaard, Arne Hejde Nielsen, “Wind power system of the Danish island of Bornholm: Model set-up and determination of operation regimes”, World Wind Energy Conference WWEC-2009, Jeju, South Korea, June 23-25, 2009, 10 p. (published)

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