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Regional Transmission Network Modelling for Facilitating Congestion Management

***Abstract**. This paper provides convenient solutions for creation of transmission network models for power flow calculation for regional interconnected electric power systems. The creation of network models is based on data provided from different Transmission System Operators (TSOs) in standard data exchange format for this purpose. The automation of the model creating process facilitates the work of the TSOs in the field of congestion management and power system operational planning.*

***Streszczenie.** W artykule przewidziano dogodne rozwiązania dla stworzenia modeli sieci transmisyjnych do obliczania przepływu mocy regionalnych systemów elektrycznych. Stworzenie modeli sieci oparte jest na danych dostarczonych od Operatorów Systemów Transmisyjnych w standardowej zmianie danych. Automatyzm procesu tworzenia modelu ułatwia pracę Operatorów w obszarze pobudzenia zarządzania i planowania systemów mocy. (**Modelowanie regionalnej sieci transmisyjnej w celu ułatwienia pobudzenia zarządzania**).*

Keywords: regional transmission network, electric power system.
Słowa kluczowe: reginalna sieć transmisyjna, system elektroenergetyczny.

Introduction

The congestion in the interconnected electric transmission networks is one of the main obstacles for further development of the electricity markets in Europe and the creation of a single Internal European Electricity Market, which is one of the main goals of the EU's energy policy [1].

Therefore a set of measures and procedures for Congestion Management are included in both the design of the electricity markets and in the power system operation planning procedures performed by the TSOs such as Cross Border Capacity Calculation and Day Ahead Congestion Forecast (DACF) [2-3].

These procedures are based on power flow forecast in regional interconnected transmission networks and N-1 analyses and are performed at a daily level. The power flow calculations and N-1 are standard procedures which can be easily automated, while the creation of the network models is regulated by ENTSO-E but still not fully standardized and automated [4].

This paper describes algorithms and software solutions for creation of regional forecasted network models from data of national network models provided in the standard format for data exchange in ENTSO-E (known as UCTE-Data Exchange Format [5]).

The software solution presented in this paper is developed in the framework of the EU FP7 project South East European Transmission System Operator Challenges (SEETSOC) [10]. Its main purpose is creation of regional forecasted network models for DACF, but it can be used for other purposes in the congestion management procedures and also for regional power system long term planning etc.

Model Creator for Day Ahead Congestion Forecast

The Model Creator is developed as a database related software solution which enables network model management [6,7]. The solution provides storage of different national and regional network models and enables creation of regional network models by merging national network models, automated creation of forecasted network models, import and export to UCTE - Data Exchange Format (UCTE-DEF), model compare etc. It includes input data validation and advanced network topology check for elimination of possible errors in the models and for its preparation for load flow calculations.

The Model Creator Module consists of the following sub modules:

- Format Converter & Storage Sub Module,
- Export Data Sub Module,
- Model Merger Sub Module,
- Model Builder Sub Module,
- Load Adjustment & Automated Model Generator (LAAMG) Sub Module and
- Model Compare Sub Module.

The principle structure of the Model Creator is shown on Fig. 1.

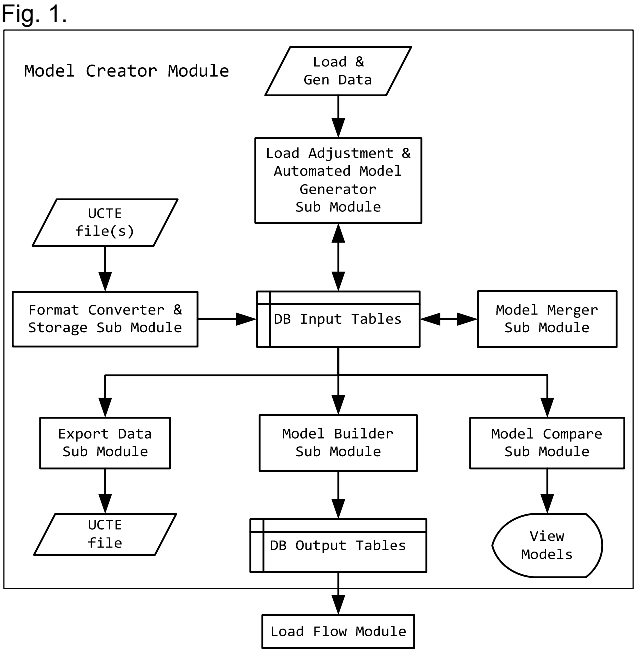

Fig. 1 Principle diagram of the Model Creator

As it is presented on Fig. 1 the database takes central place in this software solution, while the sub modules are performing different types of actions to the network data thus creating new network models.

The database is consisted of two sets of data tables: DB Input Tables and DB Output Tables. The DB Input Tables are used for storage of different network models, which can be: national or regional models merged by this software; forecasted or snapshot models with data collected from SCADA. The structure of DB Input Tables is similar to the UCTE- DEF. The DB Output tables are used for storage of data from network models which are prepared for load flow calculation and its structure is adapted for the load flow calculation procedure.

The functionalities of the sub modules are described in the following sub sections.

Format Converter & Storage, Export Data and Model Compare Sub Modules

The Format Converter and Storage Sub Module provides connection between the raw network model data stored in UCTE-DEF formatted ASCII files and the DB Input Tables from the database. It reads one or more UCTE formatted files describing national or regional networks, incorporates error checking and warning mechanisms that check the validity of the input data and stores the data into the database for further use. In this procedure the code, date and the time of a network model are extracted from its file name and put into the database. This data is used for identification of different network models.

The Export Data Sub Module allows export of a selected network model from the database to UCTE-DEF file format. The selection of the model is done by the user by entering its code, date and time.

The Model Compare Sub Module enables visualization of the network model data and visual comparison of different network models. This is very useful when handling with many different network models so the user can compare them and find similarities or differences between them.

Creation of Regional Transmission Network Models

The Model Merger Sub Module enables creation of regional network models by merging national network models. It is one of the most important features of the Model Creator alongside with the creation of forecasted models.

The model merging procedure starts with a selection of multiple national network models from the DB Input Tables. The data from these models is put into a single dataset. Afterwards the connection of the networks is done at the bordering, so called X-nodes. In the connection process certain active power imbalance could appear in the merged network model. This imbalance is distributed at the boundaries of the region and the regional network model is finally created and written to the Input DB Tables [3,7]. The reasons for the existence of this power imbalance are described below.

In order to enable description of transmission networks which are part of greater synchronously interconnected power systems and its balancing the UCTE-DEF includes definition of X-nodes as fictitious nodes located at the electric middle or at the geographical boundary on the interconnecting power lines [5]. When a network which is a part of an interconnected power system is presented, the power flows at the interconnection lines are simulated by adding load or generation at the X-nodes. This way the active power balance of the model is maintained.

Because the exact power flows at the interconnection lines are not known before the creation of the merged network model and the calculation of load flow, often estimated values are set by the TSOs in its national network models as load and generation at X-nodes. The active power balance P_{BalQQ} of a national network QQ is equal to the sum of load minus generation at its X-nodes. It is positive if the country exports active power or negative if the country imports power and it can be calculated by using the following equation:

$$P_{BalQQ} = \sum_{i \in XQQ} \left(P_i - G_i\right) \tag{1}$$

where XQQ is a set of X-nodes at the national network model QQ.

Because estimated power flows at the interconnection lines are used, sometimes neighbouring TSOs can use different flows in their models for the same interconnection line i.e. different injections for the same X-node. Therefore if the networks are simply connected at X-nodes an active power imbalance appears i.e. the power balance of the region calculated as sum of national balances of the countries from the region, differs from the sum of injected power at the X-nodes located on the boundary of the region. The X-nodes at the boundary of the region are known as non-paired X-nodes and they are marked as set XNP. This imbalance P_{Imbal} can be calculated by the equation (2):

$$P_{Imbal} = \sum_{j \in C} P_{Bal\,j} - \sum_{i \in XNP} \left(P_i - G_i\right) \tag{2}$$

where C is the set of countries in the region.

In order to achieve active power balance in the merged regional network model this imbalance has to be somehow distributed to the non-paired X-nodes. The proposed software solution distributes the power imbalance over a selected subset of non-paired X-nodes marked as XS and the distribution method is pro rata regarding to the previous (old) active power injection by using equation (3) [6,7].

$$\Delta P_i = P_{Imbal} \cdot \frac{\left|P_i^{old} - G_i^{old}\right|}{\sum_{j \in XS} \left|P_j^{old} - G_j^{old}\right|},\ i \in XS \tag{3}$$

If only loads with zero active power injections have been selected, the additional load would be distributed over the selected nodes equally.

At the end of the merging procedure the status of both sections of each interconnection is checked. If the topology status is not equal for both sections, the whole interconnection line is switched off, as well as the corresponding X-node.

Preparation of network model data for load flow calculations

The Model Builder Sub Module is used for preparation of data from a model selected from the DB Input Tables for load flow calculation. This sub module changes the data structure of a network model into a form which is more suitable for load flow calculations and performs different tests on the network model data in order to ensure efficient and correct calculation.

For example, the data structure of the Input DB Tables is similar to UCTE- DEF and contains different data tables for lines and transformers, also there are additional tables which describe the voltage regulation properties and tap position of a transformer etc. Therefore this data format is not appropriate for load flow calculation which requires list of branches with its equivalent parameters, no matter whether they are lines transformers etc. and list of nodes and its power injections.

This sub module includes the following functionalities in order to ensure efficient and correct calculation of load flow:

- small impedance branches and bus coupler elimination;
- topology check;
- node numbering (indexing), assigning index 0 to the global slack node;
- active power balance check;
- per unit conversion and calculation of line and transformers parameters;
- model data writing into the DB Output Tables.

Creation of Forecasted Transmission Network Models

The Load Adjustment and Automated Model Generator (LAAMG) Sub Module allows creation of forecasted national network models by using existing base network models from the database and input data from the user. This functionality is very important for DACF but it is also useful for Cross Border Capacity Calculation and power system planning studies.

Because the network elements parameters and the way they are connected are not changing in time the most of the network data for the forecasted network model can be taken from the, so called, base model. The other data that is changeable with time has to be provided by the user. In this software solution a special LAAMG CSV file format, for this purpose, is developed. The program enables creation of future network models for multiple hours during the day. The user should enter the following additional data for each hour:

- total system active power load,
- total active power import/export,
- active power generation at generation nodes,
- active power load at certain nodes,
- changes in network topology.

The LAAMG Sub Module is used in a three step procedure. In the first step, an empty LAAMG CSV file is created. It contains list of all generation and load nodes from the base model, but no data for the future load or generation.

In the second step, the data for total system active power load and total import or export, for each hour for the forecasted models, should be added to the LAAMG CSV file. Also the planned active power generation at each generation node should be entered from the generation schedule. The forecasted data for some load nodes can be added if it is available. For each load node without provided load for the forecasted model, the user sets whether the load data will be taken from the base model or to be adjusted pro rata in order to meet total system load. The changes of the network topology i.e. the switching of certain network elements should also be entered in the LAAMG CSV file.

In the third step the forecasted network models are created by using the data from the base scenario and from the LAAMG CSV file and written to DB Input Tables.

The principle diagram of the LAAMG Sub Module is presented in Fig. 2.

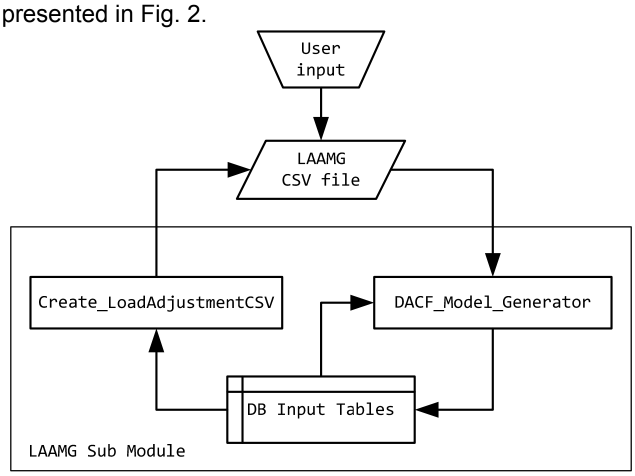

Fig. 2. Functionality of the LAAMG Sub Module

The load at the nodes that are set in the LAAMG CSV file to be adjusted pro rata is calculated by the following equation:

$$P_i^{new}(h) = P_i^{base} \cdot \frac{TotalLoad(h) - \sum_{j\in\beta} P_j^{base}}{\sum_{j\in\alpha} P_j^{base} - \sum_{j\in\beta} P_j^{base}} \quad (4)$$

where: P_i^{base} is the load at bus i in the base model, $P_i^{new}(h)$ is the calculated new load for the forecasted model at bus i at the hour h, $TotalLoad(h)$ is the total load in the system at the hour h provided in the LAAMG CSV file, and α is the set of all nodes, while β is the set of nodes that are not adjusted pro rata (with load taken from the base model or from LAAMG CSV file).

Exchanges at X-nodes are calculated by using the following equation:

$$X_i^{new}(h) = X_i^{base} \cdot \frac{NetImport(h)}{NetImport^{base}} \quad (5)$$

$X_i^{new}(h)$ denotes the new exchange (generation or load) at X-node i at hour h, $NetImport(h)$ denotes the total net import at hour h in the new model, the same variables with subscript base are referring to the base model .

The reactive loads at nodes are calculated by using the $P_i^{new}(h)$ and the power factor ($\cos\varphi$) for node i from the base model.

Example of regional network model creation

In this section a simple example of network models merging by using the algorithm described in this paper is shown. The procedure for model merging starts with selection of the national network models that should be merged, from DB Input Tables. These models can be previously imported from UCTE-DEF or created by LAAMG Sub Module as forecasted network models. In the both cases the models' data is validated for errors and the considered networks are balanced in terms of active power.

The balance of a national network model which is a part of greater synchronously interconnected system is achieved by adding generation or load at X-nodes in order to simulate the power flow through the interconnection lines. Because the exact power flows though the interconnection lines are not known prior the merge, the load or generation at the X-nodes is assumed. The active power balance of each national network model has to be equal to the sum of injected power at the X-nodes of the used national network model.

The Fig. 3 shows an example of three national networks, which are part of a greater synchronously interconnected power system that should be merged into a regional network model. The import of active power through an interconnection in the national models, simulated with negative load or positive generation at corresponding X-node, is indicated with an arrow pointing to the interior of the zone. The export of power at the X-node is positive load or negative generation and is marked with an arrow pointing outside the zone. Also the names of the X-nodes and its voltage level are depicted on the picture.

Fig. 3 also shows the balances of each network model calculated as negative sum of the injected power at the X-nodes of each zone by using equation (1). The sign "+"' denotes that the zone (national network) exports active power, while the sign "-" denotes that the zone imports active power. We can see that Networks 1 and 3 export 200 MW and 75 MW respectively, while Network 2 imports 250 MW. Paired X-nodes are X-node 10, X-node 11, X-node12, while the other X-nodes are non-paired X-nodes.

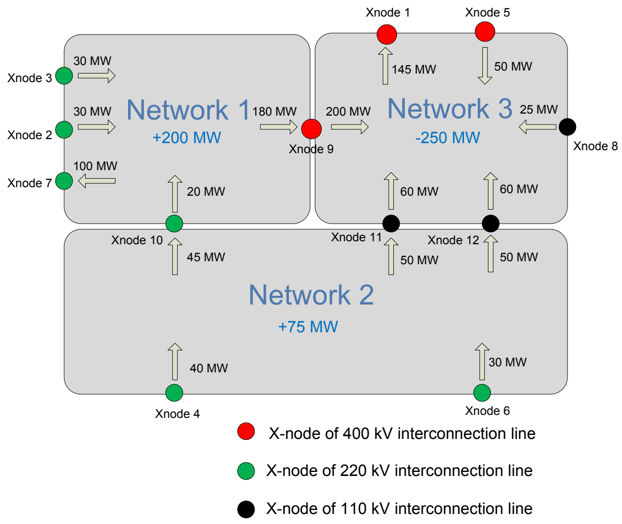

Fig. 3 National network models before the merge

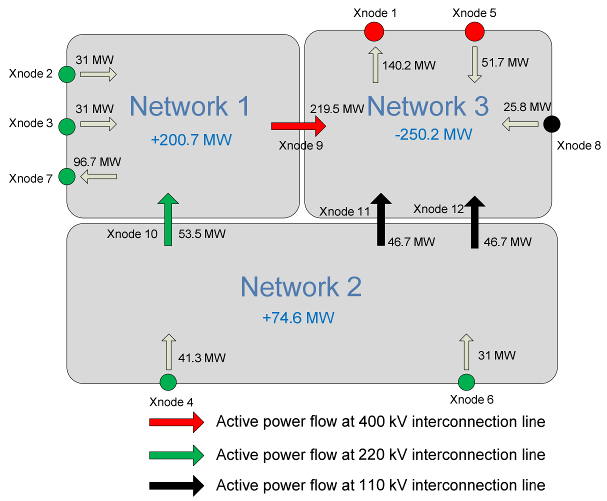

Fig. 4 National network models after the merge – regional network model

Because the assumption of the power flows in each network is done by its responsible TSO, different power flows are set at one interconnection line in different neighboring national network models (Fig. 3). Consequently, the balance of the region calculated as sum of national balances which is +25 MW (the region exports 25 MW), does not correspond to the sum of power at non-paired X-nodes which is +40 MW. Therefore an active power imbalance of -15MW which can be calculated by (2) is distributed to all non-paired X-nodes by using the equation (3). It is assumed that all non-paired X-nodes are selected for adjustment. After this is done the power injections at paired X-nodes are not needed and can be removed.

The Fig. 4 shows the network model after the imbalance distribution and the active power flows of the interconnections calculated by power flow analysis performed on the regional network model.

The balances of the national networks are slightly changed because the power flows in the interconnections and in the whole network are different than in the situation prior the merging when assumed flows through the interconnections were used. Therefore, the losses in elements are different. Another reason is the usage of single slack node in the power flow calculation. If a distributed slack power flow calculation method [8, 9] is used, the change of the national balances in the merged model will be even smaller. The change of the balances is insignificant having in mind that these models are mostly used for forecast.

After the merging procedure is done, the merged regional network model is written to the database. Furthermore this model can be prepared for load flow calculations by using of the Model Builder Sub Module.

Conclusion

From this paper we can conclude that the presented database related software solution for storage and creation of regional network models and forecasted network models could be very useful in the everyday work of operational planning of the TSOs. The software facilitates the creation of network models for DACF, cross border capacity calculation and also it can be used for power system planning purposes. This solution can also be used for these purposes by researchers.

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