Chapter 2
Load Flow and Dynamic Model

André Seack, Johannes Schwippe, Ulf Häger and Daniil Panasetsky

2.1 Introduction

Based on the general requirements presented in Chap. 1, particular consideration has to be given to different scenarios of joint operation of the ENTSO-E- and IPS/UPS-systems. To provide a basis for the following investigations in this book, this chapter focuses on the development of an aggregated network model of these power systems which will be used as general test case in the following chapters.

Detailed information of the network topology and the used equipment are confidential data of TSOs which is difficult to access. Furthermore, if confidential data is used, publication of results is difficult. Therefore, a reduced network model was created by using only public available data. A core of this power system model consisting of the CWE region and a few more surrounding countries was already available at the Institute of Energy Systems, Energy Economics and Energy Efficiency (ie^3) at TU Dortmund University [1].

2.2 Aggregated Network Model

In the following sub-sections the general modeling method of the grid, the unit commitment and the enhancement for dynamic simulations are described.

A. Seack (✉) · J. Schwippe · U. Häger
TU Dortmund University, Dortmund, Germany
e-mail: andre.seack@tu-dortmund.de

J. Schwippe
e-mail: johannes.schwippe@tu-dortmund.de

U. Häger
e-mail: ulf.haeger@tu-dortmund.de

D. Panasetsky
Energy Systems Institute, Irkutsk, Russia
e-mail: panasetsky@gmail.com

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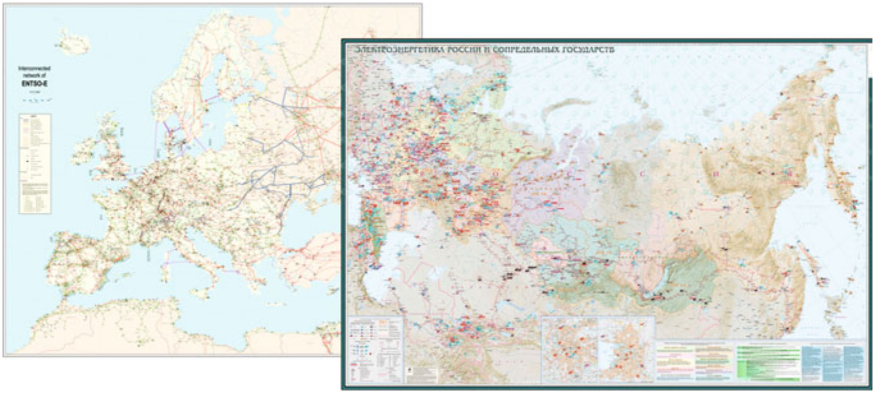

Fig. 2.1 Interconnected network of ENTSO-E and IPS/UPS [2, 3]

The aggregation method was for the first time introduced in [1], when the ENTSO-E CWE part of the model was developed. The methodology of the aggregation process is divided into four steps:

- Identification of important network areas to reduce the number of network nodes.
- Aggregation of transmission lines in the considered network area to the reduced number of network nodes.
- Allocation of loads and generation to the aggregated nodes and the unit commitment by a Merit-order model.
- System enhancement with dynamic data of the power stations to allow detailed analysis of the power system response to disturbances and innovative network assets.

The geographical maps of the European and Russian transmission network with the interconnections are available from public sources [2, 3]. These maps are outlined in Fig. 2.1.

The geographic location and voltage levels of nodes in the aggregated grid model are determined according to these grid maps. Additionally, the length and the number of transmission lines between these nodes are estimated according to these sources. Not public documented ties between these areas are neglected.

The specific electrical parameters and the nominal current correspond to typical transmission lines according to [4, 5]. Regional differences of these parameters are considered whereby the voltage level of the transmission lines is mainly 380 kV in the European part. Due to the longitudinal structure, the Russian network part is dominated by transmission lines with the voltage level of 330, 500 and 750 kV.

2.2.1 Aggregation of Detailed Network Nodes

In order to build a representative network an aggregation technique which maintains the electrical characteristic of the real transmission network was used. Based

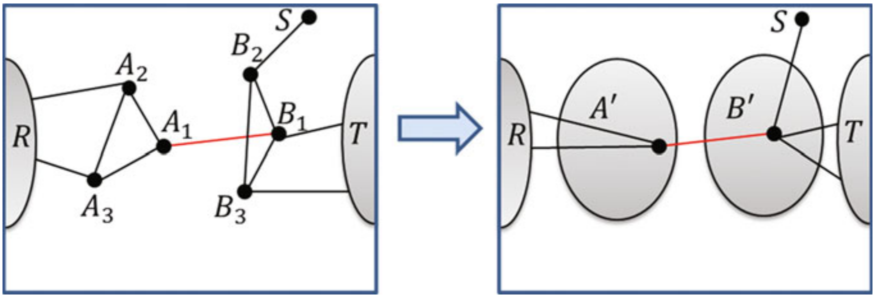

Fig. 2.2 Congestion limited node aggregation (*left* detailed network, *right* aggregated network)

on public available grid maps [2, 3] important network areas are identified, which typically represent load or feed-in areas.

Real nodes, which build a highly meshed grid in contrast to the surrounding network, represent one node in the aggregated network model (Fig. 2.2). The internal connection capacity $TC^{XY}_{d,\text{int,m}}$ of this area has to be higher than the transfer capacity between two potentially aggregated nodes $TC^{XY}_{d,\text{ext,n}}$ of the resulting areas for every connection.

$$TC^{XY}_{d,\text{ext,n}} \leq TC^{XY}_{d,\text{int,m}} \tag{2.1}$$

If the restriction is not met, congestion may occur and additional nodes are required to achieve a similar behavior as the original network.

Figure 2.2 shows a typical situation where an area cannot be aggregated because of insufficient internal transfer capacity between A_1, A_2, A_3 and B_1, B_2, B_3. The internal connection capacity in the detailed network TC^{AB}_d does not exceed the connection capacity of the nodes to the surrounding network R, S and T.

$$\begin{aligned} TC^{AB}_d &\leq TC^{AR}_d \\ TC^{AB}_d &= TC^{AS}_d \\ TC^{AB}_d &= TC^{AS}_d \end{aligned} \tag{2.2}$$

Even though an aggregation of the network areas (A' and B') would be suitable in terms of feed-in and load concentration, the network restricts the aggregation process to the substituted nodes A' and B'.

The opposite situation is shown in Fig. 2.3. The internal connection capacity exceeds or is equal to the external connection capacity for every connection. This enables the aggregation of the individual nodes A_1, A_2, A_3 and B_1, B_2, B_3 to the aggregated network node A'. For this particular example six nodes of the detailed network can be simplified to one node while maintaining the system transmission characteristic under these conditions:

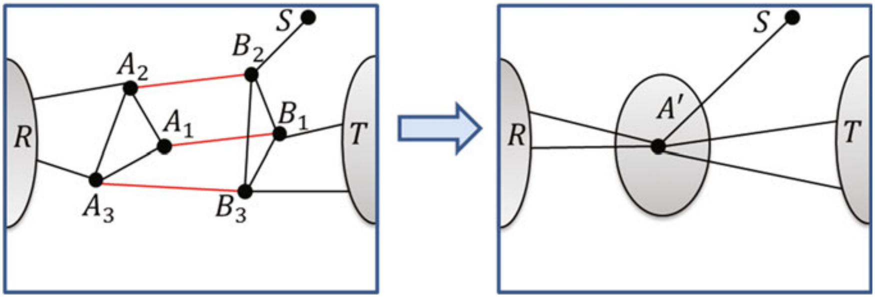

Fig. 2.3 Node aggregation process (*left* detailed network, *right* aggregated network)

$$\begin{aligned} TC_d^{AB} &= TC_d^{AR} \\ TC_d^{AB} &> TC_d^{BS} \\ TC_d^{AB} &> TC_d^{BT} \end{aligned} \tag{2.3}$$

With the described methodology the original network data of the ENTSO-E and IPS/UPS network with an overall complexity of more than 8,000 nodes is reduced to 545 aggregated nodes, while maintaining the transmission characteristic of the interconnected network.

2.2.2 Aggregation of Transmission Lines

To meet the reduced number of nodes in the aggregated network model the connecting transmission lines have to be matched to the aggregated network configuration. The voltage level, length and number of transmission lines between the aggregated nodes is estimated according to publicly available data. Transmission capacity TC_a^{KI} between node K and I of the aggregated network is calculated for n paths in the detailed network with all sections of a path as Ψ^{KI} according to:

$$TC_a^{KI} = \min\{TC_{d,n} | TC_{d,n} \subset \Psi^{KI}\} \tag{2.4}$$

It states, that the limiting factor between two aggregated nodes is the connection with the lowest transfer capacity.

Figure 2.4 shows a simple example where node A and node D are identified as aggregated nodes. Node B and C are removed in the aggregation process due to insignificance. With $TC_d^{AB} = 2$, $TC_d^{BC} = 1$ and $TC_d^{CD} = 1$ the resulting transmission capacity for the aggregated network interconnection is limited by either TC_d^{BC}

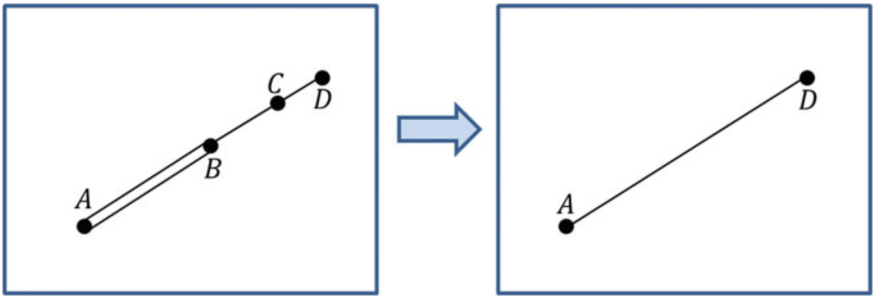

Fig. 2.4 Aggregation of transmission line path sections

or TC_d^{CD}. In this example the resulting transfer capacity for the aggregated connection is $TC_a^{AD} = 1$ limited by $TC_d^{BC} = 1$ and $TC_d^{CD} = 1$.

$$\begin{aligned} TC_d^{AB} &= 2 \\ TC_d^{BC} &= 1 \\ TC_d^{CD} &= 1 \end{aligned} \tag{2.5}$$

The aggregated path length between aggregated nodes K and I is the sum of all path sections m in the detailed network.

$$l_a'^{KI} = \sum\nolimits_{n=1}^{m} l_{d,n}^{KI} \tag{2.6}$$

In the particular example, shown in Fig. 2.4 the resulting path length is:

$$l_a'^{AD} = l_d^{AB} + l_d^{BC} + l_d^{CD} \tag{2.7}$$

Parallel transmission lines on the same path between aggregated nodes are not simplified and reduced to an alternate impedance. As illustrated in Fig. 2.5 every system is modeled as a single line in the aggregated network. A transmission line can be disabled independently without disabling the whole transmission path between aggregated nodes. This is essential for considering n − 1 situations.

The transmission lines in the aggregated network are modeled as typical overhead lines. In the Western European part of the network model the conductor type 253/40 Al/St is used as 2-wire bundle for the 220 kV-level and as 4-wire bundle for 380 kV-level. The corresponding specific parameters of these transmission lines are shown in Table 2.1.

In the Western European part the voltage level of 380 kV is dominant whereby a detailed model of the 220 kV-level is neglected. The electrical characteristics of the 220 kV-level are transferred to the voltage level of 380 kV. The remaining voltage layers in IPS/UPS network are modeled with similar line parameters.

The aggregated network models level of detail for the Central Europe region is summarized in Table 2.2. Interconnection lines between neighboring countries are

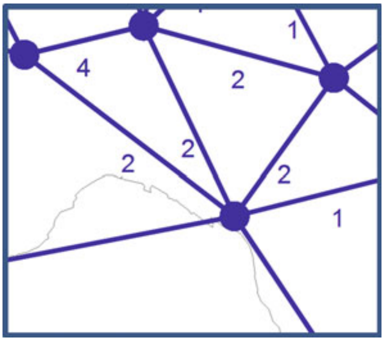

Fig. 2.5 Parallel lines on aggregated transmission system paths

Table 2.1 Exemplary aggregated line parameters for 220 and 380 kV systems [4]

Conductor configuration	TC [kA]	$R'_L\left[\frac{\Omega}{\text{km}}\right]$	$X'_L\left[\frac{\Omega}{\text{km}}\right]$	$C'_L\left[\frac{\mu S}{\text{km}}\right]$
220 kV overhead line (2 × 240/40 Al/St)	1.28	0.08	0.32	3.8
380 kV overhead line (4 × 240/40 Al/St)	2.56	0.03	0.26	4.3

Table 2.2 Level of detail of the Central Europe Region

Country	Number of aggregated nodes	Number of aggregated lines
Austria	8	44
Belgium	4	15
Czech Republic	7	22
Denmark	5	17
France	13	79
Germany	31	159
Poland	13	42
Netherlands	10	28
Switzerland	7	53

not assigned to one country. The level of detail of every country is based on the system complexity of the original network. For example, important transfer corridors as well as load and feed-in centers in the Belgium system are easier to be identified as in the German system. This results in a significant difference in terms of node and line count in the aggregated network model.

The IPS/UPS network model includes two parts: the transmission grid of Russia, Belorussia and Baltic countries and the transmission grid of the Ukraine and Moldavia.

Table 2.3 Existing interface lines

ENTSO-E RG CE		IPS/UPS		Voltage (kV)	Length (km)	Capacity (MVA)
Substation	Country	Substation	Country			
Rzeszow	Poland	Khmelnitska NPP	Ukraine	750	395	2,600
Vel'ke Kapusany	Slovakia	Mukachevo	Ukraine	400	51	900
Sajoszeged	Hungary	Mukachevo	Ukraine	400	142	692
Albertirsa	Hungary	Zakhidnoukrainska	Ukraine	750	479	2,600
Kisvarda	Hungary	Mukachevo	Ukraine	220	96	312
Tiszalok	Hungary	Mukachevo	Ukraine	220	54	310
Rosiori	Romania	Mukachevo	Ukraine	400	115	831
Isaccea	Romania	Pivdennoukrainska	Ukraine	750	409	2,600
Isaccea	Romania	Vulkaneshty	Moldova	400	59.7	955

For the transmission grid of Russia, Belorussia and Baltic countries the node count is not directly associated with the real network complexity. A diversity of voltage layers was taken into account and modeled as separate network nodes for every transmission system station.

The transmission grid of Ukraine and Moldavia is modeled in detail, as these countries include the interconnection between the European grid and IPS/UPS. These interconnection lines have been modeled based on the data of the existing but not operational lines between the systems. A list of these lines is presented in Table 2.3. These transmission lines were operated as an integrated part of the IPS/UPS and power system "Mir" until 1995 when Poland, Hungary, Slovakia and Czech Republic were synchronously interconnected to UCTE.

2.2.3 Allocation of Load and Generation

Every node of the aggregated network model is equipped with a load and a generation cluster representing the total load and generation of the aggregated area.

It is assumed, that the load is proportional to the population. To determine the load at the aggregated network nodes, statistical data on the population of districts from the European statistic database Eurostat [6] is analyzed and the population is added to the nearest node of the aggregated network model. Finally all data of one country is normalized to the total population of the country. The result is a nodal load distribution factor for every country, which can be scaled by the country specific residual load for every time frame determined by public available load statistics [7].

Figure 2.6 shows the exemplary allocation of seven communities to three nodes of the aggregated network model. The geographic distance between area centers and the aggregated nodes is determined for the allocation to the nearest node and

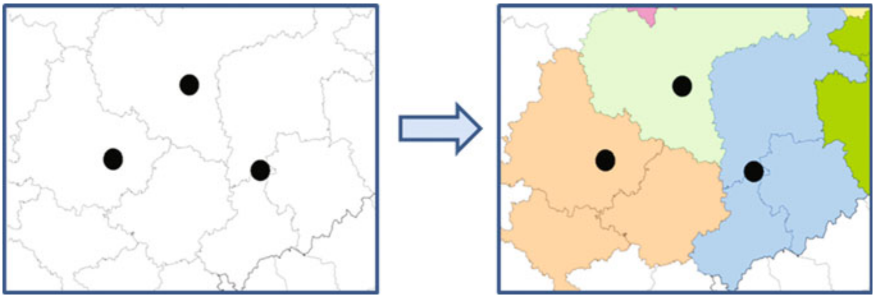

Fig. 2.6 Allocation of population per district

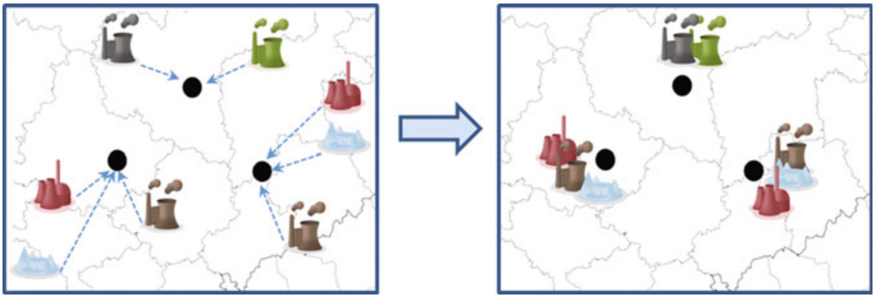

Fig. 2.7 Geographical allocation of power stations

the population is summed up. If an area contains several network nodes the load is distributed pro rata.

Analog to the load allocation all power generating units, taken from the open database [8] were assigned to the geographically nearest node in the corresponding country. Figure 2.7 illustrates the allocation process for three exemplary nodes of the network. In contrast to load allocation the individuality of every power station is maintained to enable detailed dynamic simulations in the network model. All unit specific information, fuel type, year of constriction and block size are kept for the unit commitment in the market model.

2.2.4 Unit Commitment

Input data for each market scenario is the load, non-controllable generation of each country, exported or imported power and the detailed power station data (location, fuel type, year of construction) [8]. To reduce the computation burden only power stations with an installed capacity of more than 50 MW are taken into consideration. The result of the market simulation is the unit commitment of the power

Table 2.4 Specific fuel costs and CO_2 emissions [1]

Fuel	$P^{Fuel}[€/MWh_{th}]$	$EM^{Fuel}[t/G]$
Uranium	3	–
Lignite	3.5	0.1
Coal	6.11	0.095
Gas	14.48	0.056
Oil	23.41	0.078

plants for each scenario, which balances the residual load, based on the marginal costs c_k. The residual load is the hourly load of every country [7] including estimated renewable feed-in and the imported or exported power. The marginal costs c_k of a power station k include the fuel costs, CO_2 certificate costs $\left(c_k^{CO_2}\right)$ and operation and maintenance costs $\left(c_k^{OM}\right)$ and is calculated as:

$$c_k = \frac{p^{Fuel}}{\eta_k} + c_k^{CO_2} + c_k^{OM} \forall k \tag{2.8}$$

$$c_k^{CO_2} = \frac{p^{CO_2} \cdot EM^{Fuel}}{0.278 \cdot \eta_k} \tag{2.9}$$

CO_2 costs $c_k^{CO_2}$ are calculated by specific prices for CO_2 certificates p^{CO_2}, emissions for the fuel type EM^{Fuel} and the scaled stations efficiency η_k, which depends on the stations year of construction. Table 2.4 summarizes the specific fuel costs and the CO_2 Emissions used for the calculation of power station prices in the model. Same prices of the last committed units result in uniformly distributed remains of generation on the units with the same price.

For the development of the static scenario a snapshot of the residual load per country is combined with import and export between neighboring countries [7, 9]. The resulting unit commitment by primary energy carrier is combined with a typical feed-in and load scenario of the IPS/UPS network in touch with best practices. Further details on the market model and unit commitment are available in [1].

2.2.5 Dynamic Model

For each scenario of the market simulation a dynamic model is created, which is based on the load situation, the unit commitment and the feed-in from non-controllable generation.

The power stations are modeled as synchronous generator with a machine transformer. The parameters of these elements depend on the type and category of the power station, whereby different characteristics of the unit are considered. Table 2.5 gives an overview, which parameters are used for different power plant categories. Additionally, the model includes speed governor (GOV), automatic

Table 2.5 Machine parameter and controller types

Synchronous generator with transformer					
	$x_d[pu]$	$H[s]$	$S_n[MVA]$	$x_e[pu]$	GOV
Nuclear	1.93	3.1	1,177	0.12	GOVNUC
Coal, Gas	1.77	3.7	471	0.09	TGOV1
Hydro	1.01	3.1	118	0.09	GOVHYD

voltage regulator (AVR, IEEE EXAC4) [10] and power system stabilizer (PSS, STAB 1).

The number and type of power stations in service is given by the unit commitment of the market simulation. If a power plant from the unit commitment has a larger nominal power S_n than the typical power stations available in Table 2.5, several blocks are modeled in parallel until the total installed capacity is reached. All remaining power plant categories are modeled as static generator without controlling devices at the aggregated network nodes.

2.3 Validation of the Network Model

In total the aggregated network model consists of 168 nodes and 1,860 power plants in continental Europe, 368 nodes and 499 power plants in the Russian part. To validate the aggregation process of the network and the used unit commitment, the NTC values between the CWE countries are calculated as described in [1] and compared to the NTC-values of the year 2010, published by the ENTSO-E [11]. The results are shown in Fig. 2.8. The NTC-values of the aggregated model have a fluctuation range, which is a result of the calculation for many load flow situations of the specific time frame. It can be noted, that the NTC values of the aggregated model are comparable to real NTC values. The differences can be justified by the aggregation process and the reduced power station count, but the behavior of the network is comparable. The NTC-values of IPS/UPS were compared to real values of the year 2012, published by the SO-UPS [12], providing a similar result.

In addition to this validation the network and market model of the ENTSO-E transmission system was used to estimate the necessary network extension for the year 2020 and 2030 in Germany. The estimated network extensions are comparable in length and location to the published extension in [13] and [14]. This allows the conclusion, that the market simulation and the network aggregation process compose a good model of the real transmission system. It has to be stated, that an identical behavior of the network model is not achievable with public available data.

To validate the dynamic network model, the system stability is determined with a modal analysis. The parameter sets of the GOV, AVR and PSS depend on the specific characteristics of every power station and the local characteristic of the network. For this reason, in reality, the parameters are determined individually for

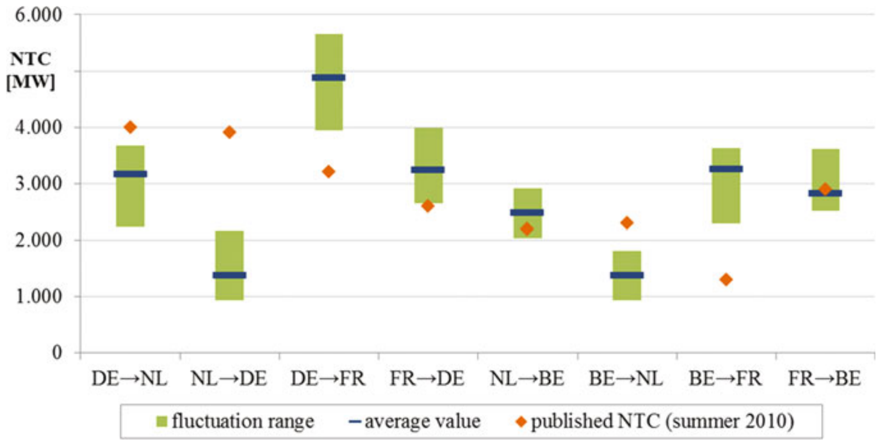

Fig. 2.8 Validation of NTC capacities of the aggregated network model

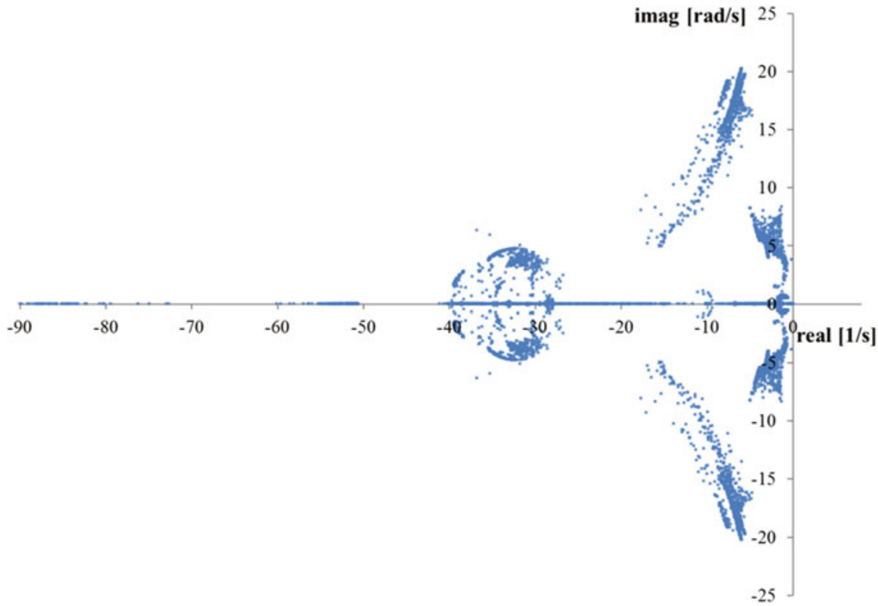

Fig. 2.9 Modal analysis results for one dynamic model

each power station and no typically parameter sets are available. As approximation to the real system calibration, the instable nodes are identified and the parameters of the involved power stations are modified to reduce the instability. With the new parameter set a new modal analysis is carried out to verify the modification. The result of this iterative process is a large scaled dynamic and stable network model. The modes of the final modal analysis for one dynamic scenario are shown in

Fig. 2.9. It can be concluded, that the dynamic model is stable but tends to oscillate more than the real transmission system.

Additionally, typical disturbances in the interconnected network are simulated and the system shows reasonable reaction on line trippings, shortcuts and unit outages.

2.4 Conclusions

The presented network model provides a first realisation of an interconnected European and Russian static and dynamic network model with a market based unit commitment. The model has 168 nodes and 1,860 power plants in continental Europe, 368 nodes and 499 power plants in the Russian part and is based only on public available data (The aggregated network model of the CWE-region can be download from http://www.icoeur.eu). The motivation for developing the reduced model is that detailed data on the network topology and the used equipment are confidential. Furthermore, the aggregation approach reduces the computation burden of the unit commitment and dynamic simulations in such large scale transmission systems and it allows for publishing results, including the network data.

Validation of the network model has shown, that the static and dynamic characteristics of the aggregated network model are comparable to the real network. Network extensions and system instabilities can be related to geographic regions. To transfer the simulation results to the real transmission network, more detailed input data is necessary, which is not publicly available.

Additionally, the aggregation process reduces the computational burden of the unit commitment and dynamic simulations dramatically that causes of instability or necessary network extensions are more likely to be identified.

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