Best Practice for Creating Dynamic Network Models based on Power Flow Models for DSA Applications

Johannis Porst [1], Ilya Burlakin [1], Elisabeth Scheiner [1], Matthias Luther [1], Stefanie Samaan [2], Markus Knittel [2], Mojtaba Momeni [2], Albert Moser [2], Hendrik Just [3] and Stefan Horn [4]

[1] Institute of Electrical Energy Systems, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), 91058 Erlangen, Germany, johannis.porst@fau.de, https://www.ees.tf.fau.de/

[2] Institute for High Voltage Equipment and Grids, Digitalization and Energy Economics (IAEW), RWTH Aachen University, 52062 Aachen, Germany

[3] 50Hertz Transmission GmbH, Berlin, Germany

[4] TenneT TSO GmbH, Bayreuth, Germany

Abstract: This paper presents the development process of dynamic network models based on power flow data of Continental Europe. Typical power flow modeling issues and feasible solutions are shown and controller models for multiple grid components are designed. For validation, a network model in DIgSILENT PowerFactory is compared to one in MatPAT, both being subject to the described development process.

Keywords: Power System Stability Studies, Standard Dynamic Models, Transient stability

1 Introduction

Due to the increasing share of converter-based components and the ongoing shutdown of conventional power plants in Germany, Dynamic Security Assessment (DSA) becomes more important in order to secure safe system operation. The German transmission system operators are currently evaluating enhancements of their system operation strategies with curative management measures [1]. To further increase the line utilization of the current state of the German power system, curative actions (i.e. fast reacting power sources and sinks) shall be used to solve possible grid congestions [2]. The higher utilization causes rising reactive power demands and shifts the operating points of the grid closer to the stability limits. Thus, efficient DSA processes in order to analyze and assess the system stability as proposed in [3] are required. However, especially for an automated DSA process, as presented in [3], it is essential to develop dynamic network models.

Therefore, in the research project “Innovations in system operation until 2030” (“InnoSys2030”), a new development process for dynamic network models is elaborated and applied to a power flow model of Continental Europe (CE) using two different simulation tools, DIgSILENT PowerFactory and MatPAT [4], respectively. Utilizing the PowerFactory network model as an example, this paper presents best practice and a Python toolbox for creating a dynamic network model based on power flow models. Starting in section 2 with the development process, section 3 presents an overview of typically power flow modeling issues that complicate and slow down the development of dynamic network models. In section 4, a modeling approach is presented to solve the usually insufficient voltage control situation in power flow models. Dynamic modeling and control system design for conventional power plants as well as converter-based units are shown in section 5. Validation of the resulting dynamic network model is done in section 6 by comparing the network models in DIgSILENT PowerFactory and MatPAT. The paper concludes with section 7.

2 Development process and simulation tools

Creating a dynamic network model starts with an initial power flow model representing one or multiple power flow scenarios. Dynamic network studies typically include transient stability analysis, which are usually only one part of system analysis. In many cases, the development of dynamic network models are based on power flow models that were created in previous studies to serve a specific (power flow) study purpose. For example in the dynamization process proposed in [5], power flow models in UCTE format are used to create a dynamic study model of CE.

During the research project “InnoSys2030”, a power flow model from the simulation tool INTEGRAL is used as input data for the dynamic network model. This power flow model was initially used for the German Grid Development Plan [6] by the German transmission system operators. The dynamic network model is created in two simulation tools: the commercial tool DIgSILENT PowerFactory and MatPAT, a research tool developed by RWTH Aachen University.

The Power System Analysis Toolbox (MatPAT) enables symmetric root mean square (RMS) simulations of power systems and their connected components (e.g. loads, HVDC systems, synchronous generators etc.) and controllers by solving differential algebraic system equations. It is based on an interface to MatPower, which is a MATLAB® toolbox for the steady-state power flow analysis [7].

DIgSILENT PowerFactory is used in combination with a Python tool box. The Python toolbox was initially developed by FAU in [5] for power flow models in UCTE format. The functionality is adapted and enhanced during this project to be adaptable to any power flow model.

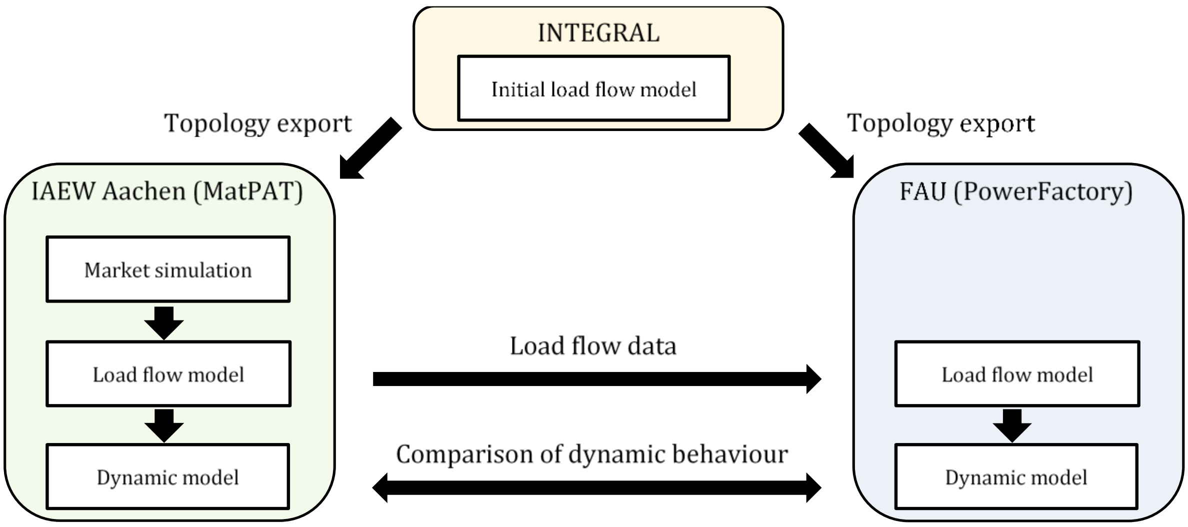

Figure 1: Development process in InnoSys2030

The modeling process of the power flow and dynamic models is shown in figure 1. Starting with an initial network model of CE in INTEGRAL, the topology of the network model is imported to PowerFactory and MATLAB® using an extended MatPower data format for power flow calculations, respectively. Subsequently, a market simulation is performed with a MATLAB® based tool of IAEW [8] in order to generate multiple power flow scenarios. Further information on creating the power flow scenarios can be found in [9].

The new power flow scenarios are created for the time scope 2030 on an hourly basis, including 8760 power flow study cases, with varying loading and mix of generating units. The power flow scenarios include all grid expansion projects planned by the German transmission operator until the year 2030. The time series of power flow data set then is transferred to PowerFactory. Based on the power flow scenarios, dynamic modeling is done and dynamic models are created in both simulation tools in order to be able to perform transient stability studies in different grid situations. Subsequently, both network models are compared in order to validate the dynamic behavior.

3 Power flow modeling

In this section, typical (modeling) gaps in power flow models as well as different options to solve them are presented.

Insufficient topology

Especially modern grid components such as HVDC links, wind parks or STATCOMs can be modelled in a simplified way in power flow models. In most cases, the particular component is directly connected to the high voltage busbar. In order to represent the correct reactive power infeed of such components, an additional impedance, e.g. a transformer, is required. Otherwise, the capacity of the component to participate in voltage control might be overestimated. In this paper, additional transformers for HVDC links, onshore wind parks at transmission system level and STATCOMs are implemented in the network model.

Isolated areas in the network model

Since the topology of the network model is usually based on earlier models, many grid components often might not be energized in the present power flow scenario. Applying a breadth-first-search can reduce the complexity of the network model by filtering and deleting all components that are switched-off. In this work, the implementation of the breadth-first-search from [5] is applied, starting with a node in Germany that is always energized.

Missing or false data for generating units

Due to the transfer of the network model from INTEGRAL to PowerFactory, all information on power limits and nominal power is lost or was never available for many generating units, especially for those located outside of Germany. In order to estimate suitable data for nominal power and power limits, multiple options are available.

If available, PQ-diagrams are used for synchronous machines and converter-based units in Germany. If no PQ-diagram is available, generalized values are calculated based on the time series of each element. Assuming a power factor of $\cos(\varphi) = 0.95$ for synchronous machines and converter-based units, an equivalent nominal power can be calculated:

$$S = \frac{P_{\max}}{\cos\varphi} \tag{3.1}$$

With P_{max} being the annual peak of the active power time series for the corresponding generator. Based on the new value for nominal power, the reactive power limits can be calculated assuming a symmetric operation range:

$$Q_{\max/\min} = \pm\sqrt{S^2 - P_{\max}^2} \tag{3.2}$$

Extensive use of extended ward equivalents

Power flow models typically use extended ward equivalents (EXTWs) in order to balance the reactive power demands of the grid. In some cases – especially if a market simulation is performed – to obtain a converging power flow scenario, even additional active power demands (e.g. system losses) are balanced by EXTWs, since those additional active power demands are only estimated by the market simulation.

The reason for implementing EXTWs is that reactive power management requires a correct modeling and optimization of the voltage controlling components and their reactive power compensation capabilities. Therefore, sufficient modeling of a realistic voltage control situation requires a high effort and is often neglected for studies focusing on the analysis of active power flows. Here, utilizing EXTWs is the easier and more practical solution. Due to the local demand of reactive power, several EXTWs must be installed in the grid to ensure sufficient compensation.

While using EXTWs can be a feasible solution for power flow studies when assessing congestion management, they are not suitable for assessing voltage control and power system stability, due to the following reasons:

- EXTWs are acting as PV-buses with a small internal impedance leading to almost constant voltage magnitudes regardless of the local reactive power demand.
- The reactive power injection of EXTWs is assumed as unlimited and continuous whereas in reality reactive power potentials are limited and often discrete (in case of mechanically switched devices).

To enable more realistic stability studies, within the presented process EXTWs are only used in grid areas which are not part of the German grid. These external EXTWs are replaced for time domain simulations after the initial power flow has been calculated. Injected active power of EXTWs, which is only necessary for balancing the active power exchange between areas, is replaced by a constant impedance. Injected reactive power of EXTWs is also replaced by constant impedance.

For the German grid area, no EXTWs are used and a heuristic method is applied to balance reactive power demand and provide reactive power compensation in order to maintain the voltage magnitudes within permissible limits.

4 Reactive power dispatch

The dispatch of reactive power compensators in the German grid area is determined by a heuristic approach. The German grid is divided into several zones within each control area. All available reactive power compensators are used to balance the reactive power demand within the corresponding regions. On the transmission level, mechanically switched reactors and capacitors with damping network (MSRs and MSCDNs), synchronous machines (including power plants and synchronous condensers), STATCOMs and HVDC-terminals are used. In addition, wind farms installed at the high-voltage level (110 kV) are modelled with Q(U)-droop controls assuming a rated power factor of cos(φ) = 0.9. Since MSRs and MSCDNs continue to account for a high share of reactive power compensators in the future German grid, they must be dispatched to meet the local reactive power demand within each region. For power flow calculations, synchronous machines, STATCOMs and HVDC-terminals are modelled as voltage-controlled PV-buses on the low-voltage side of their respective block transformers. To improve power system stability, it is crucial to maximize dynamic reactive power reserves from synchronous machines and power electronic devices (e.g. STATCOMs and HVDC-terminals). Hence, MSRs and MSCDNs are dispatched to maintain reactive power injections of the PV-buses and bus voltages within permissible limits for each region by iteratively switching one MSCDN or MSR during sequential power flow calculations (see figure 2).

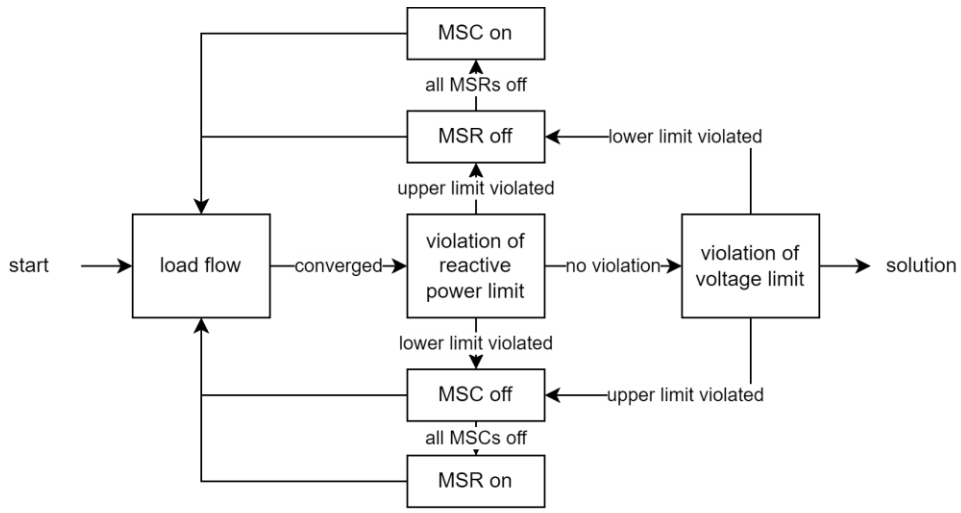

Figure 2: Dispatch of MSCDNs and MSRs

At first, switching decisions are decided based on violated reactive power limits of synchronous machines and power electronic devices. If upper reactive power limits are violated within a region, the algorithm switches off one MSR within each region with a limit violation. In case no MSR can be switched off, an MSCDN is switched on. For lower voltage limit violations, MSCDNs are switched on before MSRs are switched off. Such sequence prevents an undesired compensating action of MSCDNs and MSRs within the same region. In case reactive power limit violations at a PV-bus cannot be avoided by switching all available MSCDNs and MSRs within the respective region, it is converted to a PQ-bus in order to limit the reactive power injection at the specified maximum or minimum value. Once the power flow solution contains no reactive power limit violations, further iterations are carried out to ensure that no voltage magnitude limit violations occur. To this end, further MSCDNs and MSRs are switched within each region using the same switching sequence as for reactive power limit violations.

5 Controller modeling

The initial power flow model presents a topology for the year 2030. Therefore, different types of power generating units exist in the grid. In addition to conventional and hydro power plants, there are also converter-based grid components such as wind parks, PV, HVDC links and STATCOMs. Using the PowerFactory network model as an example, the dynamic modeling of these components is presented and briefly explained, in the following section.

5.1 Synchronous machines

The synchronous machines are enhanced with a controller system including a governor model (GOV), an automatic voltage regulator (AVR) and a power system stabilizer (PSS). Before implementing dynamic control models for each synchronous machine, the dynamic machine parameters must be reviewed and completed. Usually, in grid models for power flow analysis the dynamic machine parameters either are not considered or kept at random values. Since the dynamic machine parameters must be in realistic ranges to derive accurate stability results, the parameter set is taken from [10] as this data is proposed for large scale networks by ENTSO-E. The dynamic machine parameters are listed in table 1.

Table 1: Dynamic machine parameters [10]

Parameter	Value	Parameter	Value
cos(φ)	0.95	x_q	1.8 p.u.
H	4 s	x_q'	0.5 p.u.
x_a	0.15 p.u.	x_q''	0.3 p.u.
r_a	0	T_d'	0.9 s
x_d	2 p.u.	T_d''	0.03 s
x_d'	0.35 p.u.	T_q'	0.6 s
x_d''	0.25 p.u.	T_q''	0.05 s

For power plants, the governor model TGOV1 [11] is implemented. The model is based on the description in [11] and corresponds to a basic representation of a steam turbine governor. The controller model is depicted in figure 3.

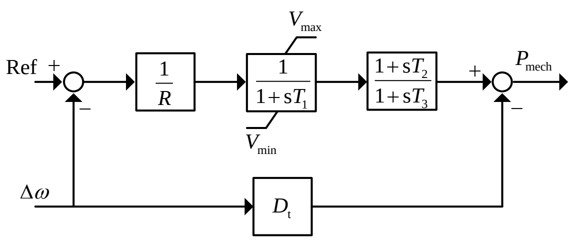

Figure 3: Governor model TGOV [11]

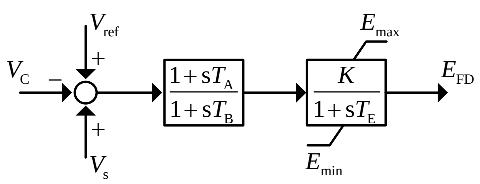

Figure 4: Automatic voltage regulator SEXS [10]

In literature often simple exciter models are applied, as e.g. in [12] or as proposed in [10]. The voltage controller model considered in this paper contains the SEXS exciter model and the

PSS2A model [10]. Figure 4 and figure 5 show the exciter model and the power system stabilizer, respectively. The control parameters for each control model are taken from [10].

Depending on the type of synchronous machine, some controller models are neglected. For synchronous condensers, the GOV model is not implemented. For pump-storage hydroelectricity, the governor model is only considered, if the system is in generating operation mode because the power plant does not participate in frequency control during pumping operation. In case the system is in pump mode, the synchronous machine is converted into a static power infeed. Additional, for each generator with P_{act} < 50 MW, the PSS model is neglected. Table 2 shows the applied controller models depending on the type of synchronous machine.

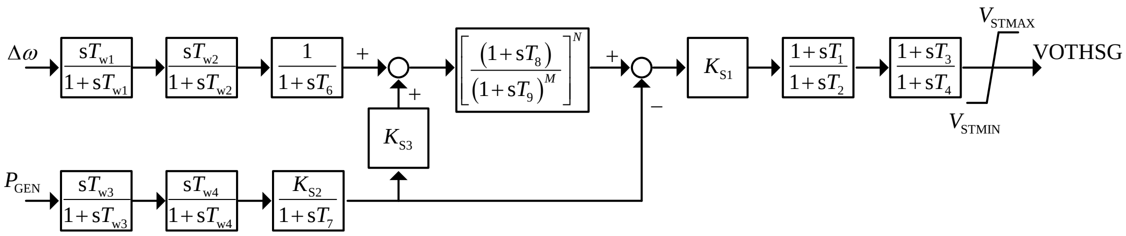

Figure 5: Power system stabilizer PSS2A [10]

Table 2: Controller models for synchronous machines

Type	GOV	AVR	PSS
Conventional power plant (P_{act} > 50 MW)	TGOV1	SEXS	PSS2A
Conventional power plant (P_{act} < 50 MW)	TGOV1	SEXS	---
Pump-storage hydroelectricity (generator mode)	TGOV1	SEXS	PSS2A
Pump-storage hydroelectricity (pump mode)	converted into constant impedance		
Synchronous condenser	---	SEXS	PSS2A

5.2 Embedded HVDC links

In this paper, the term “embedded HVDC links” describes HVDC connections that are part of the surrounding AC-system, i.e. HVDC connections whose converter stations are part of the same synchronous area. In Germany, these HVDC links are for example the planned systems ULTRANET, SuedLink and SuedOstLink [6]. Other examples are the INELFE system between France and Spain or the ALEGrO link between Belgium and Germany. All these embedded HVDC links are modelled as point-to-point bipolar HVDC system, as shown in figure 6, utilizing the PWM converter model in PowerFactory to represent the converter station.

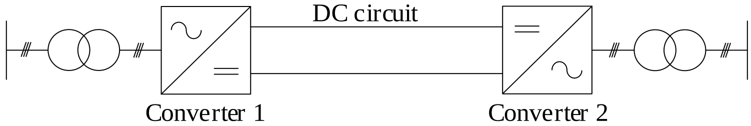

Figure 6: Modeling of HVDC links as bipolar HVDC

Figure 7 shows the reactive power control loop (blue block) including a second control path for the additional reactive current injection (red block) during grid faults, which is based on a I(U)-static. According to [13], the reactive power set point is calculated by a slower Q(U)-

characteristic (green block). This characteristic has usually a time scale of several ten seconds up to one minute. Since the scope of the dynamic model is the system behavior several seconds after a grid contingency, the Q(U)-characteristic is neglected in this paper.

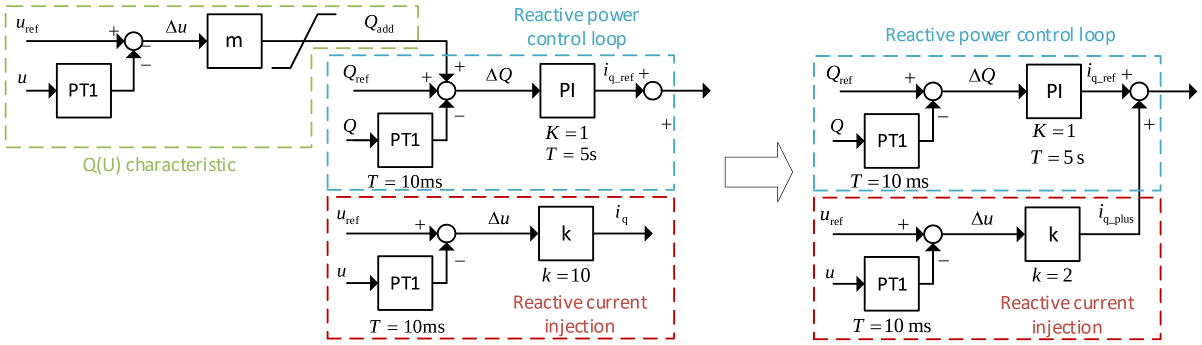

Figure 7: Simplified reactive power control loop for an HVDC converter station

The active power and DC voltage control loop is shown in figure 8. Depending on the control mode of the converter station, the control mode can be switched between PQ-control or U_{DC}Q-control, respectively. In PQ-control mode, an additional P(U_{DC}) droop is provided in order to reduce the power transfer in the DC circuit in case of a fast rising DC voltage. The current control loop is modelled using the built-in current controller of the PWM converter model considering a time constant T_{idq} = 10 ms. The overall HVDC converter modeling therefore corresponds to a controlled current source.

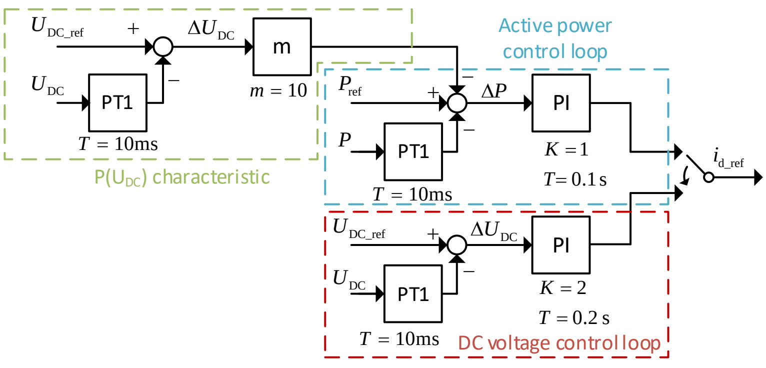

Figure 8: Active power and DC voltage control loop

5.3 Onshore wind parks

Multiple types of renewable energy resources (RES) are modelled in the network model. Wind parks represent the highest share of all RES. Therefore wind parks are also enhanced with a dynamic full converter interface (corresponds to WECC Type 4). Figure 9 shows the reactive power control loop of the dynamic wind park. Similar to the HVDC dynamic model, an additional reactive current injection is modelled to support the grid voltage during voltage drops. The active power control loop is modelled identical as shown in figure 8. Other RES represent a small share of the total installed power and are considered as constant impedance.

Converter-based systems are usually modelled as current source, as in the case of HVDC links in section 5.2. Due to the high share of converter-based RES, the current-source-modeling approach can significantly disturb the convergence of the RMS solver. Therefore, all converter-based systems are modelled as voltage source utilizing a grid interface introduced in [14] using the following equation. Further information on the applied equations and the interface can be found in [14]. Figure 10 shows the block diagram of the grid interface. The current loop dynamics are approximated using a PT1-block with time constant T_{idq} = 10 ms.

$$E_{\text{d}} = V_{\text{d}} + i_{\text{d}}R - i_{\text{q}}X \qquad (5.1)$$
$$E_{\text{q}} = V_{\text{q}} + i_{\text{q}}R + i_{\text{d}}X$$

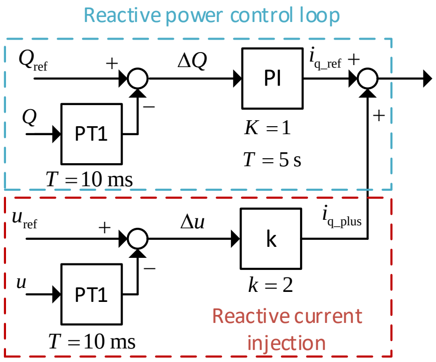

Figure 9: Reactive power control loop for wind parks

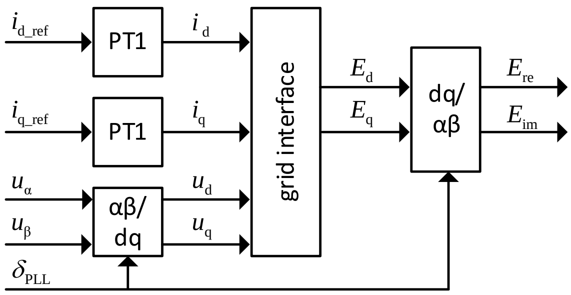

Figure 10: Grid interface for wind parks

5.4 Offshore wind parks

Offshore wind parks directly connected to the AC system and using an AC connection are modelled like onshore wind parks. Offshore wind parks connected via HVDC links are simplified. In the present study case, only the dynamic response of the onshore converter is relevant for large-scale dynamic studies. Therefore, the DC circuit and the offshore converter of the HVDC system including the actual offshore wind park are neglected. This simplification reduces the modeling effort, since no HVDC control and no U(f)-control must be modelled for the offshore converter. However, the simplification can lead to unrealistic results regarding grid faults close to the respective HVDC system. In addition, the impact of grid faults on the DC circuit can not be calculated in detail. The converter control for the remaining onshore converter is identical to onshore wind parks (section 5.3). Figure 11 shows the modeling simplification.

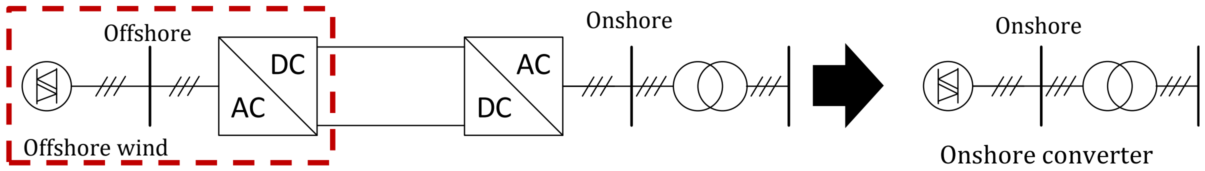

Figure 11: Simplification of offshore wind parks

5.5 STATCOMs

STATCOMs are modelled like onshore wind parks including the grid interface block. The only difference is the power control loop. The path of the active current i_{d} is set to zero while only the reactive current injection path is modelled to obtain the set point for the reactive current (figure 12). The droop constant is set to $k = 10$ in order to activate the full potential of the STATCOM if a voltage drop of 10% occurs. Even though this is a simplified approach, the main dynamic behavior of the STATCOM control is modelled sufficiently. In case, a more sophisticated model is required, detailed approaches can be found in [15].

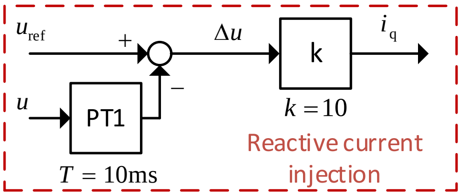

Figure 12: Simplified STATCOM control

5.6 Loads

To analyze the system voltage in case of grid contingencies, dynamic loads can be used. However, in this paper, the loads are modelled as constant impedance to simulate a worst case scenario and to stress the system even more regarding voltage instabilities.

6 Validation and results

To validate the development process for dynamic network models and to outline the resulting affects in different simulation tools, the network model in PowerFactory is compared to the network model in MatPAT. For the comparison, two different study cases are selected. The first one is representing a conventional power flow scenario with approximately 30% share of RES and a load of 85 GW in Germany. The second study case represents a power flow scenario with high share of RES (approximately 90%) and a slightly lower load of 82 GW in Germany. Both power flow scenarios are compared regarding the level of short circuit power, power flow results and dynamic behaviors after a grid contingency.

6.1 Validation of short-circuit power

To compare the level of short circuit power, several nodes in Germany are selected and the short circuit power is calculated. Table 3 shows the calculation results. In general, it can be seen that the short-circuit level in both grid models reflects the reduction of the short-circuit power in the second study case. However, it is also noticeable that small deviations between the grid models occur due to the many preparation steps and modeling assumptions.

Table 3: Comparison of short circuit power

Node	Conventional study case [GVA]		High share of RES [GVA]	
	MatPAT	PowerFactory	MatPAT	PowerFactory
Node A	48.5	49.9	42.0	45.7
Node B	31.3	32.8	30.2	32.0
Node C	32.8	33.1	31.5	32.2
Node D	61.0	56.1	39.9	43.8
Node E	48.7	47.7	43.4	45.9

6.2 Validation of power flow results

As mentioned, the market simulation is previously performed with an IAEW tool in MATLAB®. Using interfaces, the market result is prepared in MatPower format for power flow calculation. Afterwards, the resulting power flow scenarios are transferred to PowerFactory. Table 4 shows the comparison of the power flow results for the conventional study case and the study case with high share of RES in PowerFactory and MatPAT, respectively. Both simulation tools lead to comparable results regarding power flow studies and the overall system loading in both study cases.

Table 4: Comparison of power flow results for the Germany grid

	Conventional study case [GW]			High share of RES [GW]		
	MatPAT	PowerFactory	Deviation	MatPAT	PowerFactory	Deviation
Generation	72.6	72.6	0.0	113.7	113.1	0.6
Losses	1.2	1.5	-0.3	4.8	3.9	0.9
Load	85.0	84.9	0.1	81.7	81.7	0.0.

6.3 Validation of time domain simulations

To compare the dynamic behavior of both models in time simulations, both power flow scenarios are subject to a solid three-phase short circuit including a subsequent switching-off of a transmission line after 150 ms. Figure 13 and figure 14 show the voltage trajectories for both simulations. Within the conventional scenario, both network models show a stable behavior with approximately constant voltages during the short circuit and a very fast voltage recovery to a new equilibrium state. In the scenario with high share of RES, both models show an instable behavior with a comparable fast voltage collapse a few 100 milliseconds after the short circuit is cleared. This dynamic behavior is also reported in [16] and the instability is mitigated by increase of dynamic reactive power reserve. Nevertheless, deviations between to the network models can also be seen in the trajectories, which are due to the numerous preparation steps and the modeling assumptions. In general, the development process for dynamic network models allows the analysis of the dynamic behavior in terms of stability and different simulation tools lead to comparable results. However, exact comparable results cannot be achieved with reasonable effort.

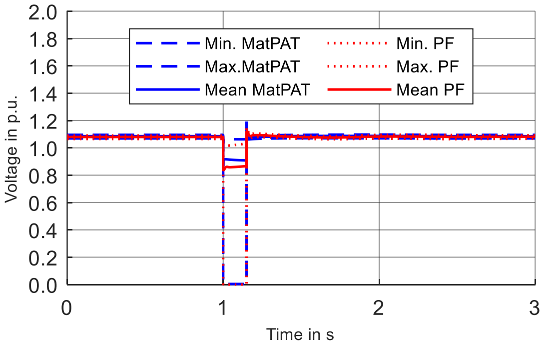

Figure 13: Conventional study case

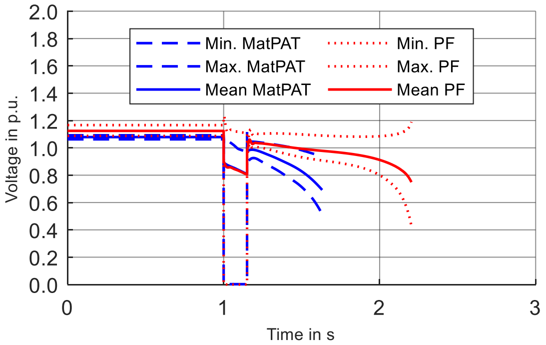

Figure 14: Study case with high share of renewables

6.4 Discussion

Both network models are based on a German power flow model for planning purposes in 2030. Therefore, there are grid components whose dynamic behavior can only be estimated nowadays, e.g. HVDC controls, as almost no operation experience is available yet for these components in the German grid. This leads to modeling and parameter assumptions (different modeling approaches and controller designs as well as different solver algorithms/ options) and introduces spaces for deviations in controller design. The assumptions result in a slightly different dynamic behavior during time domain simulation in PowerFactory and MatPAT, respectively, as shown in the previous sections. In addition, many preparation steps are necessary to perform the dynamic simulation, which may also lead to deviations between the network models.

However, the dynamization process, developed in the research project “InnoSys2030” and proposed in this paper, leads to sufficiently accurate dynamic network models to asses transient stability. Even though, there are differences in dynamics, both models showcase a similar dynamic behavior in comparable grid situations.

7 Conclusion

In this paper, best practice for creating dynamic network models were presented. Starting with an initial power flow model from INTEGRAL, two network models were developed in PowerFactory and MatPAT, respectively. Subsequently, typical power flow modeling issues were described and possible solutions were presented. Applying the dynamization process of the research project “InnoSys2030”, two dynamic network models were derived. In this paper, the process is presented for the Power factory model exemplarily. For validation, both models were compared regarding short circuit power, power flow results and dynamic behavior. Even though, the results display deviation due to modeling assumptions, both network models show similar dynamics. Next steps will focus on applying more detailed controller for synchronous generators, as only very simple models were used in this paper. In addition, more detailed models for STATCOMs and RES on distribution grid level will be in the scope of future work.

8 Acknowledgement

This paper is based on the project “InnoSys2030” and was funded by the German Federal Ministry of Economic Affairs and Energy under the project number 0350036. The authors of this publication are responsible for its content. The content presented is only part of the overall project and should not be understood as a project result.

The authors would like to thank Axel Müller (Amprion GmbH), Jörg Michael Schmidt (TenneT TSO GmbH), Alexander Raab and Dr. Gert Mehlmann (both FAU) for their support during this project.

9 References

[1] T. van Leeuwen, A.-K. Meinerzhagen, S. Raths, and A. Roehder, “Integration kurativer Maßnahmen in das Engpassmanagement im deutschen Übertragungsnetz,” in *16. Symposium Energieinnovation, Graz*, 2020.

[2] M. Lindner, D. Mende, A. Wasserrab, I. Sacar, M. Ariatabar, C. Lakenbrink, T. van Leeuwen, M. Lässig, and U. Häger, “Corrective congestion management in transmission networks using fast-responding generation, load and storage,” in *IEEE Canada Electrical Power and Energy Conference (EPEC2021)*, 2021.

[3] A. Raab, G. Mehlmann, J. Schindler, M. Luther, M. Abel, S. Horn, C. Heyde, P. Wiest, R. Krebs, and A. Kubis, “Security assessment for higher loaded power system operation to 2030,” in *ETG Congress, VDE*, 2021.

[4] A. Roehder, B. Fuchs, J. Massmann, M. Quester, and A. Schnettler, “Transmission system stability assessment within an integrated grid development process,” in *Cigre Science & Engineering*, 2017, pp. 67–84.

[5] R. Dimitrovski, G. Mehlmann, M. Luther, J. M. Schmidt, C. Ivanov, M. Abel, A. Wasserrab, and V. Milic, “Dynamic Network Security Assessment Model for the Interconnected Power System of Continental Europe,” in *Cigré Dublin 2017*, 2017.

[6] 50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, and TransnetBW GmbH, “Grid Development Plan 2035 (2021), second draft,” 2021.

[7] R. D. Zimmerman, C. E. Murillo-Sánchez, and R. J. Thomas, “MATPOWER: Steady-state operations, planning, and analysis tools for power systems research and education,” *IEEE Transactions on Power Systems*, vol. 26, no. 1, pp. 12–19, 2011.

[8] L. Wyrwoll, M. Nobis, S. Raths, and A. Moser, “Evolution of Fundamental Price Determination within Electricity Market Simulations,” *Energies*, vol. 14, no. 17, p. 5454, 2021.

[9] K. Kollenda, A. Hoffrichter, M. Schneider, A. Schrief, and A. Moser, “Planungsorientierte Simulation kurativer Maßnahmen im Deutschen Übertragungsnetz,” in *16. Symposium Energieinnovation, Graz*, 2020.

[10] ENTSO-E SG SPD Report, “Documentation on Controller Tests in Test Grid Configurations,” 2013.

[11] IEEE Technical Report, “Dynamic Models for Turbine-Governors in Power System Studies,” 2015.

[12] A. Semerow, S. Hohn, M. Luther, W. Sattinger, H. Abildgaard, A. D. Garcia, and G. Giannuzzi, “Dynamic Study Model for the interconnected power system of Continental Europe in different simulation tools,” in *2015 IEEE Eindhoven PowerTech*, Eindhoven, Netherlands, 2015, pp. 1–6.

[13] VDE, “VDE-AR-N 4131 Anwendungsregel:2019-03: Technische Regeln für den Anschluss von HGÜ-Systemen und über HGÜ-Systeme angeschlossene Erzeugungsanlagen (TAR HGÜ),” 2019.

[14] D. Ramasubramanian, Z. Yu, R. Ayyanar, V. Vittal, and J. Undrill, “Converter Model for Representing Converter Interfaced Generation in Large Scale Grid Simulations,” *IEEE Transactions on Power Systems*, vol. 32, no. 1, pp. 765–773, 2017.

[15] Cigré, “Static Synchronous Compensator (STATCOM): Working Group 14.19,” 2000.

[16] 50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, and TransnetBW GmbH, “Assessment of System Stability: Supporting document for Grid Development Plan 2035 (2021), second draft,” 2021.