On the Art of Electric Power System Modelling and Simulation for Integrated Transmission-Distribution Analysis

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1 Introduction

Future electricity supply needs to ensure a reliable and affordable low-carbon power generation, which will greatly depend on renewable energy sources (RES) such as solar photovoltaic and wind power. Growing demand for energy from environmentally friendly sources is challenging modern grids to provide a reliable power supply that includes high fluctuating sources. Power grid operators must ensure that energy networks continue to provide the highest levels of reliability and performance at reasonable cost. Grid modelling and analysis supports the design and engineering of the power grids transition process with various states of grid evolution from its present centralized, carbon-based architecture to a future de-carbonized state. The present contribution discusses various power grid modelling applications within the context of the energy transition process in Germany. In doing so, electric power system modelling and simulation is shown as a technological 'art form,' highlighting that

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the experience of the engineer is of paramount importance when it comes to defining the system under consideration.

2 Electricity Network Modelling and Analysis—Overview

In the domain of electrical and power systems engineering,[1] there are basically three different types of electrical network modelling and studies.[2] The first one is the *steady-state study*, which involves load flow analysis of AC (alternate current) systems that gives an idea about the level of voltage in different buses—understood as the nodes of the grid—of active and reactive power, and of the load conditions of transmission lines, generators and transformers. Software like PSS/E and PowerFactory[3] are commonly used as commercial tools for this purpose, while software systems like MatPower, GridLab-D and PypSA are mainly used in the research and academic field. The second type of studies is called *stability analysis* and deals with short circuit studies in the time order of 1 second. Software tools such as PowerFactory,[4] PSS/E and PSS-Sincal are available for this kind of studies. The third one is *transient studies* for the electro-mechanical (RMS, root-mean-square) and for the EMT (electro-magnetic transients) time domains, which also deals with short circuit analysis and load step effects, but in very short periods of time in the order of microseconds in EMT to milliseconds in RMS studies. Software applications like MATLAB/Simulink, PowerFactory[5] and PSCAD are used in the latter kind of studies. For real-time studies (PHIL, power hardware in the loop), digital-twin and control system design, specific hard-/software systems are available, like RTDS or Opal-RT. All this is accomplished by integration of modern power electronics systems like converters as used for the interconnection of renewable energy (RE) sources, like wind and solar power generators,[6] to the traditional AC grid where mainly synchronous machines were and still are used as generators.

[1] Schwab (2012).

[2] Çakmak et al. (2015).

[3] Gonzalez-Longatt et al. (2014).

[4] Gonzalez-Longatt et al. (2018).

[5] Gonzalez-Longatt et al. (2020).

[6] Bundesnetzagentur Power Plant List (2023).

In addition, we need to model compensation units (FACTS—flexible AC transmission systems) as used for voltage and reactive power control in the integrated transmission network. Examples for FACTS are stepped reactors and capacitor banks, but also power electronics-based systems like STATCOM units, which combine both inductive and capacitive reactive power.

In order to study future electricity supply which needs to ensure a reliable and affordable low-carbon power generation greatly depending on renewable energy sources (RES) such as solar photovoltaic and wind power, we deal with all of the above listed types of power grid modelling and analysis, and hence with a high complexity of interconnected and large-scale models. For this reason, our very complex electricity network and system models (see Table 1 and Figs. 1–3) include network models of all voltage layers as used in electrical power supply. This ranges from low-voltage level (LV), as used in the end-user installations of the distribution network (400 V), the medium-voltage level (MV, in Germany typical: 6/10/20/33 kilovolts), the high-voltage level (Germany: 60/110/150 kV), up to the very high-voltage layer (Germany: 220/380 kV nominal) as used in the transmission grid and the interconnected European power transmission network ENTSO-E. In addition, this is accomplished by HVDC links (high-voltage direct current), which are used to transmit high volumes of electrical power over long distances (> 300 km) with minimum losses (< 2% over a + 500 km distance). Typical losses in the 380 kV grid are about 1% per 100 km transmission distance.

When we combine network models of different voltage layers into one integrated study, we call this 're-bundling,' since due to European market

Table 1 Number of elements in the power grid models as mentioned in the following sections

Model	*Nets*	*TSOs*	*Trans*	*Lines*	*Buses*	*Stations*	*Switches*	*Comp*	*Gen*	*Loads*
ENTSO-E CE	28	32	5622	15,255	18,728	9206	78,278	1801	19,325	11,198
Germany	2	4	219	1492	2894	1291	10,281	137	4139	1250
BW	6	1	1970	1187	2036	586	13,408	40	689	972
KIT CN	1	1	125	522	198	46	1060	63	17	430
KA-N-4018	1	1	11	179	31	12	109	–	9	116

Abbreviations: Trans.: Transformers, Comp.: Compensation devices, Gen.: Generators

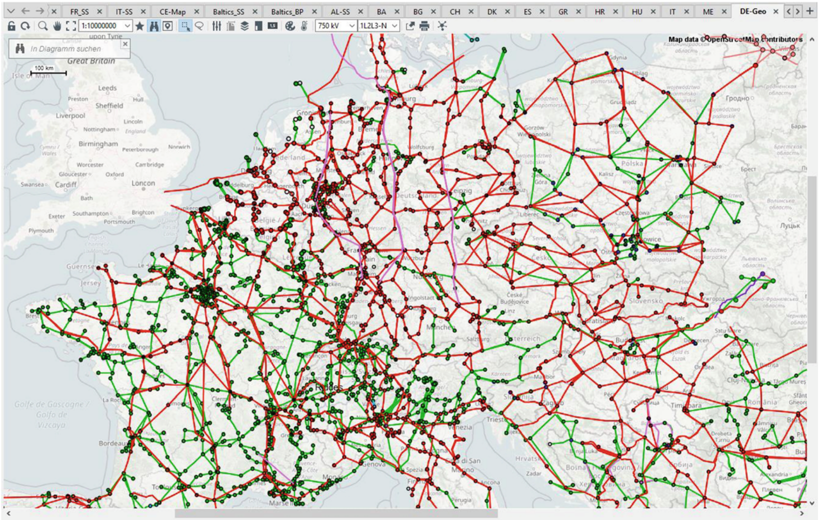

Fig. 1a Interconnected Electricity Transmission Network in Central Europe, ENTSO-E CE (© KIT Karlsruhe Institute of Technology)

regulations the previously regionally integrated power supply networks had to be split over the last 20 years into independent companies and operators for generation, transmission and distribution of electricity. This process is (was) called 'un-bundling.' Its initial intention was competition between electricity generation and supply companies, thus reducing the cost of electricity for the end-user. In consequence, the various Transmission System Operators (TSOs) and Distribution System Operators (DSOs) look—and model—only at their own power region and voltage layer. However, as we like to get an integrated view at the whole interconnected system—over all voltage layers and regions—we 're-bundle' (physically and operationally). Thus, a change of load or generation in Denmark or Bulgaria will affect the power system state in Portugal or Poland, and a power step in the lowest voltage layer on household level will slightly effect the state in the transmission grid, i.e. the voltage on busbars and the loading of lines and transformers.

This very high complexity of interconnected and large-scale models cannot be derived as mathematical equations are derived: for every task of study, a respective modelling perspective has to be taken into account, in

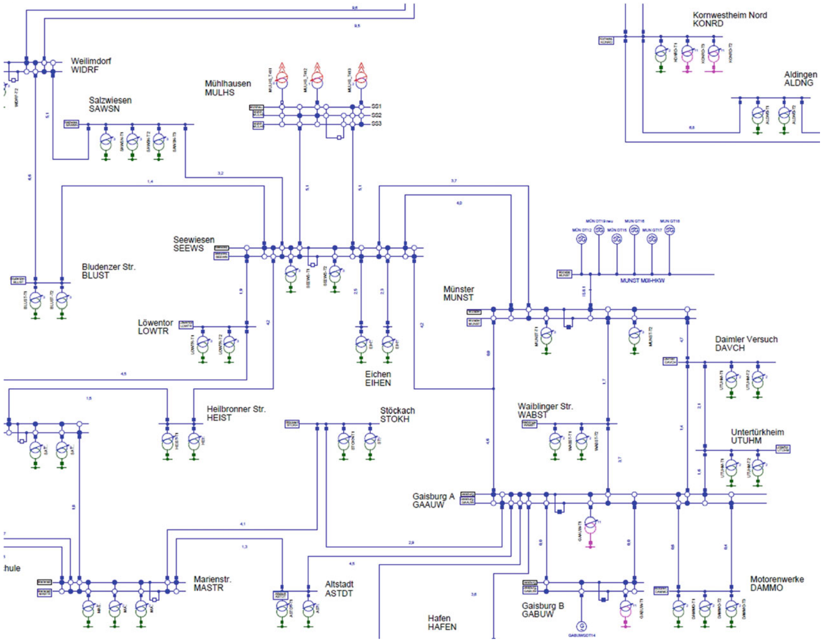

Fig. 1b Section of the 110-kV network (© KIT Karlsruhe Institute of Technology)

view of the defined task, in order to be able to overcome calculation problems and to achieve meaningful results. This process depends heavily on the experience of the engineer, a point of view which has been confirmed recently—especially for future power systems—by a statement of Martin Schmieg, Chairman of the Advisory Board of DIgSILENT GmbH, the company that produces the PowerFactory modelling and simulation tool:

> It is quite obvious that increasing numbers of power electronic converters leads to a clear overlap of the EMT- and RMS-based analysis functions, whereby the complexity of models in conjunction with the model scope leads to calculation problems that are sometimes difficult to solve. Here,

the experience of the engineer is of paramount importance when it comes to defining the system under consideration.[7]

Examples of the various complex power system models and their combinations are presented in the next sections.

3 Transmission Grid Modelling

The largest models we model and study constitute the interconnected transmission grid in the Central Europe region (region ENTSO-E, European Network of Transmission System Operators for Electricity),[8] as shown in Fig. 1a. In addition, we have developed grid models of large portions of the 110 kV voltage network in Germany, including the entire region of Baden-Württemberg (BW), as shown in Fig. 1b. The 110 kV model BW includes the transformation-layer down to the medium-voltage grids, 10/20 or 30 kV, depending on the region and operator. As shown in Fig. 1b, displayed is a small part of the 110 kV cable grid in Stuttgart, the 10 kV is used for the medium-voltage feeders into the living quarters and industrial users. Accumulated loads and generation, i.e. the summarized electric loads of all end-users connected to this feeder (households, small industry and commerce), as well as all generators (e.g. rooftop PV, Biomass small wind, biomass, block-heating stations and run-hydro generators), are connected to the electricity network on this voltage level (MV busbars). The 110 kV and the VHV transmission networks have a meshed topology, and the MV and LV networks are operated as radial topology.[9]

For the transmission grid, various controller structures are required for balancing load and generation and for balancing the international and inter-regional energy trade between grid operators. For each control region, a frequency/power-controller is implemented,[10] which controls the operation (power and voltage setting) of the operational thermal power stations in the specific control region. Renewable generators (wind, solar, biomass, run-hydro, block-heating) have priority in energy supply,

[7] Schmieg, Foreword, in Gonzalez-Longatt and Torres (2020, p. V).

[8] Kopernikus-Projekt ENSURE (2023).

[9] Föllinger (2013).

[10] Föllinger (2013).

and the thermal stations are used to balance the electricity generation with the regional and temporal reactive power load demand of the end-users. In general, the load demand is not regulated, and so-called load shedding (temporal restriction of electricity supply) is only used in emergency situations.

For grid compensation (voltage, reactive power demand and control), passive elements (reactors and capacitor banks for inductive and capacitive reactive power, respectively) and active power electronics devices like STATCOM (Static Synchronous Compensator) are used. A STATCOM is a fast-acting device capable of providing or absorbing reactive current and thereby regulating the voltage at the point of connection to a power grid. It is categorized under flexible AC transmission system (FACTS) devices. STATCOM allows for linear reactive power compensation, thus for voltage control, over a broad range in both directions (inductive and capacitive). All FACTS devices, active or passive, require a controller model. In addition, most transformers are equipped with a stepping unit, which is used to change the transformation in steps within a certain range (typical: ± 10%) with respect to its nominal value.

4 Distribution Grid Modelling

Examples of distribution grid sub-models are shown in Fig. 2a, 2b. Such models cover, in terms of type, complexity and region, street-level MV/LV subsystems of urban housing areas and industrial plants.

Each urban supply area (Fig. 2b) has one MV feeder with a 20/0.4 kV transformer. Radially connected are LV loads and generation units, with manually operated switchboards for topology change, to enable construction work. Typical characteristics for this type of model are: a 20 kV feeder substation and 400 V supply cables to the buildings with up to 100 loads, which are separately metered, and up to 3 megawatts (MW) power per substation and transformer. In the example shown in Fig. 2b, a 630 kVA transformer is used. Connected to the LV grid are RE generators (rooftop PV systems), electro-mobility load stations, a mix of public and private buildings and households. This type of models can be used in 'smart-grid' studies as well.

Another application of a HV/MV/LV model, as shown in Fig. 2a, can be characterized as an industrial area. The example shows the electricity

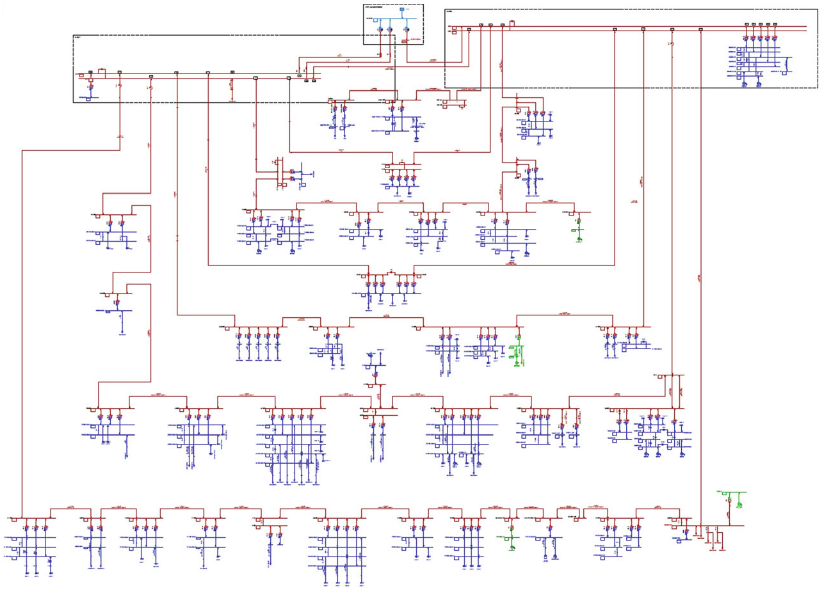

Fig. 2a KIT-Campus North Grid (© KIT Karlsruhe Institute of Technology)

network of the KIT Campus North (KIT CN).[11] Our model shows the 110/20 kV connection to the public electricity network with 3 transformers 110/20 kV with power ratings of 2 × 23,5 MVA and 40 MVA. Four CHP (combined heat and power) generators use natural gas as primary fuel and are rated in sum with 13,5 MW (rating 2 × 4,5 MW, 2,5 MW, 2 MW). In addition, 8 diesel generators provide emergency power in case of electricity outages. A 1,5 MW solar PV field, together with a battery storage rated at 1 MWh, is used as experimental RE units.[12] The PV unit feeds directly to the public power grid. Maximum load in the KIT CN power grid is up to 20 MW.

[11] Energy Lab 2.0 (2023).

[12] Erdmann et al. (2019).

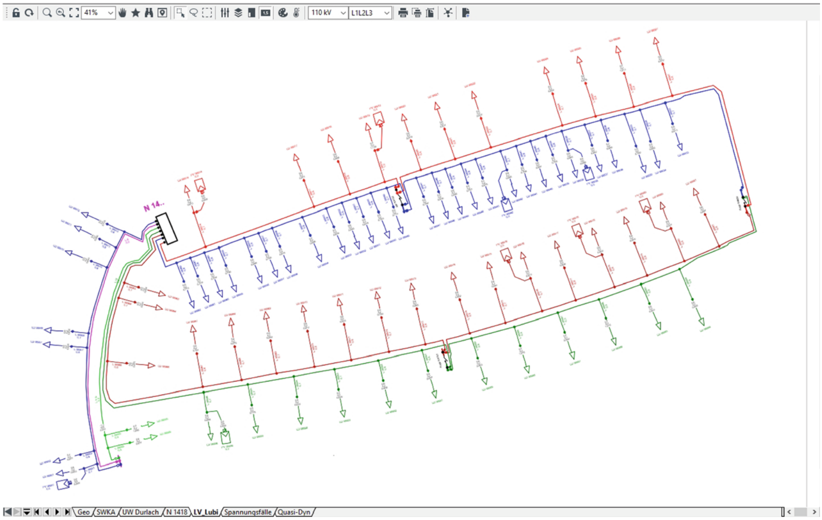

Fig. 2b Typical living quarter, 20 kV Feeder in a suburb of Karlsruhe with 74 houses, 12 roof-top PV, highly detailed components (cables, interconnectors, protection) (© KIT Karlsruhe Institute of Technology)

5 Study 1: Demo Region—Power Balancing in High-Wind Region

For the ENSURE demonstration region (Schleswig–Holstein), the grid model of the demo region was created.[13] This comprises the transmission grid of TenneT and the 110 kV distribution grid of SH-Netze in the Steinburg district and in the entire area between Hamburg, Augsburg and Heide. While the wind farms in the demo region are directly connected to the 110 kV stations, the remaining wind farms are connected to the MV busbars of the respective HV/MV transformers. For modelling the time series data, the data for the real year 2019 (load, generation by category) have been taken from the TenneT transparency platform and adjusted according to the weekdays and holidays of the target year. The model created was then dynamized by FAU, i.e. equipped with plant controllers,

[13] Kopernikus-Projekt ENSURE (2023).

and is used to prepare for the demo phase, which includes the integration of MVDC (medium-voltage DC) plants and a solid state transformer (SST).

The regional area Schleswig–Holstein is identical with the transmission grid zone D21, operated by the TSO TenneT. Three offshore wind regions with a combined generation rating of 2130 MV are connected to the 380 kV station Büttel with HVDC cables. These are: SylWin1 (sea station SylWin Alpha, ± 320 kV DC, 864 MW), HelWin1 (sea station HelWin Alpha, ± 250 kV DC, 576 MW) and HelWin2 (sea station HelWin Beta, ± 320 kV DC, 690 MW). According to the power plant list of the Bundesnetzagentur (BNA Kraftwerkliste), the accumulated peak generation of onshore wind parks in the D21 region is 7227 MW. The maximum power load within the D21 region is about 2 gigawatts. Combining these numbers, there is an over-production of about 7,3 GW in the D21 region, if we want to avoid positive re-dispatch measures (limitation of generation power by grid control limitation from the TSO, generation reduction). To balance this over-generation capacity in the D21 region, there are a number of grid balancing projects either already in operation or under construction: in the 380 kV station Brunsbüttel, the SuedLink A HVDC link (± 525 kV, 2000 MW) will connect the D21 zone to the station Großgartach in the Transnet-BW control zone D41 (operational 2026). In the 380 kV station Wilster-West, the HVDC link SuedLink B (± 525 kV, 2000 MW) connects the D21 zone to the 380 kV station Grafenrheinfeld-West in Bavaria. The NordLink HVDC sea-cable (± 525 kV, 1400 MW) connects the HVDC converter station Wilster-West to the HVDC converter station Tonstad in southern Norway (operational since December 2021). And another HVDC link called Baltic Cable, rated with ± 600 MW transmission capacity, connects the station Herrenwyk (close to Lübeck) with the station Krusenberg in southern Sweden.

Study case for the year 2026: For the year 2026, when all national HVDC links (SuedLink A, B) and the interconnectors NordLink and Baltic Cable will be operational, we define a grid balancing case study. For this, the target is the transfer of wind energy from the D21 zone to southern Germany and through the HVDC interconnectors NordLink and Baltic Cable to Norway and Sweden, respectively. A real weather situation (Sept. 2020) is used to define a quasi-dynamic load flow case, as shown in Fig. 3a. The load and generation scenarios are transposed into

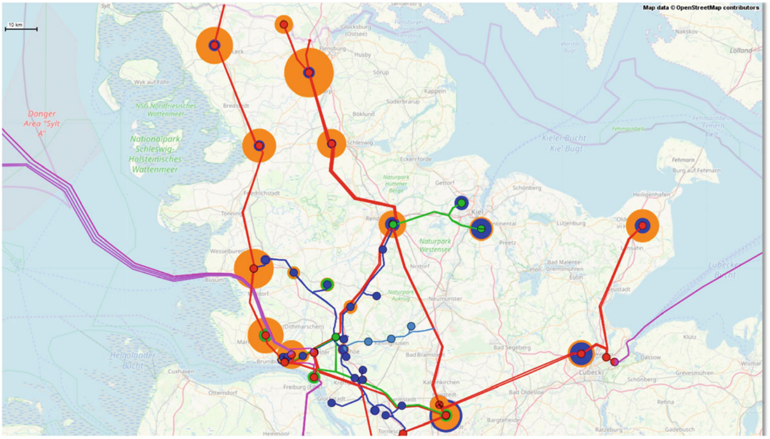

Fig. 3a Electricity infrastructure in the study region D21 and load/generation diagram (© KIT Karlsruhe Institute of Technology)

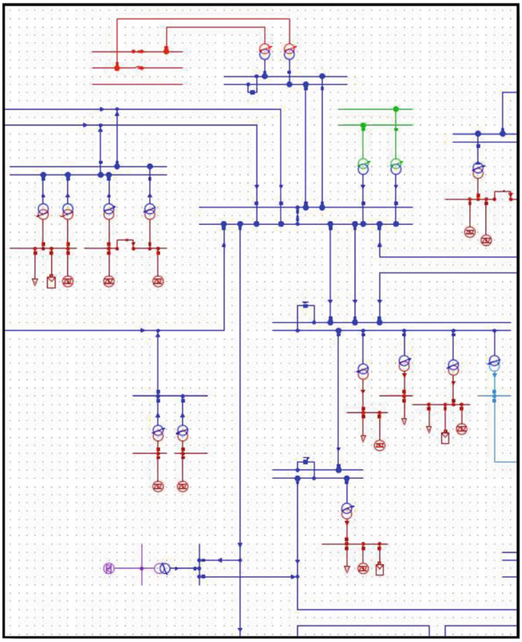

Fig. 3b 110 kV infrastructure in the demo region (district Steinburg) (© KIT Karlsruhe Institute of Technology)

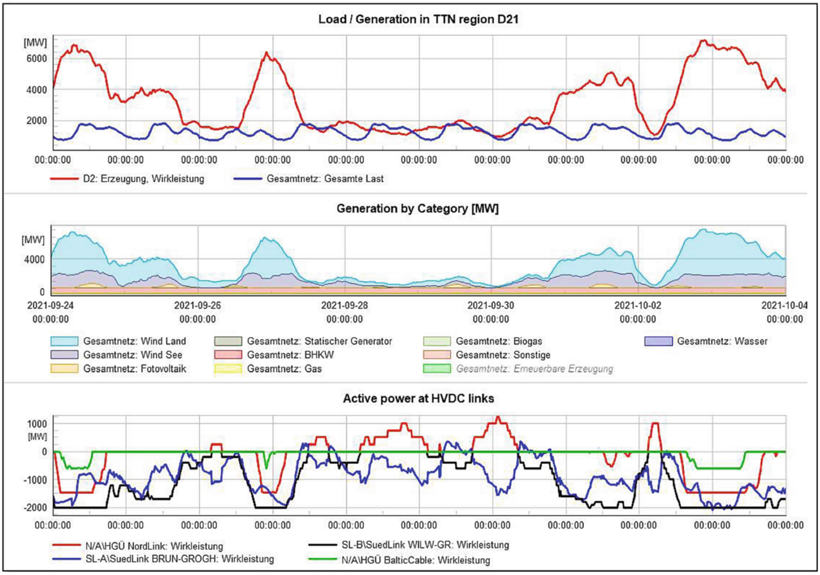

Fig. 3c 10-day QDSL simulation with a high generation surplus due to very high wind generation on- and offshore (24.9.–4.10.2020) (© KIT Karlsruhe Institute of Technology)

the comparable period in 2026. A controller model is defined for operation of the HVDC links and other generators in the zone D21. The 10-day generation/load QDSL simulation with extreme weather situations (max./min. wind) shows that the very high over-production of wind power[14] can be balanced with the 2 GW load in the region, in combination with the transfer.

6 Study 2: Region Transnet-BW—Grid Balancing Using 2 HVDC Links

In study 1 as described in the previous section, we proved that a massive over-production of RE generation in one region (D21, Schleswig–Holstein) can be balanced through HVDC links and interconnectors. In

[14] Kyesswa et al. (2020).

study 2, we look at a similar region in Baden-Württemberg with control zones D41 and D42 for the same year (2026), located in the control region of the TSO Transnet-BW (D4).

Figure 4 shows the grid model in Baden-Württemberg and a 7-day QDSL study during an extreme situation. As well as in study 1, we use real weather data for PV and wind generation in the target period (April 2026). For the study, we chose the Easter holiday, which is characterized by minimum consumption load due to industry closure of the public holidays, together with an already very high PV generation in the D4 zone due to cold temperatures in combination with already high solar radiation. In our study case, the maximum PV generation is 4,5 GW.

For the study, we have developed a simulation model of the Transnet-BW transmission grid (220/380 kV AC), together with the 110 kV grid of all DSOs (Netze-BW, Stadtwerke Karlsruhe, Stuttgart, Ulm, Freiburg, Heilbronn, MVV in Mannheim and the SYNA grid). In the D4 region, there is a population of around 11 Mio. people, and a combined maximum power load of about 10,5 GW. In the D4 region, the generation of the previously used nuclear power stations Neckarwestheim-2 and Philippsburg-2 (final closure end 2019 and April 2023), with a summarized generation capacity of about 3 GW, has to be compensated by the two HVDC links ULTRANET (± 320 kV, 2 GW, Osterrath-Philippsburg) and SuedLink A (± 525 kV DC, 2 GW, Brunsbüttel-Großgartach). The latter two HVDC links are projects with the intention to transfer wind power from the north-sea offshore wind

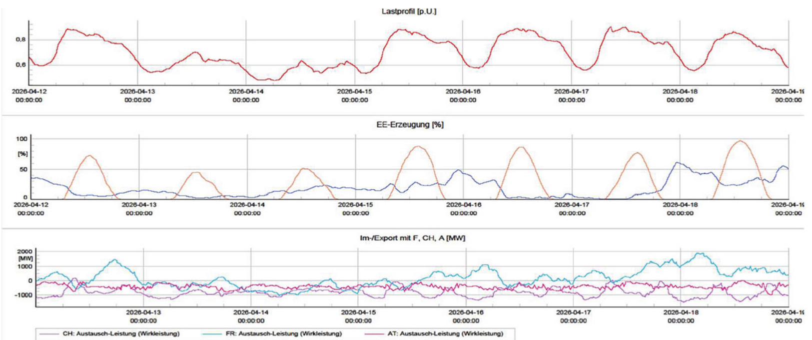

Fig. 4a Electricity Network Baden-Württemberg with HVDC, 380-/220-/110-kV-model layers (© KIT Karlsruhe Institute of Technology)

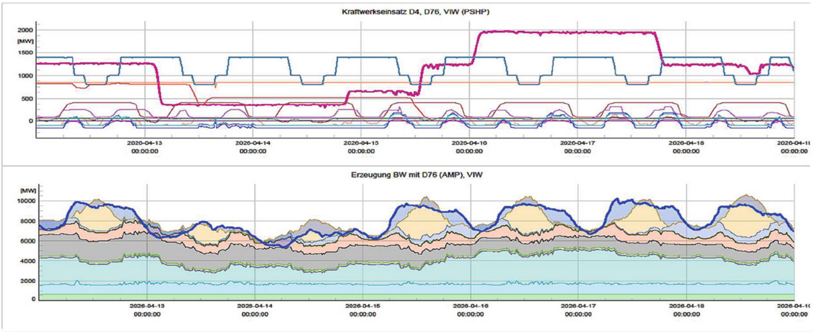

Fig. 4b Result diagrams of 1-week Quasi-Dynamic-Simulation (load, wind/solar, import/export, generation by power station, generation by primary energy sector) (© KIT Karlsruhe Institute of Technology)

parks to southern Germany. In addition, the control region D4 has to cope with a high transfer power from and to the neighbouring countries France, Switzerland and Austria with the German neighbouring zones of the TSOs Amprion and TenneT.[15] Baden-Württemberg had a high portion of solar PV in 2022, with an accumulated peak generation of 7,8 GW. Another feature of the Transnet-BW control zone is the high portion of pumped storage hydro plants in the southern black-forest region and in Vorarlberg/Austria (rated in sum approx. 4 GW). Along the rivers Rhine and Neckar, there are run-river hydro plants, rated with about 800 MW. About half of the generation capacity is connected to the DSO grids, the other half is under direct control of the TSO. In terms of grid operation, the daily load and generation balance is a challenge in terms of maximum security of grid supply and of the economic goal of a low rate of re-dispatch measures with regard to the high rate of flexibility needed in view of the highly volatile RE generation (mostly PV) in Baden-Württemberg.

Figure 4b shows results of study for the year 2026, when both HVDC links (ULTRANET, SuedLink) are supposed to be in operation:

- The goals are reachable with 2 HVDC links (both rated 2 GW).
- All requirements of the grid-code are fulfilled (voltage limits, load limits of transformers, lines, cables and switchgear).

[15] Weber (2021).

- Pumped storage and NG stations compensate primary and secondary control power with high $\Delta P/\Delta t$ rates of PV-KW in the morning and evening hours.

7 Conclusion

The present contribution discusses some highly advanced power grid modelling applications that are key to the energy transition process in Germany. Yet by presenting ways of tackling this immensely complex mesh of resources and data management, the modelling and simulation of electric power systems shows itself not only as a strategy of regulation and control, but also as a technological 'art form,' introducing a variety of visual representation formats to enhance its arguments and make its data fit. Moreover, the report we gave from deep inside the modelling activities within our EnergyLab also highlights the often neglected and sometimes precarious fact that the experience of the engineer is of paramount importance when it comes to defining the system under consideration, especially in view of overcoming calculation problems and competing modelling alternatives. However, the importance of the engineers' experience for obtaining meaningful results does not call into question the profession of modelling, nor does it minimize its efficiency, as long as it is taken into account. In our example, a detailed and complex modelling of power grids provides the basis for a number of operational and grid studies in electrical power supply, e.g. in order to act for grid expansion in the future. Based on the respective high complexity models described above, the combined studies 1 and 2 show that the operational control of a future power grid with a very high share of renewable energy is possible in view of the TSO perspective with respect to balancing the generation/load flows of their individual control regions. However, in the studies 1 and 2, we cover only the steady-state load flow analysis. Since our grid models include—on a different complexity level—the dynamic control models of the generators, in other modelling applications we will look into the short time transient dynamics aspects of some of the components (generators, HVDC links, FACTS) of our power grid models. Meaningful results are obtained when a fitting picture of all the modelling aspects is achieved in the eye of the engineer, based on calculations and experiments, but also on the lifelong training of the modeller.

To sum up: the very high complexity of interconnected and large-scale power system models cannot be derived as mathematical equations are derived: for every task of the study, a respective modelling perspective has to be taken into account in view of the respective task and on the basis of the experience of the engineer in order to be able to overcome calculation problems and to achieve meaningful results. This modelling process is absolutely necessary in order to be able to develop the design of future power grids mainly based on renewables.

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