A modelling approach for dynamic short-circuit analysis of the German power system considering all voltage levels

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Abstract

In this paper, a dynamic model of the German power system is presented which can be used to analyse the impact of three-phase short-circuits in the extra high voltage level on the power system behaviour. The model is set up in PSS NETOMAC and can be used for RMS-simulation. It represents all voltage levels from 380 kV to 0.4 kV and all generating units, including conventional power plants, PV and wind energy units. It is thereby possible to estimate the amount of short-circuit current provided by distributed generation depending on different stationary control strategies such as cosφ(P) and Q(U), as well as total reactive current injection during the fault period. The accompanied effect on voltage stability and short-circuit power can also be investigated. Furthermore, the power of PV and wind energy units within the low voltage level that are disconnected due to voltages lower than 0.8 pu can be determined.

1 Motivation

1.1 Analysis of different voltage controller strategies of decentralized energy resources (DER)

In Germany, there is a network connection guideline for each voltage level. These guidelines are reworked from time to time. At the moment there are revisions of the requirements for the connection of Distributed Energy Resources (DER) to the medium and low voltage levels ([1], [2]). In the past it was sufficient to look at the local impacts of these resources as the installed capacity was small [3]. However, today it is necessary to look at the impact on each of the other voltage levels, as the installed capacity has reached a size that has an influence on the whole electrical system. In this context, two different controller states are regarded in the guidelines. Firstly, methods of stationary control such as Q(U), cosφ(P) and constant cosφ have an impact on the stationary voltage behavior. Such strategies attempt to hold the voltage values within the allowed limits at each node (DIN EN 50160). Due to the different ways of using available reactive power, each control strategy has different influences on the dynamic behavior during a voltage dip caused by a three-phase fault in the extra high voltage (eHV) level. The second controller state describes the behavior during a voltage dip at the connection node of the DER. In the guidelines for eHV/HV and MV, low voltage ride through (LVRT) requirements are stated. On the low voltage level each DER detecting a voltage lower 0.8 pu at the connection node has to disconnect within a defined time frame [4]. This is no longer beneficial, as the amount of solar power infeed in Germany during a sunny day is up to 25 GW (15.04.2015) [5] and about 65% (16.3 GW) [3] is installed on the LV level. Therefore, the disconnected power after a fault in the eHV level could reach a value which is critical for the whole system stability, as the maximum primary control power in the ENTSO-E area is 3 GW.

1.2 Determination of disconnected DER on the low voltage level

At the moment it is only possible to estimate the amount of disconnected power after a three-phase short-circuit in the eHV level [6]. Therefore, the geographical expansion of the voltage dip on the eHV level is used to get an idea of the disconnected power on the LV level. In this case the interactions of DER on different voltage levels are neglected and the error in the amount of disconnected power can be arbitrarily high. Regarding the presented approach for modelling the whole German power system, a powerful model is set up which can be used to determine the disconnected power depending on the fault location with a significantly higher accuracy. Furthermore, the model can be used to get an idea of development of the short-circuit capacity in times with a small number of active conventional power plants.

2 Modelling approach

The development of the model can be seen as a top-down approach. Going down the voltage levels from eHV to LV, the level of detail is reduced, as the model is used to analyse effects of the lower voltage levels on the eHV level during a three-phase short-circuit in the eHV level. The electrical distance grows and thus fewer details in the lower voltage levels have lower influence on the quality of the results. Nevertheless the whole installed capacity of DER, all loads and their distribution on the different voltage levels should be represented. Therefore, Germany is subdivided in 401 regions which are equal to the postal code areas as shown in Figure 1 and Figure 2. Each area must include nodes of the HV level, as the equivalent MS and NS networks are connected to these nodes. In order to

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get a representative number of nodes in each area, the HV nodes of the 380/110 kV and 220/110 kV transformers are used. As mentioned above, small conventional power plants and large scale wind parks are connected to the HV level. Therefore, these nodes are also taken into consideration. Finally, it is necessary to distribute randomly a number of nodes which depends on the size of the area. Furthermore, these areas are grouped by HV network groups (see Figure 2). This is important for the generation of a reduced HV level network. The methods of modelling each voltage level are described in this chapter.

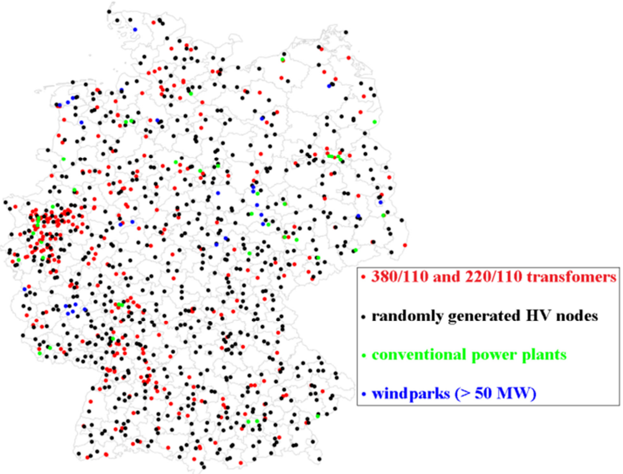

Figure 1: Postal code areas and regarded HV nodes

Figure 2: Grouped areas for HV network groups

2.1 Extra high voltage (eHV) level

The basic way of modelling this voltage level is described in [7]. The topology is generated based on geographical information in Google Earth. There are 380 and 220 kV lines, 380/220 kV, 380/110 kV and 220/110 kV transformers. Synchronous generators are included. In difference to the presented modelling approach in [7], no residual loads at the 110 kV nodes are used. As described in the following points, an equivalent network topology is generated for the HV, MV and LV level.

2.2 High voltage (HV) level

Usually this voltage level has two tasks. On the one hand it acts as a part of the transmission system in the same manner as the eHV level and on the other hand it has distributive functions. Furthermore, smaller conventional power plants and comparatively large DER, such as solar and wind parks, are connected to this voltage level. To consider these different aspects it is necessary to model the HV level in as much detail as possible. Due to a lack of data and with the objective of getting a manageable model of the whole system a method is developed to create an equivalent HV network.
As shown in Figure 3, the method is divided in three steps,. During the first step, real HV networks are used to determine typical R/X (R…resistance, X…reactance) and R/D (D…distance) values and the cumulative probability of node degrees. The R/D parameter and the geographical information of the available nodes (see Figure 1) are used as input parameters for the developed Topology Generator in step 2. Finally, in step 3 the combination of the adjacency matrix (i.e. the output of the Topology Generator) and the typical R/X and R/D values provides the equivalent HV network.

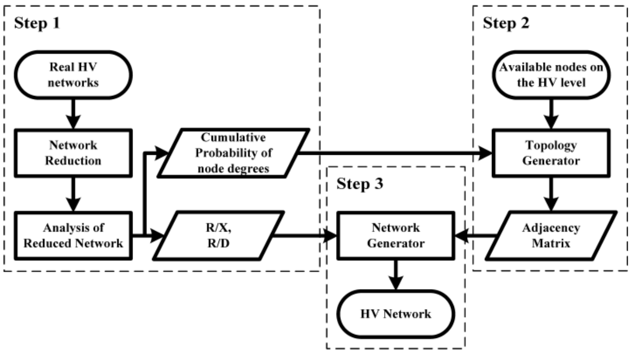

Figure 3: Three steps for generating equivalent HV network

2.2.1 Step 1

In order to determine the impedance between two nodes dependent on the distance, three parameters R, X and D have to be evaluated. As it is planned to connect the regarded HV nodes directly with single equivalent impedance, it is not possible to evaluate the original real network topologies. These topologies have parallel lines between nodes and there are also nodes which are connected by a Y-connection. These problems can be avoided by running a network reduction. After the reduction process there are nodes where usually

- load
- DER
- conventional power plants
- transformers

are connected. For the network reduction all shunt elements like loads and DER are eliminated and only series elements are regarded. So there is no influence of a specific load flow situation on the network reduction and a reduced network topology with equivalent impedances between the nodes is achieved. These impedances are analysed regarding the R/X and R/D values. Finally the

medians of all regarded branches are given to the Network Generator in step 3.
The Topology Generator in step 2 needs as an input parameter the cumulative probability of the node degrees of the reduced network. This is very important, as the meshing of the final equivalent HV network should be similar to the reduced one. In Figure 4 the number of nodes with the same node degree and the cumulative probability for different reduced networks are shown. Regarding the number of nodes, Network 1 is the largest and as there are only large HV network groups, as shown in Figure 2, its cumulative probability is used as input for the Topology Generator.

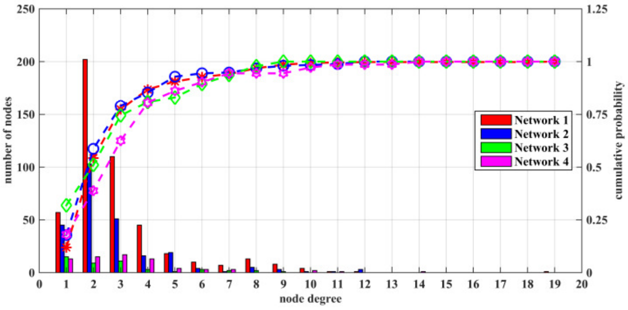

Figure 4: Analysis of node degrees

2.2.2 Step 2

The Topology Generator works as shown in Figure 5. First the geographical information (longitude and latitude) of all available nodes in the area of one HV network group is collected. Using this data, the distance matrix is calculated. The distances between all nodes are stored in this matrix. The following steps are processed for each node. Using the cumulative probability of the node degree, the number of connected lines is determined randomly. After that the same number of nearest nodes b is identified with the help of the distance matrix and the probabilities p_{ij} to establish a connection based on the node distances are calculated as shown in formula (1) and (2).

$$(1)\quad d_{max} = \max(d_{ij})\ with\ 1 \le j \le b$$

d_{ij} ... *distance between regarded nodes i and j*

$$(2)\quad p_{ij} = \frac{d_{max} - d_{ij}}{\sum_{k=1}^{b} d_{max} - d_{ik}}\ with\ 1 \le j \le b$$

This is necessary as nearer nodes are preferred to connect to. Then the determined number of connections is established, but several connections to the same node are not allowed. Finally the results are saved in the adjacency matrix by changing the entry from zero to one. After that same procedure starts with the next node of the regarded HV network group. At the end there are equivalent networks for each HV network group. This is as the HV level is structured in reality. It is not completely meshed over whole Germany.

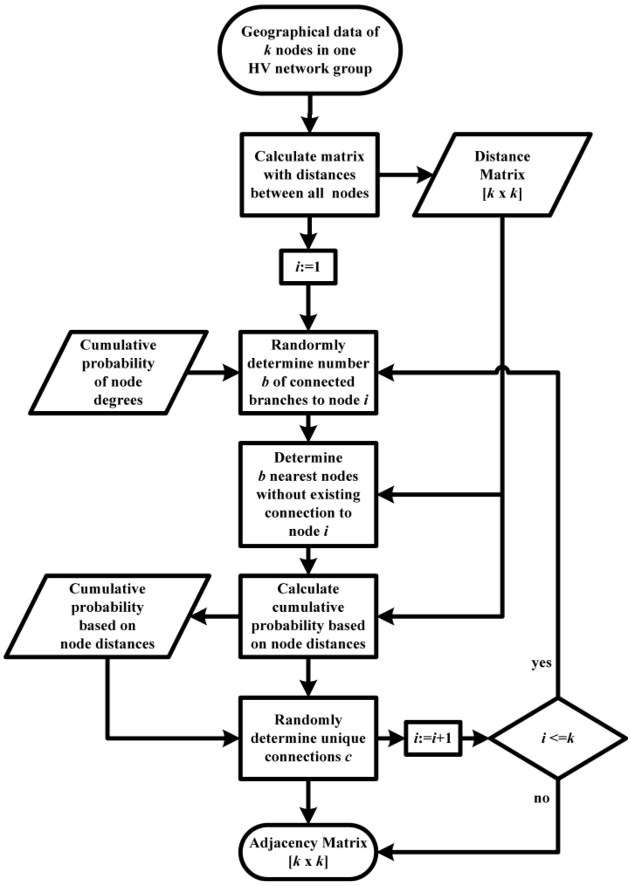

Figure 5: Flow chart of Topology Generator

2.2.3 Step 3

During the last step, the results of step 1 and step 2 are combined by using the Network Generator. Each entry in the adjacency matrix is weighted with the impedance. The impedance $Z_{ij} = R_{ij} + jX_{ij} with\ 1 \le j \le c$ is calculated using formulas (3) and (4).

$$(3)\quad R_{ij} = R/D \cdot d_{ij}\ with\ 1 \le j \le c$$

$$(4)\quad X_{ij} = (R/X)^{-1} \cdot R_{ij}\ with\ 1 \le j \le c$$

In Figure 6, the resulting topology for the equivalent HV network is shown. Finally, there are more HV network groups than shown in Figure 2. That is also typical for HV network operation in reality. The network of one HV system operator is usually actuated in a disconnected way. That leads to a higher level of service security and helps to better manage disturbances in the system.
In summary, the result is a randomly generated topology for the HV level by representing real equivalent impedances between nodes and the degree of intermeshing of reduced HV network groups.

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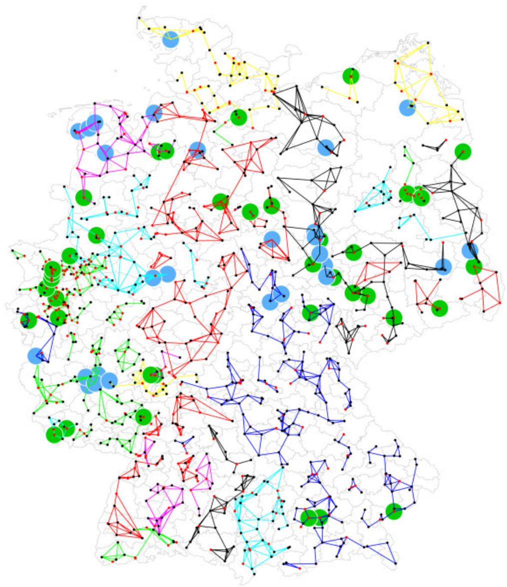

Figure 6: Equivalent HV network

2.3 Medium voltage and low voltage level

The modelling method for the MV and LV level is different to the presented method for the HV level. The resulting topology should be as simple as possible to limit the final model size of the whole system. Basically aggregated MV and LV topologies are connected to all nodes (see Figure 2) of the HV level as shown in Figure 7. The aggregation of the detailed networks is processed in two steps. Firstly, typical LV and MV networks have to be reduced to aggregated PV and wind units, aggregated load and equivalent impedances. Following this, the number of represented LV and MV aggregated networks at each HV node must be determined and the second aggregation step can be performed.

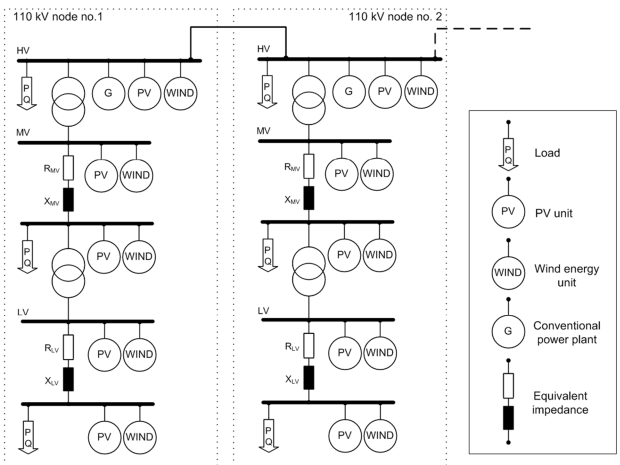

Figure 7: Aggregated network topology of MV and LV level

2.3.1 Aggregation method for LV and MV networks

The modelling approach of these voltage levels is based on the requirement of using existing dynamic models of PV and wind parks. Therefore, it is necessary to separate topological information and shunt elements like load and DER. To achieve this, typical low voltage networks as described in [8] are generated. There are finally three different types of LV networks regarded, each with three different transformer sizes. An overview of all typical LV networks is given in Table IV.

For generating aggregated MV networks, four real networks are used. Two of them are rural and the others are urban networks.

In Figure 8, the method for the determination of the equivalent impedance is shown. It is based on the approach presented in [9]. This impedance should represent the topology of the regarded network in a way that the error between the RMS simulation results (i.e. active power and reactive power flows at the high-voltage side of the transformer) of the complete and the aggregated network is smaller than a defined limit *x*. To get an impedance which is suitable for different penetration of DER and independent of the remaining voltage at the high-voltage node of the transformer after a short-circuit in the eHV level, different variants are simulated and compared. If the error is higher than the defined limit *x*, $R_{NV/MV}$ and $X_{NV/MV}$ are changed and the variants of the aggregated network are simulated again and compared to the results of the complete network. Finally, values for $R_{NV/MV}$ and $X_{NV/MV}$ can be found which lead to comparable results for the dynamic behaviour of active power, reactive power and reactive current of the reduced network at the high-voltage side of the transformer.

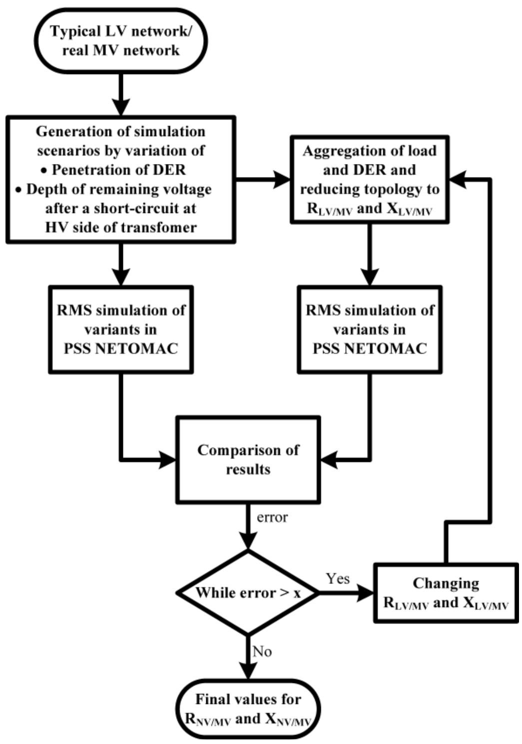

Figure 8: Method for determination of an equivalent impedance

2.3.2 Aggregation of multiple LV and MV networks

As the topology of the HV level is reduced to a certain number of nodes, more than one MV network and thus several LV networks must be connected to each HV node. This problem is solved by combining networks of the same type. Therefore the equivalent impedances Z_{MV}/Z_{LV}

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and the transformer capacities $S_{T,HVMV}/S_{T,MVLV}$ must be adapted, as shown in formulas (5) to (8). The represented numbers of MV and LV networks are m and n. This aggregation is based on the assumption that the load, installed capacities and power generation of PV and wind units is equal in all aggregated networks.

(5) $S_{T,HVMV,m} = m \cdot S_{T,HVMV}$

(6) $S_{T,MVLV,m,n} = n \cdot m \cdot S_{T,MVLV}$

(7) $Z_{MV,m} = Z_{MV}/m$

(8) $Z_{LV,m,n} = Z_{LV}/(m+n)$

2.3.3 Result

Finally, the topology connected to one HV node is shown in Figure 9. The values of the transformer capacities $S_{T,MVLV,m,n}$ depend on the number of represented MV networks and LV networks and on the type of area where the HV node is placed. Each area is categorized as rural, village or suburban/urban. The final numbers of represented transformers and networks is presented in section 4.1.

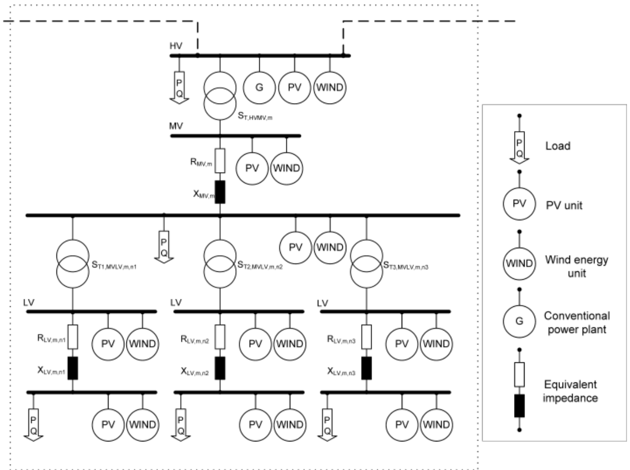

Figure 9: Final topology connected to one HV node

3 Analysis of installed DER

The suggested modelling approach in this paper also includes the distribution of PV and wind parks as main representatives of DER in Germany. Here the regional distribution and the distribution between voltage levels are regarded. Furthermore, the typical installed capacities of PV and wind parks depending on the voltage level are determined. All these results are based on the database provided by [3].

3.1 Regional distribution and voltage level distribution

In Figure 10 and Figure 11 the distribution of PV and wind units in Germany on the HV, MV and LV level are shown for the year 2022. The shown regions are equal to the ones presented in chapter 2. The results are based on the analysis of the database for the year 2014 and then they are scaled with the forecasted values of installed PV and wind capacities in [10]. It can be seen that all over Germany PV units are primarily connected to the LV and MV level with a focus on the south of Germany. Wind units are located in the north of Germany and they are predominantly connected to the HV and MV level.

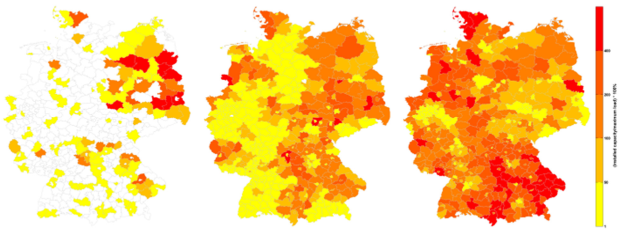

Figure 10: Regional distribution on HV, MV and LV level of PV units in 2022 [(installed capacity/maximum load)*100%]

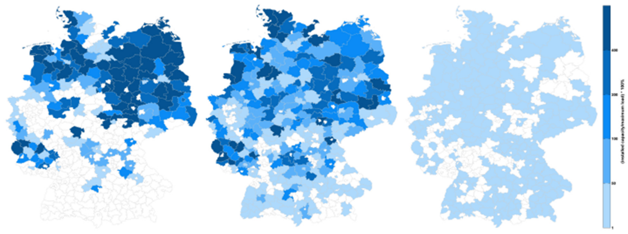

Figure 11: Regional distribution on HV, MV and LV level of wind units in 2022 [(installed capacity/maximum load)*100%]

3.2 Typical sizes of PV and wind units on each voltage level

The behaviour of PV and wind units, concerning the amount of reactive power exchanged with the grid, depends on the installed capacity of each unit. To get values for each voltage level the installed capacities of every unit in the database [3] are analysed (as far as the numbers were valid). The final capacities are the values corresponding to 50% in the cumulative frequency (medians). The results are shown in Table I. There are no values for PV units of the eHV and eHV/HV level as no unit is connected to these levels.

Table I: Median of installed capacities on each voltage level

Voltage level	PV units	Wind units
eHV	---	14,5 MW
eHV/HV	---	14,2 MW
HV	13,3 MW	11,0 MW
HV/MV	4,5 MW	9,2 MW
MV	0,43 MW	1,50 MW
MV/LV	0,05 MW	0,23 MW
LV	0,01 MW	0,02 MW

4 Combination of network data and load flow data

As the basic structure of the final model is now defined, network and load flow data have to be added. Therefore the distribution of load on the different voltage levels is calculated and the numbers of HV/MV and MV/LV transformers must be determined.

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4.1 Load distribution

For each region i (see section 2) the maximum load $P_{Load,i}$ is calculated dependent on different parameters as shown in formula (9). This approach is taken from [11].

$$(9)\quad P_{Load,i} = \frac{BEV_i}{\sum_n BEV_n} \cdot P_{Load,DE,BEV} + \frac{BWSIND_i}{\sum_n BWSIND_n} \cdot P_{Load,DE,IND} + \frac{BWSLAND_i}{\sum_n BWSLAND_n} \cdot P_{Load,DE,LAND}$$

BEV ... $Population$
$BWSIND$ ... $Gross\ value\ added\ of\ industry$
$BWSLAND$ ... $Gross\ value\ added\ of\ agriculture$
$P_{Load,DE,BEV}$ ... $Maximum\ laod\ of\ commerce/households/transport$
$P_{Load,DE,IND}$ ... $Maximum\ load\ of\ industry$
$P_{Load,DE,LAND}$ ... $Maximum\ load\ of\ agriculture$

The values for $P_{Load,DE,BEV}$, $P_{Load,DE,IND}$ and $P_{Load,DE,LAND}$ are listed in Table II.

Table II: Load distribution on business sectors in Germany

$P_{Load,DE,BEV}$	$P_{Load,DE,IND}$	$P_{Load,DE,LAND}$	$P_{Load,DE,sum}$
43.6 GW (52%)	38.7 GW (46%)	1.7 GW (2%)	84.0 GW (100%)

The distribution of load across the voltage levels is based on the analysis of given maximum yearly load of ten big DSOs in Germany. The results are shown in Table III.

Table III: Statistical values for load distribution on voltage levels

Statistical number	HV	MV	LV
Mean value μ	28.9%	42.5%	28.7%
Standard deviation σ	12.9%	11.7%	6.8%
	HV-MV	**MV-NV**	**HV-NV**
Correlation factor ρ	-0.852	-0.092	-0.443

According to the values in Table III, the load distribution on the voltage levels is determined randomly by using the formulas (10) to (12).

$\underline{V}$ ... $Result\ vector$
$\underline{Z}$ ... $Vector\ with\ random\ numbers$

$$(10)\ \underline{V}_{HS} = \mu_{HS} + \sigma_{HS} \cdot \underline{Z}_{HS}$$

$$(11)\ \underline{V}_{MS} = \mu_{MS} + \sigma_{MS} \cdot \left(\rho_{HS-MS} \cdot \underline{Z}_{HS} + \sqrt{1-\rho_{HS-MS}^2} \cdot \underline{Z}_{MS}\right)$$

$$(12)\ \underline{V}_{NS} = 100\% - (\underline{V}_{HS} + \underline{V}_{MS})$$

Finally, there are percentage values for each region for each voltage level which describe the load distribution in Germany.

4.2 HV/MV and MV/LV transformers

The installed capacities of HV/MV and MV/LV transformers are given by [12] and [13]. In summary, in 2022 there will be an installed capacity of 280 GVA of HV/MV transformers and 200 GVA of MV/LV transformers.
As there is just a 40 MVA HV/MV transformer type used in this model, the final number of represented HV/MV transformers is about 7000. However, there are three different MV/LV transformer types for each type of area. So the whole installed capacity and load has to be distributed on nine different transformer types. The final number of MV/LV transformers is achieved by using relative frequencies. The values are taken from [8] and adapted to the year 2022. The final numbers for the different transformer types and the relative frequencies are shown in Table IV.

Table IV: Final numbers for all MV/LV transformers

Area type	Capacity [kVA]	relative frequency	Final number
Suburban/ urban	630	0.5	141693
	400	0.3	85102
	250	0.2	56758
Village	630	0.1	9032
	400	0.55	49702
	250	0.35	31638
Rural	250	0.1	20857
	160	0.4	83428
	100	0.5	104285
Sum	---	---	**582495**

4.3 Load flow scenario

The parameters of the regarded load flow scenario in 2022 are shown in Figure 12. It is a heavy load scenario with 80.7 GW P_{Load} and a total power generation of 74.8 GW (P_{Gen} + P_{Wind} + P_{PV}). Thus, there is an import of 5.9 GW. The installed capacity $S_{installed}$ of the active generators is 62.5 GVA. The power generation of wind units is about seven times higher than of PV units. The residual load of each area is presented in Figure 13. Reversed load flows from the distribution network to the transmission system can be observed predominantly in the north of Germany. High load densities are located in the areas of large cities, e.g. Berlin, Munich and Hamburg.

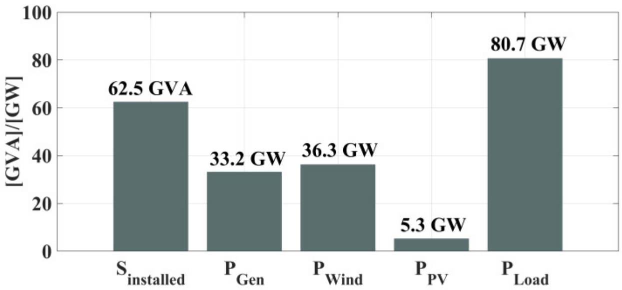

Figure 12: Load flow parameters Scenario 2022

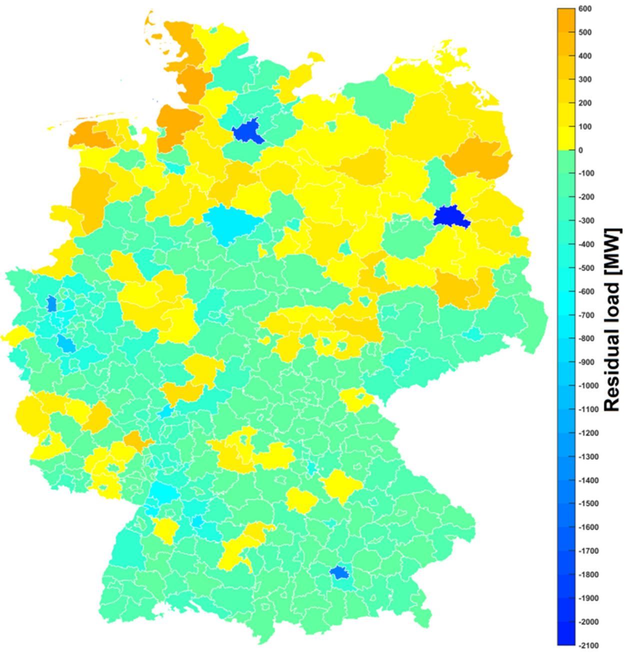

Figure 13: Residual load of each area

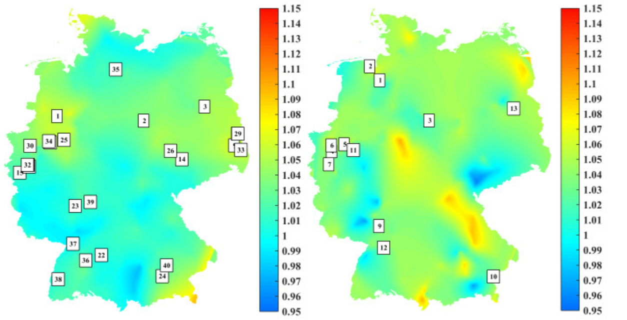

Figure 14: Voltage profiles of the eHV level (380 and 220 kV)

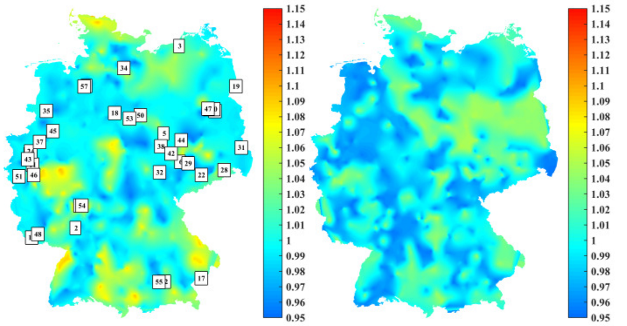

Figure 15: Voltage profiles of the HV and MV levels

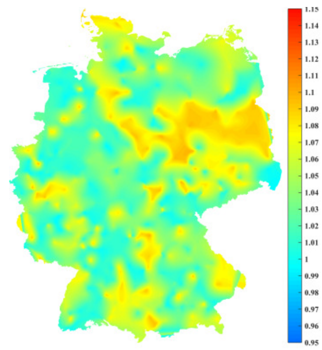

Figure 16: Voltage profile of the LV profile

5 Simulation

Load flow calculation and RMS-simulation are performed with PSS NETOMAC. The input structure is set up in a modular way. The information of each voltage level, split into topology/load and generation information, is written to different macro files. Thereby, it is a very flexible model which can be easily adapted for different scenarios and projects.

5.1 Load flow calculation

In Figure 14, Figure 15 and Figure 16 the voltage profile of each voltage level, as a result of the load flow calculation, is visualized. The figures show that the voltage range across all voltage levels is between 0.95 pu and 1.10 pu. There are lower voltages on the HV and MV levels than on the eHV and the LV. The reason for this effect is based on the tap changer positions of the eHV/HV and HV/MV transformers. It is necessary to raise the voltage ratio. Thus the resulting voltage on the LV level is below 1.10 pu, as requested in DIN EN 50160. In Figure 14 and Figure 15 (HV level), the locations of all synchronous generators are marked.

5.2 RMS-simulation

For looking at the dynamic behaviour of the model, a three phase short-circuit is simulated for 300 ms at a 380 kV node in the south-west of Germany (Pulverdingen). In Figure 17 the resulting voltage curves are presented. Shortly after the short-circuit occurrence, the voltage rises to a higher remaining voltage. This happens due to the reactive current infeed of DER connected to the HV and MV level after detecting the voltage drop. After the short-circuit event, for a short period of time the voltage increases to a value significantly higher than before the fault. The reactive current infeed is still active and the set point in the controller of each DER is not yet adjusted to the new voltage value. Thus, there is a delay until the reactive current infeed is reduced according to the implemented characteristic of each generating unit. After that, the system remains stable and the voltage curves get back to the pre-fault values.

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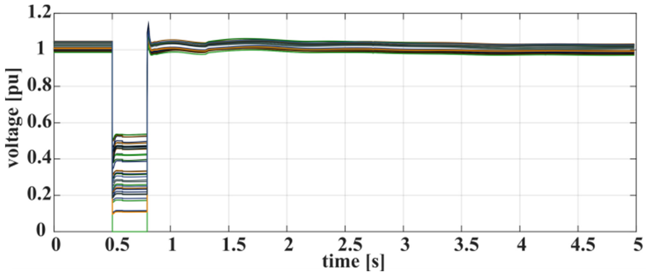

Figure 17: Voltage curves at different nodes near the short-ciruit location on the eHV level

6 Summary

In this paper, the modelling approach for three-phase short-circuit analysis of the German power system is presented. The main idea is to consider all voltage levels with different degrees of detail. As the eHV level is the main area of focus, a top-down approach is implemented. The eHV level is modelled in as much detail as possible. Due to the very important role of the HV level in the German power transmission system, a methodology is developed to represent the topology characteristics of this voltage level by using data of a few real HV networks. Thereby, it is not necessary to gather real network data for all of Germany. The final models of different MV and LV networks are designed to be relatively small, as the model complexity has to be kept in certain limits. Therefore, an equivalent impedance approach is used. Each MV and LV network is reduced to aggregated load, aggregated PV and wind units and equivalent impedances, such that the dynamic behaviour of active power and reactive power flows in the reduced model is close to that of the complete network. These reduced network topologies can be further aggregated to represent a certain number of equal LV and MV networks.

In order to get a model which is suitable for load flow calculation and RMS-simulation, the network data must be combined with load flow parameters. A load flow scenario in the year 2022 is presented. It is a heavy load scenario with more than 50% power production by PV and wind units. The results of analysis of the distribution of DER and load in Germany are also presented. In addition, the final numbers of represented transformers and the typical sizes of PV and wind units on each voltage level are shown.

Finally, the results of a load flow calculation and a RMS-simulation performed with PSS NETOMAC are presented. It is shown that the voltage values on each voltage level are within the allowed limits. Furthermore, it can be seen that the voltage behaviour during a RMS-simulation of a three-phase short-circuit in the south-west of Germany remains stable.

In further investigations, this model will be used to determine the switched-off capacity of DER on the LV level due to the occurrence of low or high voltages during three-phase short-circuit simulations at different locations in Germany. At the same time, the short-circuit current/capacity and the affected load as defined in [14] will be investigated (compare to [15]).

7 References

[1] VDE/FNN. (2014, Dec.). Verhalten von Erzeugungsanlagen im Fehlerfall. Berlin. [Online]. Available: http://www.vde.com/DE/FNN/ARBEITSGEBIETE/STUDIEN/Seiten/fehlerfall.aspx

[2] VDE/FNN. (2015, June). VDE-AR-N 4110: Technische Anschlussregeln für die Mittelspannung. Berlin. [Online]. Available: http://www.vde.com/de/fnn/arbeitsgebiete/seiten/n4110.aspx

[3] Deutsche Gesellschaft für Sonnenenergie e.V. (DGS). (2015, June). [Online]. Available: www.energymap.info

[4] VDE-AR-N 4105, „Erzeugungsanlagen am Niederspannungsnetz – Technische Mindestanforderung für Anschluss und Parallelbetrieb von Erzeugungsanlagen am Niederspannungsnetz“, VDE/FNN, 2011.

[5] Agora Energiewende. (2015, June). Agorameter: Stromerzeugung und Stromverbrauch. [Online]. http://www.agora-energiewende.de/service/aktuelle-stromdaten/?tx_agoragraphs_agoragraphs[initialGraph]=powerGeneration&tx_agoragraphs_agoragraphs[controller]=Graph

[6] J. Bömer, T. Kumm, M. van der Meijden, „Weiterentwicklung des Verhaltens von Erzeugungsanlagen am Niederspannungsnetz im Fehlerfall – Sicherheitsaspekte“, Internationaler ETG-Kongress 2013, VDE VERLAG GMBH, Berlin/Offenbach, 2013.

[7] S. Altschäffl, R. Witzmann, T. Ahndorf, „Generating a PSS™NETOMAC model of the German Transmission Grid from Google Earth and visualizing load flow results“, IEEE International Energy Conference ENERGYCON, Dubrovnik, 2014.

[8] G. Kerber, „Aufnahmefähigkeit von Niederspannungsverteilnetzen für die Einspeisung aus Photovoltaikkleinanlagen“, Dissertation, Fakultät EI, Technische Universität München, 2011.

[9] E. van Ruitenbeek, “Impact of Large Amounts of Photovoltaic Installations in Low-Voltage Networks on Power System Stability During TransmissionSystem Faults”, Master thesis, Electrical Sustainable Energy, Delft University of Technology, Delft, 2014. [To be published Online: repository.tudelft.nl].

[10] Amprion GmbH, TenneT TSO GmbH, TransnetBW GmbH, „Netzentwicklungsplan Strom 2012“, 2012.

[11] S. Dierkes, F. Bennewitz, M. Maercks, L. Verheggen, A. Moser, „Impact of Distributed Reactive Power Control of Renewable Energy Sources in Smart Grids on Voltage Stability of the Power System“, Electric Power Quality and Supply Reliability Conference (PQ), Rakvere, 2014.

[12] Deutsche Energie-Agentur GmbH. (2015, June). Stromumwandlung durch Transformatoren. [Online]. Available: http://www.effiziente-energiesysteme.de/themen/intelligente-stromnetze/stromumwandlung.html

[13] Deutsche Energie-Agentur GmbH, „dena-Verteilnetzstudie: Ausbau- und Innovationsbedarf der Stromverteilnetze in Deutschland bis 2030.“, Berlin, 2012.

[14] S. Altschäffl, R. Witzmann, „Analyse von Spannungstrichtern in Folge von Kurzschlüssen im deutschen Übertragungsnetz“, Power and Energy Student Summit (PESS), Dortmund, 2015.

[15] S. Altschäffl, R. Witzmann, „Effect of reduced rotating inertia on expansion of voltage dips caused by three-phase faults in the German power transmission network“, 23rd International Conference on Electricity Distribution, Lyon, 2015.