DEVELOPMENT OF AVAILABLE SHORT-CIRCUIT POWER IN GERMANY FROM 2011 UP TO 2033

Andreas KUBIS Sven RÜBERG Christian REHTANZ
TU Dortmund - Institute of Energy Systems, Energy Efficiency and Energy Economics - Germany
andreas.kubis@tu-dortmund.de sven.rueberg@tu-dortmund.de christian.rehtanz@tu-dortmund.de

ABSTRACT

This paper is an excerpt of an extensive study about the development of short-circuit power in Germany due to the changing generation portfolio from 2011 up to 2033. The study identifies that the bandwidth between minimum and maximum available short-circuit power will only change slightly. Nevertheless, the short-circuit power at certain nodes will change significantly. Despite the decreasing number of conventional generators, the short-circuit power will increase due to grid enforcements. Furthermore, considerations need to be made whether inverter coupled RES should be committed to provide a short-circuit current contribution even in situation without primary energy carrier supply.

INTRODUCTION

Due to the public and political will to prioritize the generation of electrical power from renewable energy resources (RES), more and more ‘green’ generating units enter the European power system. As it is targeted that by the year 2020 20 % of the European energy consumption shall be provided from RES [1], a considerable amount of conventional power generation from synchronous generators will go out of service. Before this background, it is expected that the available amount of short-circuit power will significantly change: On the one hand, a study of TenneT TSO in the Netherlands predicts an increase of short-circuit power of their control area over the next years due to the increasing number of grid assets connected to the Dutch grid [2]. They substantiate this prognosis by a set of short-circuit current measurements. On the other hand, a study of Fraunhofer IWES in Germany expects a decreasing short-circuit power level in the German power system due to the foreseeable replacement of conventional synchronous machines by inverter coupled generating units which are not capable of providing short-circuit currents as high as those ones of synchronous machines [3].

Both the aforementioned contradictory predictions and the importance of sufficient short-circuit power for the reliable detection of asset failures and the provision of an acceptable voltage profile in general make a detailed analysis desirable. Therefore, this paper presents the main results of a detailed analysis for the years 2011 and 2033 [4] and is structured as follows: First, the aggregated network model and the representative scenarios that are used are presented. Second, a set of short-circuit calculations according to IEC 60909 (DIN VDE 0102) [5] is performed for the German transmission network and selected 110-kV distribution systems in Germany, taking into account a mutual exchange of short-circuit power between the transmission and the distribution system through the intertie transformers on the one hand and the short-circuit power capabilities of the distribution grid itself (including a supposed short-circuit power support provided by inverter coupled RES units) on the other hand. Finally, the obtained results are interpreted and the importance of the supposed short-circuit support from RES units is discussed.

MODELING

The short-circuit calculations are performed using a model of the European power system that consists of an aggregated transmission layer and a detailed distribution system. The grid injections (conventional power plants, HVDC converters, inverter coupled RES units etc.) are represented by standard models from EMTP libraries. Setpoints for loads and injections are determined by a market simulation taking into account the parameters of the reference scenario. Grid models, the generating-unit models and the reference scenario used are described in the following sections.

Grid Model

Transmission grid modeling

The transmission grid model is an aggregated representation of the European transmission layer that consists of approximately 200 380-kV nodes (of which 31 are located in Germany), approximately 550 transmission corridors and all relevant HVDC interconnectors. The aggregated model was identified by merging electrically close substations of the detailed transmission grid into aggregated 380-kV nodes and by merging the transmission lines between them into transmission corridors with appropriate power rating. Transmission grid reinforcements until 2033 have been considered according to the German Grid Development Plan (GDP) 2012 [6]. The detailed methodology of this aggregated grid modeling is described in [7].

Distribution grid modeling

The distribution grid model is a detailed representation of a German distribution layer that consists of approximately 60 110-kV nodes, 160 transmission lines, 7 interface transformers (380/110 kV) and 7 conventional power plants. This distribution system was verified to be a reasonable approximation of the ‘average’ German distribution system in terms of geographical size, transmission capacity, loading, conventional power generation, and RES penetration [4]. Detailed data of this distribution grid (including transmission line parameters, interface transformer parameters, load curves, and conventional unit commitment) was provided by the corresponding distribution system operator (DSO).

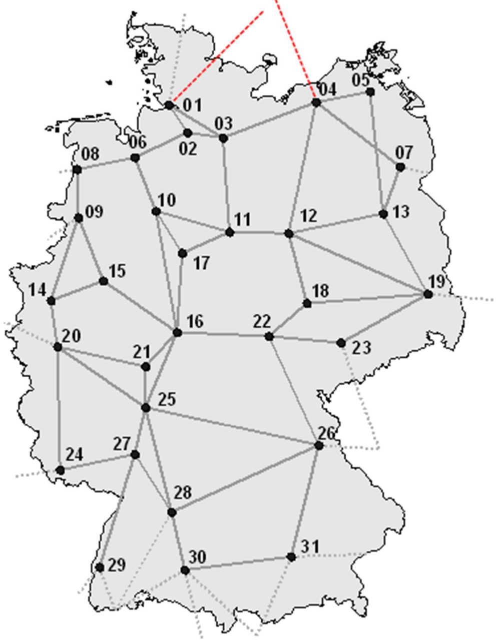

Figure 1: Geographic location of the considered German nodes

Generator and Load modeling

Conventional Power Plants

Conventional generating units are modeled by synchronous machines which are connected by a step-up transformer to the respective grid. The synchronous reactance X_{d}, the transient synchronous reactance X_{d}' and the subtransient synchronous reactance X_{d}'' are of high importance for short-circuit calculations. Thus, these parameters have been carefully determined by a linear approximation of real generator data from an institute internal database. Conventional power plants of different types and rated powers have been subdivided into groups of different synchronous generator sizes.

Renewable Energy Sources

RES are considered as self-commutating electronic power inverters with a dc voltage link. Their short-circuit behavior depends on the connected primary generation resource and the used inverter. At time of writing, there exists no valid standard about how inverter coupled RES should be considered in a short-circuit calculation. Hence, the short-circuit contribution of them was derived from the German fault-ride through requirements stated in the grid connection requirements [8]: Their short-circuit contribution depends on the voltage at their grid connection point during the faulty situation. By definition, inverter coupled RES with low or nearly no overload capability[1] are treated as minor short-circuit current contributors. Minor short-circuit current contributors have to provide 2 % of their rated current per 2 % voltage decrease in form of reactive current. Consequently, they have to contribute with their rated current, if the voltage drops below 0.5 pu. According to the current German grid connection requirements, inverters do not need to be oversized. Thus, the maximum short-circuit current contribution is assumed to be their rated current. For a trend analysis of the prospective short-circuit power development, it is sufficient to assume that all RES of the affected voltage level participate in the voltage support, while generators in other voltage levels do not participate due to their high electrical distance. This ensures the identification of the maximum possible short-circuit power of the observed network level.

Loads are considered as standard active-power and reactive-power loads with no dynamic behavior. It is self-evident that this representation does not reflect the reality, but in order to analyze the development of short-circuit power under consideration of increasing shares of RES, this representation enables the comparability.

Generator Unit Commitment

The generator unit commitment is an integral part for the analysis of the short-circuit power development. Thus, adequate modelling is necessary and done with the institute internal advanced market simulation model, which already performed well in several former studies like [4] and [9].

As mentioned above, this study focuses on the short-circuit power development in Germany. Due to this restricted observation area, it is sufficient to reduce the market simulation down to Germany and its neighboring states plus Italy in order to model the interdependencies with neighboring countries grids at failure situations in Germany.

Besides, the addition of generator capacity in form of RES, also displacement processes of fossil generators by RES have to be taken into account. In this study, we modelled the generator unit commitment based on German market restrictions including privileged RES infeed in compliance with technical restrictions, i.e. line loading conditions and compliance with operational voltage restrictions. The comparability for the observation of the influence of RES between the simulation years 2011 and 2033 is provided by assuming the same weather conditions and load demands for both calculations. The results of the market simulation are calculated for a whole year and the data of each hour is extracted for each transmission grid node. In the following, the results of each node are subdivided according to dependencies of the regional power plant diversity. For the accurate calculation of short-circuit current contribu-

1 The overload capability of an inverter coupled generator is defined by the ability of providing at least short-circuit currents twice as big as its rated current.

tions, it is furthermore necessary to subdivide the accumulated sums of generation and load demand over the voltage levels of interest. Therefore, the load demand is dispersed in the following way:

- transmission grid (≥ 220 kV): 30 %
- distribution grid (110 kV): 30 %
- distribution grid (< 110 kV): 40 %

In this study, a representative network expansion state with defined switching conditions in all scenarios is assumed in order to guarantee comparability.

REFERENCE SCENARIOS

Scenario Modeling

For the analysis of low and high short-circuit current contributions of RES units, their contributions are considered independent from meteorological conditions in two extreme-value scenarios: Scenario 1 reflects the highest expectable short-circuit current level, while scenario 2 focuses on the lowest. Basis for the maximum scenario is the hour of the respective year with the largest share of conventional power plants connected to the power grid. In this case, the short-circuit current contribution of RES units is considered in addition to the ones of conventional generators due to the technical inherent properties of inverter based generators, which are capable of providing reactive currents in any case.

In the following, this paper excerpts the major results of the analysis of maximum short-circuit power on transmission level and minimum short-circuit power on distribution level. Please note that all presented and further details including additional variant calculations are extensively explained in the full study [4].

RESULTS

Short-Circuit Calculation

All short-circuit calculations are performed according to DIN EN 60909 (DIN VDE 0102), which is an established standard for grid planning purposes. In the following, three-phase (3-ph) short-circuits at the bus bars of each node in the German grid model are recognized for this analysis. For the consideration of maximum short-circuit currents, the voltage factor c_{max} is assumed to be 1.1 and RES units contribute with their rated power to the short-circuit power. In minimal case, RES units do not contribute and the voltage factor c_{min} is set to 1.0.

Transmission Grid

The following explanations are referring to exemplary nodes. A comprehensive overview of all considered nodes and their geographic location is depicted in Fig. 1. The transmission grid evaluation is based on the maximum extreme-value analysis (scenario 1) of the short-circuit power development. In this scenario, node 20 is the node with the highest available short-circuit power. Thus, this node is considered as reference for all other observation spots. An overview about the relations between all other nodes compared with the largest in 2011 is depicted in Fig. 2. Nodes with large short-circuit power (e.g. nodes 14, 20 and 27) represent industrial areas in western and southern Germany. Nodes in more likely rural areas (e.g. nodes 4, 5 and 7) represent the nodes with the smallest amount of short-circuit power.

Fig. 3 shows the relative change of short-circuit power in 2033 compared with 2011. The chart should be interpreted in the way that positive values represent an increase and vice versa. Obviously, the short-circuit power may differ more than 100 %; it may increase and decrease significantly. However, nodes with large values will also have large values in 2033 and face only moderate deviations.

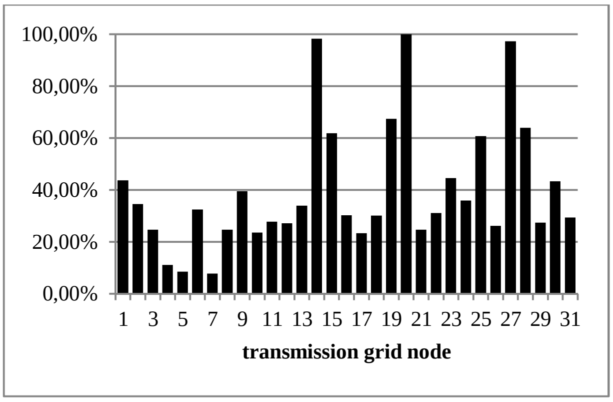

Figure 2: Representation of the short-circuit power in 2011 based on the node with the largest short-circuit power (node 20) in 2011

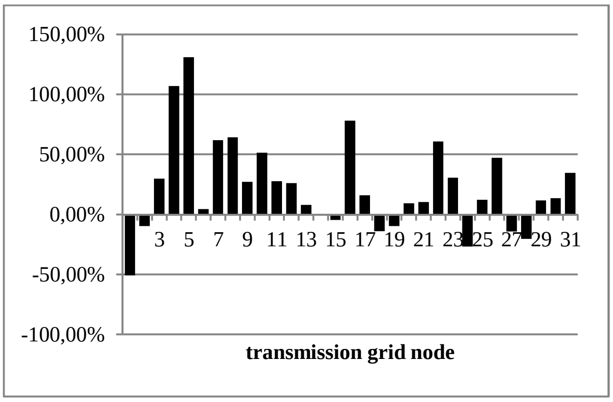

Figure 3: Relative changes in the maximum short-circuit power at each node in 2033 relative to 2011

Table 1 shows the available short-circuit power for 3-ph short-circuits at each transmission node under consideration of the contribution from the distribution grid compared with the above discussed isolated consideration referred to the minimum and maximum extreme value cases. The additional contributions of the underlying distribution networks increase the available short-circuit power in every case. Nodes in rural areas face explicitly contributions of at least more than 15 % in minimum case and 10 % in maximum case, which can be traced back to contributions from RES units.

Distribution Grid

According to DIN EN 60909 (DIN VDE 0102), any short-circuit current contribution of inverter coupled generators can be neglected at minimum short-circuit power calculations. In some 110-kV exemplary distribution grids situations have been identified in which no conventional power plants will be in operation. Thus, the remaining short-circuit power capacity of such an isolated 110-kV distribution network is 0 MVA, if contributions from loads are neglected. From distribution grid perspective, the determination of minimum short-circuit powers in combination with the 380-kV network is of high importance.
In the following, the 110-kV distribution network is calculated in combination with the 380-kV transmission network in order to assess the short-circuit power development in the distribution network in interaction with the transmission network. The trend analysis of short-circuit power development on distribution level is done by comparing 3-ph short-circuits at each distribution network node for both scenarios.

Table 1: Relative short-circuit power at 380-kV busbar short circuit taking into account the contribution from the 110-kV level

year	rural node		industrial node	
	min	max	min	max
2011	116.0 %	110.8 %	101.5 %	101.8 %
2033	115.2 %	109.5 %	101.7 %	102.7 %

Fig. 4 shows the results for the 110-kV network, which underlies a transmission node in a rural area, as explained in the transmission network analysis. Here, the calculated values for the short-circuit power of each node in 2033 refer to the values in 2011. The largest change in short-circuit power is about 124 % in the maximum and 121 % in the minimum case. The absolute highest available value of short-circuit power in 2033 will increase about 24 % compared to 2011. In 2033, the absolutely lowest available short-circuit power is about 2 % higher than in 2011. Thus, the necessary absolute minimum values for the short-circuit power will not be underrated.
Analogous, the results for the industrial 110-kV distribution network area are depicted in Fig. 5. The largest increase in short-circuit power is about 154 % in the maximum case. In the minimum case, the short-circuit power will reduce down to 61 % of 2011. The absolute highest value of short-circuit power will decrease to 84 % in 2033 compared with 2011. Like in the rural area, the absolute lowest value will stay nearly equal at about 99 % of 2011. Thus, the necessary absolute minimum values for the short-circuit power are maintained.

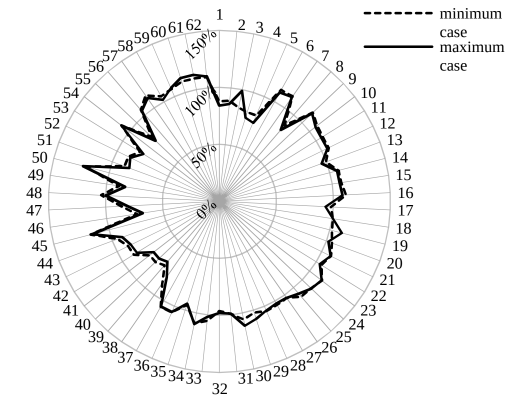

Figure 4: Relative changes of the short-circuit power from 2011 to 2033 in the minimum and maximum case at node in a rural area

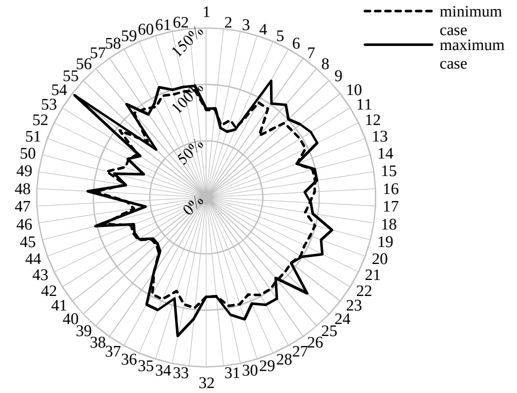

Figure 5: Relative changes of the short-circuit power from 2011 to 2033 in the minimum and maximum case at node in an industrial area

FURTHER RESULTS AND CONCLUSION

The analysis shows that nodes with high short-circuit power in 2011 will also have high short-circuit power in 2033. The available short-circuit power in industrial areas will also tend to be higher than the one of rural areas in the future. Nodes with low short-circuit power in 2011 will also have a low short-circuit power in 2033 compared with all other available nodes. Nevertheless, these nodes will face significant increasing short-circuit power, in some cases even more than 100 % compared with their values of 2011. The bandwidth between lowest and highest available short-circuit power in Germany will only change slightly. However, significant changes within this bandwidth have been observed. The average available short-circuit power in Germany tends to increase about 20 %. All in all, the short-circuit power extreme values of 2011 will not fall below or exceed the values of 2033, but the distribution will change.
Moreover, the largest share of RES units will be connected to the distribution networks. The analysis shows that the prospective available short-circuit power will be highly dependent of the weather situation and the daytime. An exemplary calculation with an isolated 110-kV network revealed that situations in which no conventional power plants as well as no RES units will be in operation, in this particular 110-kV network, are possi-

ble. This may happen in a windless night. Thus, this network is not able to retain short-circuit power. However, in combination with the transmission network, acceptable short-circuit power levels have been identified. Nevertheless, the available short-circuit power increased about 30 to 40 % in 2033 compared with 2011 in situations in which photovoltaic and wind generators were in operation. Thus, the available short-circuit power is subject to fluctuations over daytime in dependency of the overall installed RES power particularly if RES units are out of operation at situations without primary energetic supply, for example photovoltaic systems at night. In order to mellow this volatility, it should be taken into consideration that weather depending RES units should stay grid connected at any time, in order to provide the ancillary service short-circuit power. The technical feasibility is discussed in the full study [4]. However, there is no sufficient financial compensation approach existing in Germany, yet.

It is remarkable that in some regions the available short-circuit power increases even if the installed generator capacity is reduced. This rise cannot be fully explained with an increasing share of short-circuit power from neighboring countries. Moreover, it was determined that this increase is based on contributions from German generation units. A detailed variant analysis in the full study identified that these increases are reasonable due to following facts: The reduced generator capacity in the near of faulty locations leads to a reduction of the instantaneously available short-circuit power from nearby generators, which is necessary for accurate voltage support. Thus, the reduction of nearby short-circuit power flattens the voltage cone, whereby farther generators contribute with higher short-circuit currents due to lower voltages at their grid connection points. Grid enforcements further enhance this effect, because they will lead to a tighter coupling between the remaining generators and will decrease the electrical distance between generators and fault locations.

It is not observed that significantly more short-circuit power is provided by generators from neighboring countries in 2033 than in 2011. Admittedly, the origin may change. Nevertheless, the question remains if in future more or less foreign generators might be involved in the short-circuit power provision at faults on the German grid side. Due to the limited available data regarding the regional grid and generation development of the European partner grids, this question could not be solved in this study.

It is expected that unmanageable high short-circuit currents from the primary equipment's point of view are unlikely. Nevertheless, further studies with detailed data should be done in order to analyze the interdependencies of the changing short-circuit power environment especially in medium voltage networks which were out of scope of this study. Furthermore, optimal asset management strategies for adapting to the changing conditions may be derived. In addition, the effects of changing short-circuit power as well as changing voltage profiles during failures should be carefully analyzed in order to readjust protection settings of used protection equipment.

REFERENCES

[1] European Commission, 2010, “The EU Climate and Energy Package”, Online: *http://ec.europa.eu/environment/climat/climateaction.htm*

[2] A.L.J. Janssen, M. van Riet, R.P.P. Smeets et al., 2012, “Prospective Single and Multi-Phase Short-Circuit Current Levels in the Dutch Transmission, Sub-Transmission and Distributions Grids”, *CIGRE Session 44*, A3-103

[3] B. Valov, 2013, “Änderungen der Kurzschlussleistung – Künftiges Energieversorgungssystem gemäß NEP 2012”, EW – Zeitschrift für Energiewirtschaft, vol. 14, 50-55 (in German)

[4] Deutsche Energie-Agentur (dena) GmbH, 2013, *dena-Studie Systemdienstleistungen 2030 - Sicherheit und Zuverlässigkeit einer Stromversorgung mit hohem Anteil erneuerbarer Energien*, Berlin, Germany (in German)

[5] Association for Electrical, Electronic & Information Technologies (Verband der Elektrotechnik Elektronik Informationstechnik e.V., VDE), 2001, *DIN EN 60909-0 (VDE 0102): Kurzschlussströme in Drehstromnetzen*, German version of standard IEC 60909-0

[6] 50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, TransnetBW GmbH, 2013, *Netzentwicklungsplan Strom 2013 – 2. überarbeiteter Entwurf der Übertragungsnetzbetreiber*, Berlin, Germany (in German)

[7] U. Häger, C. Rehtanz, N. Voropai (Eds.), 2014, *Monitoring, Control and Protection of Interconnected Power Systems*, Springer, Berlin, Germany

[8] Verband der Netzbetreiber e.V. (VDN), 2004, „*EEG-Erzeugungsanlagen am Hoch- und Höchstspannungsnetz: Leitfaden für Anschluss und Parallelbetrieb von Erzeugungsanlagen auf Basis erneuerbarer Energien an das Hoch- und Höchstspannungsnetz* (in German).

[9] Deutsche Energie-Agentur (dena) GmbH, 2012, *dena-Verteilnetzstudie*, Berlin, Germany (in German).

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