EFFECT OF REDUCED ROTATING INERTIA ON EXPANSION OF VOLTAGE DIPS CAUSED BY THREE-PHASE FAULTS IN THE GERMAN POWER TRANSMISSION NETWORK

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ABSTRACT

In Germany a massive change is going on concerning the generation of electrical energy. On the one hand, conventional power plants are more and more substituted by distributed renewable energies. This leads to a significant reduction of rotating inertia. On the other hand, all nuclear power plants will be shut down by the end of the year 2022. A large amount of permanent grid connected rotating inertia will then be lost. Consequently, provided system services like voltage support, short-circuit current and short-circuit capacity are decreased during three-phase faults in the transmission network. In order to get impressions of the effect of reduced rotating inertia on expansion of voltage dips, different scenarios regarding changes of the residual load and the number of active power plants are investigated and the averaged affected load for Germany and its constituent regions is determined. Affected load is defined as residual load where the voltage magnitude at the connection node is below a certain value. It is calculated by using the results of root-mean-square simulation of a dynamic AC model of the German power transmission network in PSS^TM^NETOMAC. Comparing the development of affected load in all scenarios leads to basic statements about the effects of reduced rotating inertia on expansion of voltage dips by three-phase faults.

INTRODUCTION

In Germany all nuclear power plants will be shut down by the end of the year 2022 as decided by the government [1]. Consequently, permanent active rotating inertia with more than 12 GW installed capacity will be lost. Moreover the installed capacity of renewable energies will grow further in the future and there will be periods of time with very low residual load and thus a small number of active conventional power plants. This will lead to a change in the expansion of voltage dips caused by three-phase faults in the German transmission network.

Model of power transmission network

For these studies a detailed AC model for root-mean-square simulation is needed. The generation of the model is explained in [2] and [3]. It is a PSS^TM^NETOMAC model of the 380 kV and 220 kV voltage levels of the

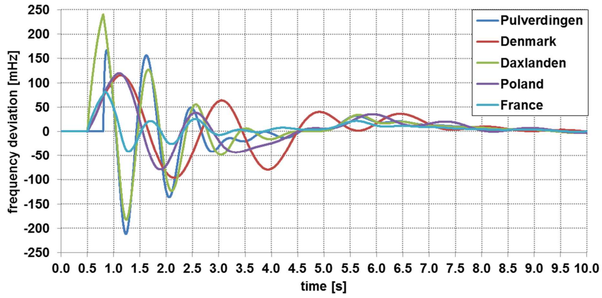

Figure 1: Frequency deviations after a 300 ms three-phase short-circuit in the south-west of Germany at the substation Pulverdingen

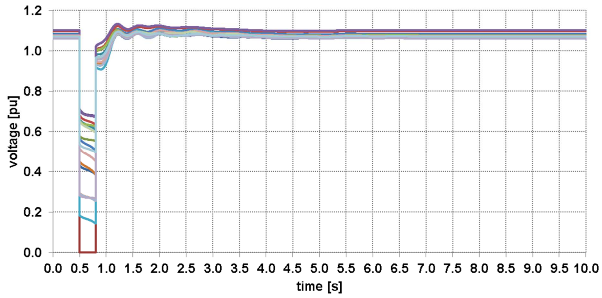

Figure 2: Voltages at different nodes near the fault location after a 300 ms three-phase short-circuit in the south-west of Germany at the substation Pulverdingen

German power transmission network with 380/220 kV, 380/110 kV and 220/110 kV transformers and generators connected to these voltage levels. Load is connected to the 110 kV buses and can be regarded as residual load, as the infeed of generators and renewable energy sources on lower voltage leveles is not considered.

The dynamic behavior of frequency and voltage in the model due to a 300 ms three-phase short-circuit in the south-west of Germany at the substation Pulverdingen is shown in Figure 1 and Figure 2. Compared to [4] the system reacts as expected in reality and the model gets back to a stable state. This is achieved in all regarded scenarios.

Table I: Generation, load and import for each scenario

Scenario	Generation [GW]	Load [GW]	Import [GW]
2012	40.0	45.3	5.3
2012rL1	40.0	39.4	0.0
2012rL2	34.2	33.9	0.0
2022	40.2.	45.3	5.3
2022rL1	40.2	39.4	0.0
2022rL2	34.4	33.9.	0.0

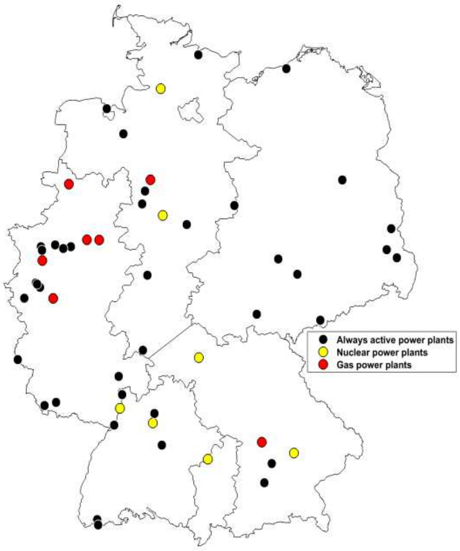

Figure 3: Locations of active power plants in the scenarios

Description of scenarios

To analyze the effect of reduced rotating inertia, six load flow scenarios as shown in Table I are considered. The basic scenarios are called *2012* and *2022*. Each scenario has the same load and import values, but the generated power differs by 0.2 GW. This is a consequence of changes concerning the active power plants. In scenario *2022* eight nuclear power plants (see Figure 3) with generating power of 7.9 GW in scenario *2012* are shut down. The missing generation is compensated by the other power plants raising their utilization and regarding the infeed of new generators at existing power plant locations. As the generated power has to be transported over longer distances higher losses are produced and the generation in *2022* is slightly increased.

In the scenarios *2012rL1/2022rL1* and *2012rL2/2022rL2* the load is reduced by two steps. The first reduction step leads to a final load of 39.4 GW (87% of original load). The generation of power plants is not changed, but the import of neighbor countries is reduced to zero. The second step leads to a change of active power plants again. Gas power plants (see Figure 3) with 5.3 GW installed capacity in 2012 and 6.7 GW installed capacity in 2022 are deactivated and generation of remaining power plants is reduced to supply finally 75% of the original load.

All scenarios are based on the same topology concerning the number and types of transmission lines and transformers. But to realize different load flow scenarios the reactive power compensation has to be adapted in order to achieve a realistic voltage profile between 1.0 pu and 1.1 pu in each scenario. The influence of additional compensation facilities on the expansion of voltage dips is regarded as negligible in comparison to the change of rotating inertia.

Method

In order to assess the expansion of voltage dips, 223 three-phase faults are simulated at substations and nodes using RMS-simulation. Germany is subdivided in five regions as shown in Figure 4 and the number of fault locations in each region is given in Table II. Thereby it is possible to get individual results for each transmission system operator in Germany and the dependency of the location in Germany can be investigated. The results of each simulation are time-domain voltage curves of every node in the 380 kV and 220 kV voltage level as shown in Figure 2 and in combination with the information of line impedances, maximum short-circuit current and the short-circuit capacity at each considered fault location are calculated as described in [2]. This information can be displayed for each three-phase fault and each scenario, as shown in Figure 5 and Figure 6. Furthermore, all loads connected to 110 kV busbars with a voltage lower than 1.0 pu are summed. The final results are presented as mean values of all simulated faults in each region with the occurred maximum and minimum value at a single fault location.

Table II: Number of fault locations in each region

TransnetBW	50Hertz	Amprion	Tennet (North)	Tennet (South)
35	47	78	43	20

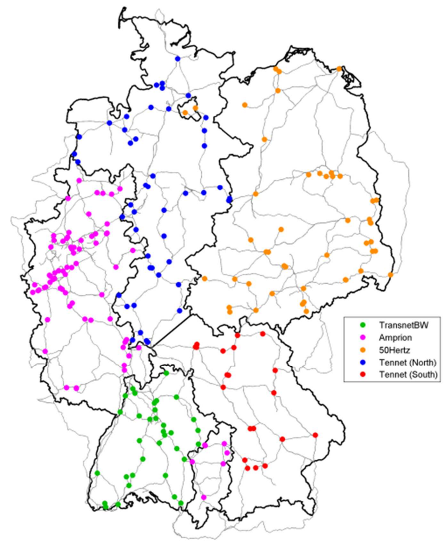

Figure 4: 223 fault locations in the German power transmission network

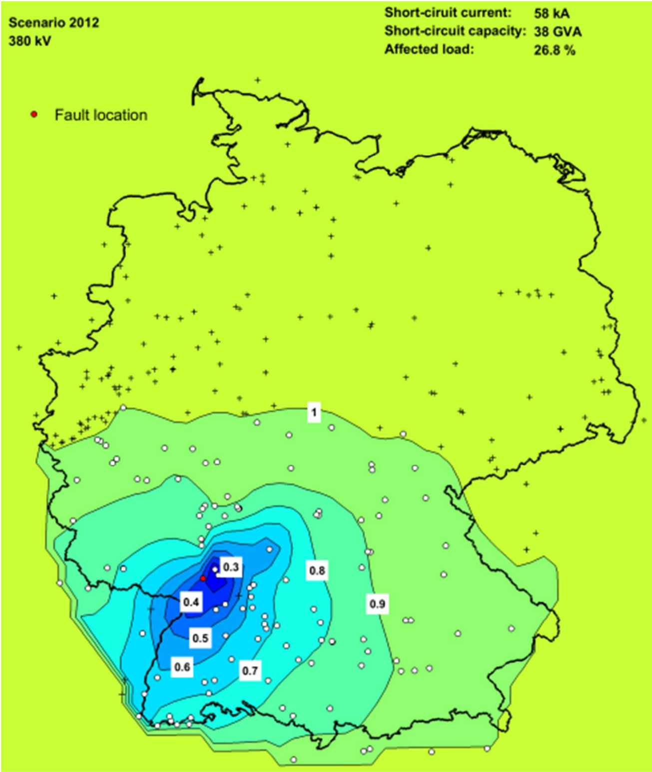

Figure 5: Voltage dip expansion during three-phase fault at substation Pulverdingen in scenario *2012*

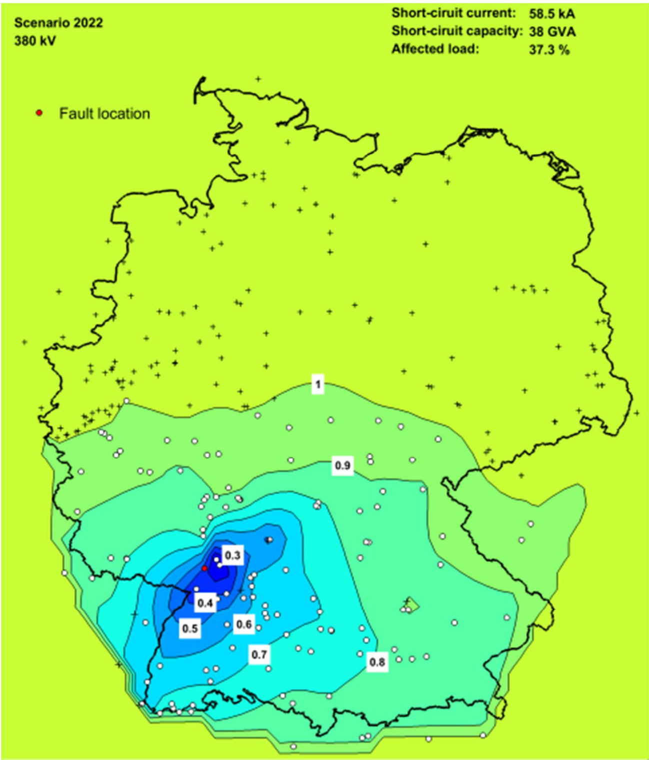

Figure 6: Voltage dip expansion during three-phase fault at substation Pulverdingen in scenario *2022*

RESULTS

Results are presented in a comparative way. Always two results of different scenarios are presented in one diagram. It is therefore possible to compare the results by taking into account the differences between the scenarios. The affected load is subdivided into load connected to the 220 kV and 380 kV voltage levels. Thereby differences in the effects on the 220 kV voltage level can also be observed.

<u>Scenarios *2012/2022*</u>

Basic scenarios are compared in Figure 7. Firstly, looking at the development in Germany it can be seen that there is an increase of affected load of ~2.5 percentage points due to a shut-down of rotating inertia of 12 GW. The minimum affected load caused by one three-phase fault stays constant with about 4.8%, but the maximum affected load goes up to 63.6%. The increase of affected load on the 380 kV voltage level is higher than on the 220 kV voltage level. This happens due to the shut-down of the nuclear power plants, which are mainly connected to the 380 kV voltage level. Three-phase faults in the transmission network of Amprion lead to the most affected load because this is the area with the highest load density [5]. On the other side, faults in the area of 50Hertz cause the lowest affected load values. However, in general an increase of affected load is given in all parts of Germany.

<u>Scenarios *2012/2012rL1* and *2022/2022rL1*</u>

Reduction of residual load in 2012 has just a small effect on the affected load, as shown in Figure 8. The averaged affected load in each area differs at most by 0.4 percentage points (Amprion). In the south of Germany (TransnetBW and Tennet South) the affected load even decreases slightly.

In general these small differences between both scenarios are due to changes of the active and reactive power distribution in the 380 kV and 220 kV voltage level. Because the import is reduced to zero, there are significant changes of the power flows on the transmission lines which lead to different reactive power flows. Thereby the expansion of voltage dips is also different.

The same effects can be observed in 2022 (see Figure 9). The differences between both scenarios increase in comparison to the year 2012, but they are still below 1%. However, the maximum affected load during one three-phase fault increases significantly in scenario *2022rL1* to 65.5% in the area of Tennet (North). Finally, it is obvious that reduction of residual load does not have a big effect on the averaged affected load for Germany and each regarded area. Only single fault locations have to be considered in order to realise appropriate measures to limit the affected load.

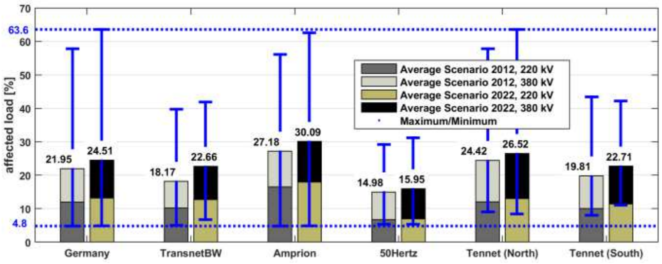

Figure 7: Affected load in scenarios *2012* and *2022*

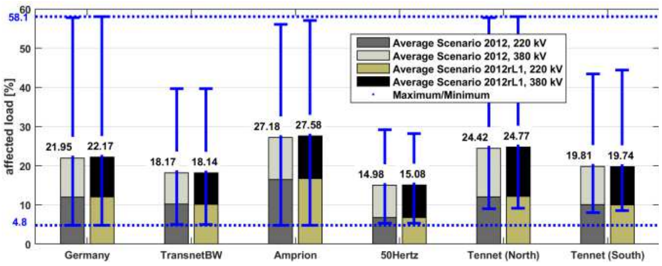

Figure 8: Affected load in scenarios *2012* and *2012rL1*

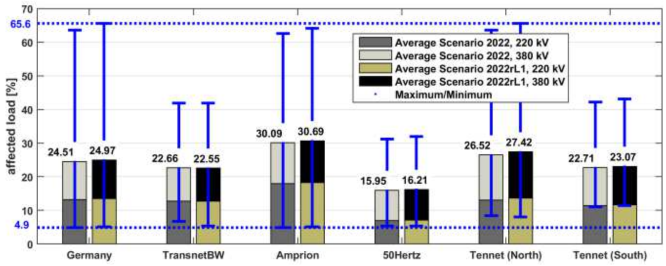

Figure 9: Affected load in scenarios *2022* and *2022rL1*

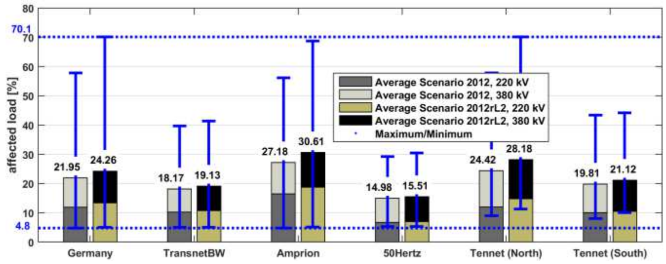

Figure 10: Affected load in scenarios *2012* and *2012rL2*

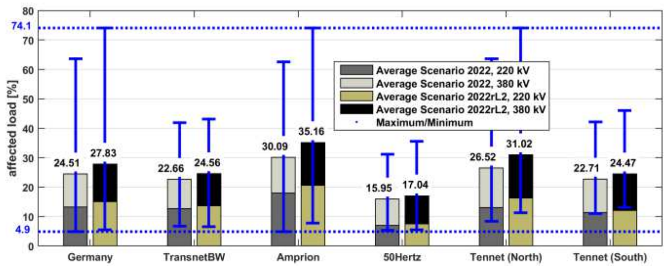

Figure 11: Affected load in scenarios *2022* and *2022rL2*

Scenarios *2012/2012rL2* and *2022/2022rL2*

Further reduction of load to 75% of the original value in combination with loss of rotating inertia leads to the values shown in Figure 10 and Figure 11. Average affected load for Germany in 2012 rises to a number close to the value of scenario 2022. There is a remaining difference of 0.25 percentage points. This means that a decreasing residual load with simultaneous deactivation of conventional gas power plants (5.3 GW) has the same effect as shutting down all nuclear power plants in 2022. In the areas of Amprion and Tennet (North), the affected load even exceeds the value in 2022. This shows that the location of the deactivated power plants also has a significant effect on the expansion of voltage dips during a three-phase short-circuit. The maximum affected load due to one fault reaches 70.1% in the area of Tennet (North) in scenario *2012rL2*. This is an increase of 12 percentage points.

In the scenario *2022rL2*, the situation worsens further. Due to the additional reduced rotating inertia of 6.3 GW, the averaged affected load in Germany increases by 3.3 percentage points compared to scenario *2022*. Faults in the area of Amprion lead to an average affected load of more than 35%. Here the increase is more than 5 percentage points as several gas power plants are located in that area (see Figure 3). The maximum of 74.1% is detected in the area of Amprion.

Overview of results

Table III and Figure 12 show an overview of all mentioned results concerning the effect of reduced rotating inertia in Germany on the affected load. Regarding scenario *2012rL2*, it can be clearly seen that reduced residual load in combination with deactivation of power plants in an area with high load density of Germany (Amprion) leads to a similar value of affected load as in scenario *2022*, where the reduced rotating inertia is more than two times higher. The correlation of reduced rotating inertia and averaged affected load in Germany is obvious. However, looking at smaller areas within Germany, the dependency between the location of deactivated rotating inertia and affected load grows. Comparison of scenarios *2012rL2* and *2022* in Figure 12 shows that the three-phase faults in the area of Amprion and Tennet (North) lead to a decreased averaged affected load, but in the area of TransnetBW it increases as nuclear power plants are shut down in that area (see Figure 3).

SUMMARY AND CONCLUSION

In this paper, the effect of reduced rotating inertia due to decreasing residual load is investigated. For this investigation, a dynamic AC-model of the German power transmission network in PSS^{TM}NETOMAC is used. The behavior of the dynamic model after a three-phase short-circuit is shown based on voltage and frequency deviation plots. To analyze the effect, six different scenarios are set up. There are changes in residual load and the capacity of rotating inertia connected to the grid. The network topology stays always the same. After explaining the method for determination of the affected load in Germany, the results are presented in a comparative way.

Table III: Change of affected load in comparison to scenario *2012* (percentage points)

Scenario	2012rL1	2012rL2	2022	2022rL1	2022rL2
Reduced rotating inertia [GW]	**0.0**	**5.3**	**12.0**	**12.0**	**18.3**
Reduced residual load [GW]	**5.9**	**11.4**	**0.0**	**4.9**	**11.4**
Germany	0.22	2.31	2.56	3.02	5.88
TransnetBW	-0.03	0.96	4.49	4.38	6.39
Amprion	0.4	3.43	2.91	3.51	7.98
50Hertz	0.1	0.53	0.97	1.23	2.06
Tennet (North)	0.35	3.76	2.1	3	6.6
Tennet (South)	-0.7	1.31	2.9	3.26	4.66

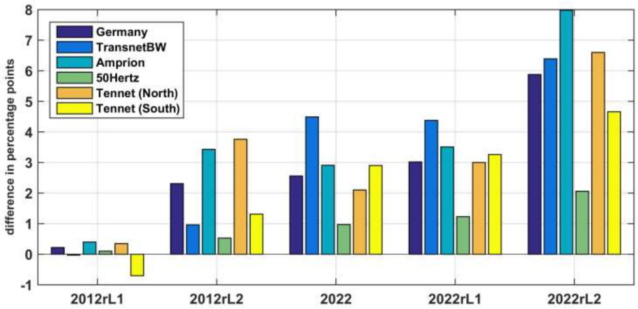

Figure 12: Change of affected load in comparison to scenario *2012*

The following points summarize the results:

- Today and 2022 reduced residual load without changing active power plants (reducing import) leads to changes of averaged affected load smaller than 1% in Germany and all regarded areas.
- Today further reduction of residual load in combination with deactivation of power plants according to merit order leads to comparable averaged affected load values as in 2022 after shut-down of all remaining nuclear power plants.
- Values of averaged affected load caused by three-phase short-circuits for each regarded area depend on the locations of deactivated power plants. Averaged affected load increases in areas with many deactivated power plants due to lower provision of short-circuit current and thereby increasing expansion of voltage dips.
- In the future, the impact of single three-phase short-circuits on the affected load increases significantly. These fault locations have to be regarded individually.

As there will be an increasing amount of renewable energies in Germany, the residual load will be further reduced or even become negative. This means that conventional power plants (rotating inertia) will also be deactivated over longer periods of time. The occurrence of a three-phase short-circuit during these periods will have a growing impact on the network stability and the supplying quality of customers. Suitable measures, e.g. installation of Flexible AC Transmission Systems (FACTS) devices or use of shut-down generators as phase shifters, must be realized in order to quickly provide additional short-circuit current.

In future work, the influence of distributed generation of renewable energies on the expansion of voltage dips and network stability has to be investigated.

IMPACT ON THE DISTRIBUTION SYSTEM

The results show that it is necessary to rework the grid connection requirements for renewable energies, especially on the low voltage level. In Germany, for example, there is no requirement for low voltage ride through capability on the low voltage level at the moment [6]. So with growing expansion of voltage dips the disconnected capacity will increase and in a worst-case scenario it could lead to stability problems in the network of continental Europe as the primary control power of 3 GW could be exceeded. Finally distribution system operators have to expect new guidelines concerning the behavior of decentralized generating plants during voltage dips. Possible requirements are low voltage ride through, voltage support by current infeed and specification of the post-fault active power recovery.

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