Comparison between Static and Dynamic Curtailment of RES in Probabilistic High Voltage Distribution Grid Planning

Pascal WIEST, Simon EBERLEIN
Institute of Power Transmission and High Voltage Technology,
University of Stuttgart – Germany
pascal.wiest@ieh.uni-stuttgart.de

Krzysztof RUDION
Institute of Power Transmission and High Voltage Technology
University of Stuttgart – Germany
rudion@ieh.uni-stuttgart.de

Alexander PROBST
Netze BW GmbH - Germany
a.probst@netze-bw.de

ABSTRACT

This paper is addressing the issues regarding reduction of the necessary network expansion by taking flexibility options into account. If a certain amount of the annual energy from renewable generation is curtailed, the expansion of the power grid can be reduced. This paper presents a comparison of the necessary expansion of a high voltage distribution grid (110kV) under consideration of different curtailment approaches for renewable energy sources. Here, the necessary expansion is calculated, if a static or a dynamic curtailment is applied and then compared with the calculations without any curtailment mechanism. The curtailment methods are tested using a probabilistic expansion planning method based on the calculation of probabilistic load flow.

INTRODUCTION

The massive increase of renewable energy sources (RES) in Germany, which are often installed in the distribution grid, leads to a change from passive to active distribution grids [1]. This process results in new requirements for planning of distribution grids [1]-[3]. Especially, the uncertainty of the volatile power feed-in from RES has to be investigated in detail [2]. Additionally, new control schemes and innovative grid components have to be applied into new planning methods [4]-[6]. Therefore, time series and probabilistic methods are often applied into the distribution grid planning [4]-[7]. New control schemes are introduced to reduce the necessary grid reinforcement [4], [8] or to increase the hosting capacity of RES [9], respectively. According to [10], a cost-optimal solution for the grid reinforcement needs to consider a curtailment of RES.

In case of high voltage distribution grids, a power feed-in from the downstream networks defines more and more the necessary network expansion [7]. However, the power feed-in from RES reaches only for a short time during the year the nominal power, since it has a dependency to their primary energy, as e.g. solar radiation in case of photovoltaics (PV) [4]. Therefore, the necessary grid expansion can be significantly reduced, if an amount of power feed-in can be curtailed, which, however, leads to a reduction of the annual energy yield. According to [4] & [8], only a small amount of curtailed energy is necessary to reduce significantly the grid reinforcement. Additionally, since 2016 the German transmission and distribution system operators are allowed, by the German Energy Act to curtail up to 3% of the annual energy of PV and onshore wind turbines within the planning process to reduce their grid reinforcement [11]. Usually, the curtailment of RES is separated in a static approach, where a fixed limit of the power feed-in is applied continuously, and a dynamic approach, where the power feed-in is only reduced, if a technical limit within the grid is reached.

This paper presents a comparison of static and dynamic curtailment within distribution grid planning for high voltage distribution grids. Therefore, the methodologies for both curtailment approaches are presented first. Afterwards, the curtailment methods are compared within a planning study of a real German high voltage distribution grid. Here, the differences in the line loadings Λ, the power flows in the connection points to the downstream grids and the curtailed annual energy are compared to each other. Finally, the benefits of both methods are highlighted.

METHODODLGY FOR CURTAILMENT OF RES

Within a static curtailment, the maximum power feed-in is defined regardless of the grid state. An alternative to that is a dynamic curtailment, where the power feed-in is only reduced, if a technical constraint is reached. Both approaches are explained in this section and the pros and cons are highlighted. In case of dynamic curtailment an approach using distribution factors as in [4] is used.

Static Curtailment

As example for the static curtailment, Figure 1 shows a measured annual duration curve for a wind turbine. Here, only the 4000 hours with the highest active power are shown.

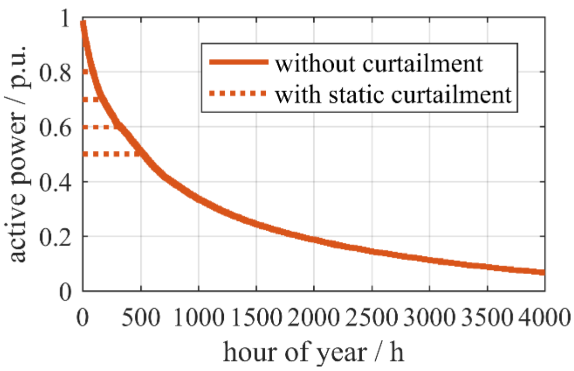

Figure 1: Static curtailment for different limits in case of wind turbine

Without any curtailment, the wind turbine only reaches for a small duration of the year a power generation near their nominal value. With the dotted lines in Figure 1, the static curtailment is marked for several limits of the maximum power generation. Here, values between 90% and 50% of the nominal value are shown. It can be seen, that in case of a static curtailment up to 50% of the nominal value only for approximately 500 h in the year the power feed-in is reduced. This results in an overall curtailed energy of about 8%.
The static curtailment can be easily implemented in the system operation since the limits can be decentral adjusted in the generation units [10]. Therefore, no communication is necessary. However, the static curtailment may lead to high curtailed energies, since it is possible that the power feed-in is continuously reduced, even if any technical constraint of the grid is reached.

Dynamic Curtailment

In contrary to the static curtailment, a dynamic curtailment only reduces the power feed-in if a technical constraint is reached. According to [10], a significant reduction of the curtailed energy is possible, however, a communication system is necessary, which may lead to higher operational costs. A communication system is needed, since the reference values for the curtailment have to be continuously provided to the RES generation units by the distribution system operator (DSO) according to the current grid state. In this work no comparison of the costs for such system is done due to their wide variance [10], which would not lead to representative conclusions.
In case of high voltage distribution grids, the technical constraints are usually the line loadings Λ since the voltage magnitudes are not decisive due to the high X/R ratio. Since the high voltage distribution grid has a meshed structure, the main question is, which impact has power feed-in from RES at some grid node to the power flows at a particular line. Similar to [4], those impacts are calculated in this paper by using a linearization of the power flow equations.

Calculation of Nodal Power

In this paper the power flow equations are linearized by using distribution factors. These, distribution factors are calculated with the superposition theorem and the non-linear AC power flow equations as in [4]. By using the linearization, the active power flows can be calculated with:

$$\mathbf{P}_{Line} = \mathbf{ACDF}_P \cdot \mathbf{P}_{Node} \qquad (1)$$

where $\mathbf{ACDF}_P$ is the active power distribution factor matrix, $\mathbf{P}_{Line}$ is the vector of active power flows and $\mathbf{P}_{Node}$ is the vector of nodal active power. The elements of the $\mathbf{ACDF}_P$ matrix express in (1) the impacts of the nodal active power on the power flows over the grid branches. A similar formulation is used for the reactive power flows with the assumption of a decoupled load flow. With (1), on the one hand the power flows in the grid can be approximated and on the other hands, a required change of a single nodal power to influence the power flow in a particular line can be calculated. Further information regarding the calculation scheme of the dynamic curtailment can be found in [4].
Other formulations for the linearization of the power flow equations, as e.g. Power Transfer Distribution Factors (PTDF) in [12] can also be applied. By using a linearization with superposition theorem and the AC power flow equations, the $\mathbf{ACDF}_P$ matrix of (1) has a dependency to the operation point. However, a sensitivity analysis has shown that the errors are negligibly small [4].

COMPARISON OF CURTAILMENT IN GRID PLANNING STUDY

The comparison of both curtailment methods is presented in this section within a planning study of real German high voltage distribution grid. First of all, there is a brief overview of the input data modelling and the simulation process.

Input Data for Planning Study

To consider a further increase of RES, the model of [13] is used to calculate the input time-series of the power flows to the downstream grid in the connection substations. Only a further increase of PV and wind turbines is considered, since it is expected that the installed capacity of these two technologies will further increase in the future. For the loads in the downstream grids, measurement data is used similar to [4]. In contrary to [4], the forecast of RES is updated which will result in different line loadings Λ compared to the results in [4]. In the considered planning study, the installed capacity of PV is 1891 MW and of wind turbines 1729 MW. At the same time the maximum load in the grid equals 1102 MW. Therefore, the installed RES capacity is about 3.3 times the maximum load which will result in high line loadings in case of a high power feed-in of RES.

Overview of the Simulation Process

An overview of the simulation process is given in Figure 2. In case of a static curtailment, the power feed-in from RES is reduced up to the given limit and the time-series based probabilistic load flow (PLF) is calculated afterwards. By using the dynamic curtailment, first the power flows are approximated using the distribution factors to prove, if a line loading limit is exceeded. In this work several limits of the maximum line loadings are simulated. By using the distribution factors, the reduction of the power feed-in from RES can be calculated to control the power flows.
Based on the results of the PLF, the curtailed energy of RES and the reduced line loadings can be compared. Since the topic of this work is the comparison of the curtailment methods, the PLF is implemented with a

Monte Carlo (MC) simulation with overall 35040 iteration points. This is equal with the duration of one year with a resolution of 15 minutes and allows a comparison of the annual curtailed energy. To compare if this number of iterations models the total maximum, a second PLF with a higher number (864000) of iteration is performed. Figure 3 show the maximum loadings of each line for both PLF calculations. As shown in Figure 3, the maximum line loading Λ decreases with the number of iteration. Since a comparison of the curtailment approaches is performed in this work, the lower number of iterations is further on used. Additionally, Figure 3 shows that the considered grid needs to be reinforced since the line loading Λ is over 100 % during normal operation which would be the technical constraint. The high voltage distribution grids are planned with the (n-1)-security, which is not considered in this work.

Comparison of Line Loadings

To compare the influences of the different curtailment methods, Figure 4 shows the maximum of the loadings for the particular lines. Here, only the maximum is shown, since the aim of the curtailment in the distribution grid planning is to reduce the maximum line loading, which is responsible for grid reinforcement. For the static curtailment a limit for the power feed-in of RES is chosen to 60% of their nominal power. In case of the dynamic curtailment, the limit of the line loading Λ is 100%. The limit in the dynamic curtailment is chosen since it is the technical constraint and in case of the static curtailment to get a comparable result for maximum line loadings.

For the first lines (No. 1-15), the differences in the curtailment methods can be seen. While the dynamic curtailment controls the line loadings to the given limit, the static method also reduces the maximum line loading but each line has an individual maximum line loading Λ.

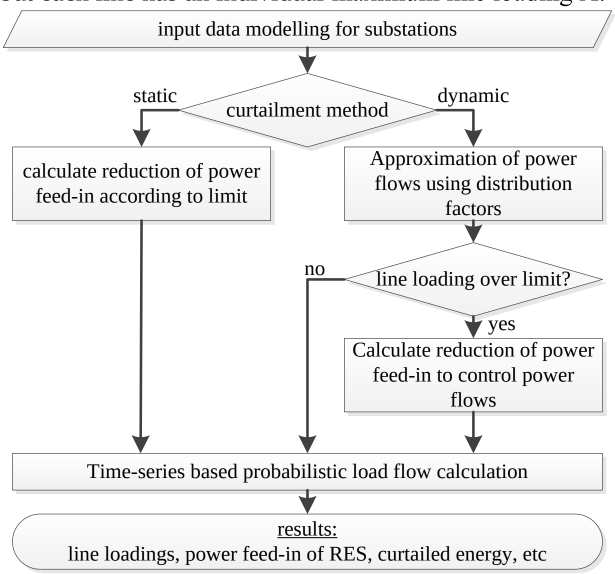

Figure 2: simulation process for the comparison of static and dynamic curtailment

Especially for the first lines, the limit of the static curtailment of RES is not sufficient to fulfill the technical constraint of 100% of the line loading Λ. Here, the dynamic approach is more reasonable, since a limit of the line loading can be reached. An exception of this is the 28th line, where the dynamic curtailment leads to a higher line loading. Here, the overlaying transmission system has an influence to the high voltage distribution grid, which can only be modelled in a simplified manner by using the linearized ACDF approach. This effect results in an error in the dynamic curtailment and a further investigation is necessary to model the overlaying transmission system. Remarkable are also the lines 65-70, where the dynamic curtailment leads to higher line loadings. Here, the reduction of individual generation units leads to higher line loadings. For the control of the line loadings a dynamic curtailment is beneficial, as shown in Figure 4, but a second criterion is the influence on the residual power of the substations to the downstream grid, which is analyzed in the next section.

Comparison of Residual Power at Substation

The different methods of curtailment lead to different power flows to the downstream grid because the power feed-in of RES is also reduced in the downstream grid. The reduction of the power feed-in can furthermore be seen in the residual load of a substation. To compare the results, a substation near the 5 highest loaded lines in Figure 4 is chosen. Since the reduction of the line loading of those lines is much higher in case of the dynamic curtailment, the curtailed annual energy must also be higher at this substation. Figure 5 shows a section of the annual duration curve for this substation.

In Figure 5, negative active power values correspond to a power feed-in. The curtailed energy is expressed by the areas between the lines with and without curtailment. Here, it can be seen that the dynamic curtailment at this substation leads to a higher curtailed energy, which results in the higher reduction of the line loadings. Remarkable at the annual duration curve is that no fixed limit is reached in case of the static curtailment, which is a result from the energy consumption.

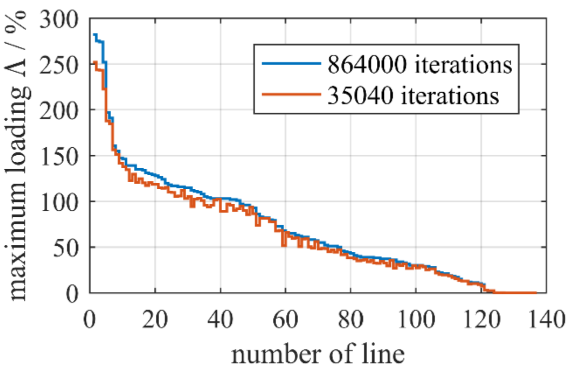

Figure 3: comparison of maximum line loading between annual simulation and probabilistic load flow

Additional, the annual duration curve shows that the dynamic curtailment leads to a residual power of 0 MW for several hours of the year. This results from a restriction in the implementation of the dynamic curtailment, where the power feed-in of RES at the substation is only reduced up to a residual power of 0 MW. This restriction is chosen since only the residual power at the substation is known. To express the mode of operation of the two curtailment methods, Figure 6 shows two exemplary days of the same substation.

As shown in Figure 6 the highest power feed-in at the substation is about midday in case, where no curtailment is used. This can be related to the high power feed-in of PV. At midday of the first day (shown by the first 12:00 hour value on the x-axis in Figure 6), the line loadings makes it necessary to reduce the power feed-in of RES up to an active power of 0 MW at this substation. In contrary to that, the static curtailment only reduces the power feed-in according to the fixed limit. However, in this case it is not enough to reduce the power flows to a given limit and line loadings above 100% will occur. Significantly different is the behavior of the second day (visible at the second 12:00 hour value on the x-axis in Figure 6). In this case a higher reduction of the power feed-in of RES can be seen with a static curtailment approach. Such a reduction of the power feed-in as in case of the static curtailment approach is not necessary for the reduction of the line loadings, which can be seen by the results of the dynamic curtailment.

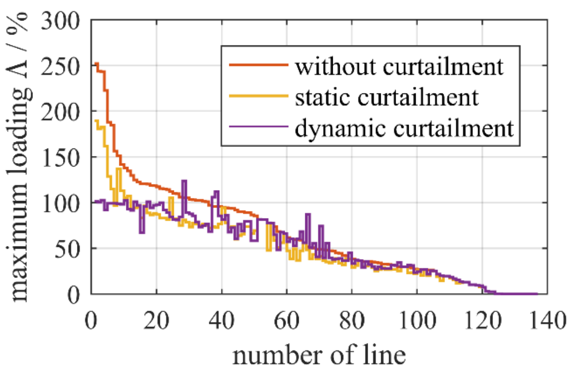

Figure 4: maximum line loadings for different curtailment methods

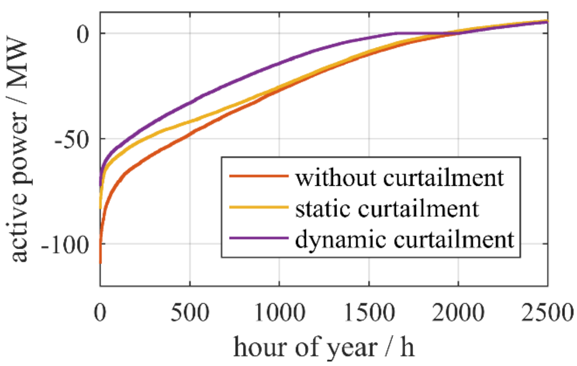

Figure 5: annual duration curve of one substation

Comparison of Curtailed Annual Energy

Both methods for curtailment lead to a reduction of the line loadings. For the DSO, the curtailed annual energy is decisive, since it corresponds to the resulting costs of compensation. Therefore, Figure 7 shows a comparison of annual curtailed energy for all substations and generation units in the considered grid. The values are normalized with overall power feed-in from RES at the particular substation or generation unit. At some substations, the amount of curtailed energy is much higher in case of the dynamic curtailment. Those substations are placed in areas, where the line loadings exceed the allowable limits, which makes such a high curtailment necessary.

Remarkable is that only 29 out of 153 substation and generation units reduce their power feed-in in case of the dynamic curtailment. The curtailment at all other substations, as applied by the static approach, is not necessary, since those substations are not responsible for the line loading above their technical limit. As shown in Figure 7, this results in an overall lower curtailed energy with the dynamic curtailment approach. With the dynamic method only 3.5% of the annual energy of RES is curtailed, while in case of the static method the curtailed energy is 6.2%.

Comparison for Different Limits

By changing the limits for the curtailment methods, it is possible to compare, which curtailed energy is necessary for a certain reduction of the maximum line loading Λ. In case of the static curtailment, the limit for the power feed-in is varied and the resulting maximum line loading is calculated. For the dynamic curtailment, the limit of the maximum line loading is defined and the curtailed annual energy is calculated. The results for those calculations are given in Figure 8.

Figure 8 shows that the static curtailment leads to higher curtailed energies for the same reduction of the maximum line loading compared to the dynamic approach. This can be related to the fact that the static approach reduces the power feed-in from RES even, if there is no technical constraint.

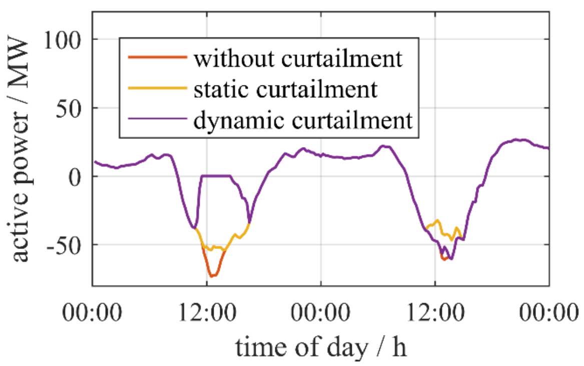

Figure 6: active power of substation for two exemplary days

Remarkable is also in Figure 8 that the dynamic curtailment leads to very low energies in case of a lower reduction of the maximum line loading. This is a result of the very low probability of occurrences for the high line loadings, which is similar to the result in [4]. For example, if the maximum line loading in this grid will be reduced from 250% to 150% only 0.9% of the annual energy from RES has to be curtailed.

CONCLUSION

This paper presents a comparison of a static and dynamic curtailment for RES analysed by a planning study of a real German high voltage distribution grid. In general, the results show that a dynamic approach is beneficial, since it needs for the same reduction of the maximum line loading significantly lower curtailed annual energy from RES. Additionally, the static curtailment approach is not able the reduce the maximum line loading to a given limit, since it only limits the power feed-in from RES without consideration of the current grid state. The results show that for a significant reduction of the maximum line loading only a very low energy from RES has to be curtailed. Since the considered network is strongly meshed, the dynamic curtailment has a generalized usability for all distribution grids. Therefore, the necessary grid reinforcement can be massively reduced by applying a dynamic curtailment approach.

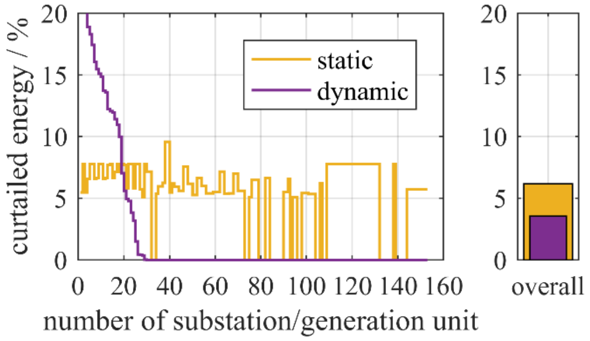

Figure 7: Comparison of annual curtailed energy for all substations or generation units

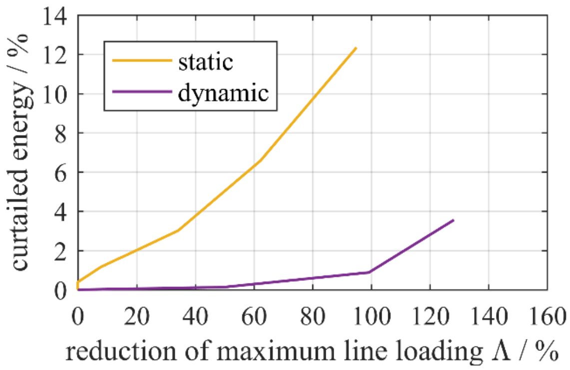

Figure 8: Curtailed energy for different reductions of the maximum line loading

Acknowledgment

The authors would like to thank Netze BW GmbH for the provision of grid data and measurements.

REFERENCES

[1] CIGRE WG C6.19, “Planning and Optimization Methods for Active Distribution Systems”, *CIGRE Technical Brochure*, 2014.

[2] F. Pilo, G. Celli, E. Ghiani and G.G. Soma, “New electricity distribution network planning approaches for integrating renewable”, *WIREs Energy Environ*, 2013, 2: 140-157 doi:10.1002/wene.7

[3] A. Keane, L. F. Ochoa, et. al., “State-of-the-Art Techniques and Ahead for Distributed Generation Planning and Optimization”, *IEEE Trans. on Power Systems*, Vol. 28, No. 2, May 2013.

[4] P. Wiest, K. Frey, K. Rudion, A. Probst, “Dynamic Curtailment Method for Renewable Energy Sources in Distribution Grid Planning “, *IEEE PES General Meeting*, Boston, USA, July 2016.

[5] A. Seack, J. Kays, C. Rehtanz, “Time series based distribution grid planning approach with decentralized voltage regulation”, *18th Power Systems Computation Conference*, Wroclaw, Poland, 2014.

[6] S. Eilenberger, et. al., “Modern Voltage Regulation Methods for Network Planning and Operation in Low Voltage Grids”, *IEEE PowerTech 2015*, Eindhoven, Netherlands, 2015.

[7] P. Wiest, K. Rudion. A. Probst, “New Hybrid Planning Approach for Distribution Grids with a high Penetration of RES”, *CIRED 2015*, Lyon, June 2015.

[8] J. Büchner, A. Moser, M. Uslar, “Moderne Verteilernetze für Deutschland”, *Study for the German Federal Ministry for Economic Affairs and Energy*, 2014.

[9] E. Wieben, T. Kumm, M. Rohr, M. Stadler, “The 5 % Approach for maximizing the Grid Connection Capacity in Energy System dominated by Renewables”, *VDE-Kongress*, Frankfurt, Germany, 2014.

[10] T. Bongers, J. Kellermann, M. Franz, A. Moser, “Impact of Curtailment of Renewable Energy Sources on High Voltage Network Expansion Planning”, *19th Power System Computation Conference*, Genova, Italy, 2016.

[11] German Energy Act, “Gesetz über die Elektrizitäts- und Gasversorgung (Energiewirtschaftgesetz – EnWG)”, 2016.

[12] M. Liu, G. Gross, “Effectiveness of the Distribution Factor Approximation used in Congestion Modeling”, *14th Power System Computation Conference*, Sevilla, Spain, 2002.

[13] P. Wiest, K. Rudion, A. Probst, “Weather Data-based Load Profile Modelling for Grid Expansion Planning”, *IEEE PowerTech 2015*, Eindhoven, Netherlands, 2015.