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Simulation of Incidental Distributed Generation Curtailment to Maximize the Integration of Renewable Energy Generation in Power Systems

Ingo Liere-Netheler *, Frank Schuldt, Karsten von Maydell and Carsten Agert

DLR Institute of Networked Energy Systems, Carl-von-Ossietzky-Str. 15, 26129 Oldenburg, Germany; Frank.Schuldt@dlr.de (F.S.); Karsten.Maydell@dlr.de (K.v.M.); Carsten.Agert@dlr.de (C.A.)

* Correspondence: Ingo.Liere-Netheler@dlr.de; Tel.: +49-441-99906-457

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Abstract: Power system security is increasingly endangered due to novel power flow situations caused by the growing integration of distributed generation. Consequently, grid operators are forced to request the curtailment of distributed generators to ensure the compliance with operational limits more often. This research proposes a framework to simulate the incidental amount of renewable energy curtailment based on load flow analysis of the network. Real data from a 110 kV distribution network located in Germany are used to validate the proposed framework by implementing best practice curtailment approaches. Furthermore, novel operational concepts are investigated to improve the practical implementation of distributed generation curtailment. Specifically, smaller curtailment level increments, coordinated selection methods, and an extension of the n-1 security criterion are analyzed. Moreover, combinations of these concepts are considered to depict interdependencies between several operational aspects. The results quantify the potential of the proposed concepts to improve established grid operation practices by minimizing distributed generation curtailment and, thus, maximizing power system integration of renewable energies. In particular, the extension of the n-1 criterion offers significant potential to reduce curtailment by up to 94.8% through a more efficient utilization of grid capacities.

Keywords: power system operation; power system security; renewable energy integration; load flow analysis; congestion management; distributed generation curtailment

1. Introduction

The integration of distributed generators (DGs), such as wind turbines or photovoltaics, causes formerly unknown load flow situations that can endanger the operational security of power systems. In Germany, particularly in rural areas, the increasing installation of DG systems coincides with low hosting capacities due to the historical dimensioning of the network [1]. Hence, violations of operational security limits, such as overvoltage problems or thermal overloadings of grid components, can occur more frequently [2]. To prevent this, grid operators are required to enhance existing congestion management regimes. In the long term, grid expansion and reinforcement measures are required to ensure larger DG penetrations without jeopardizing the operational security of power systems. However, several studies have analyzed the grid expansion demand in Germany and agreed that the provision of a system without any bottlenecks solely through grid expansion or reinforcement is neither the most efficient solution at the distribution level (≤110 kV) [3] nor at the transmission level (≥220 kV) [4]. Consequently, an efficient utilization of existing grid capacities through operational congestion management approaches will become more relevant in the future in times of high renewable feed-in [5].

In the literature, a wide range of congestion management regimes is investigated. Market design approaches, such as nodal pricing or market splitting [6], consider network restrictions in the trading stage and therefore prevent congestions from the outset. Technical solutions, such as control of generation [1], consumption [7], or power flow controlling devices [8], are used to solve congestions in short-term network security management. These can further be subdivided into market-oriented and direct congestion management measures [9]. Market-oriented approaches require contractual agreements between grid operator and flexible consumers or generators, respectively. Local flexibility markets are a possible organizational form of these agreements. However, these markets face challenges regarding illiquidity, lack of customer participation, and regulatory problems [10]. Direct congestion management measures are executable by the grid operator without the necessity of additional agreements. These can either be the application of controllable grid components, such as switching actions, or the control of generation or consumption in emergency situations [9].

In Germany, both transmission system operators (TSOs) and distribution system operators (DSOs) are allowed to temporarily reduce the power injections of DGs to maintain grid security in critical situations. DG operators are then legally required to reduce their power generation output. Hence, this measure constitutes a direct emergency action and is called feed-in management (FIM). Although DG curtailment can only be exploited as a last resort in Germany [1], a significant historical increase of these measures can be observed. In 2017, FIM caused annual costs of approximately 610 M€ because each curtailed DG was financially compensated [11]. Consequently, reducing DG curtailment offers the potential to both significantly reduce the costs for congestion management and increase the hosting capacity of power systems for renewable energy generation. The remainder of the paper will thus focus on optimizing the practical implementation of DG curtailment as a congestion management measure.

Therefore, this work presents a simulation framework for DG curtailment based on load flow analysis. Different operational aspects to enhance grid capacity utilization compared to the recent best practice are investigated. Consequently, this work demonstrates possibilities to improve the practical implementation of DG curtailment and, thus, maximize the integration of renewable energy generation into power systems.

Several studies have examined selected aspects of DG curtailment as an operational congestion management measure. The effect of increasing the controllability of DGs on the resulting curtailment demand is analyzed in [1]. The authors show that the amount of curtailed energy can be reduced by controlling small scale DGs individually and thus increasing the granularity of curtailment measures. In [12] a linear state estimation algorithm and a remedial action scheme are developed and used to determine the optimal amount of DG curtailment based on the DC power flow model. The algorithms enable the substitution of preventive DG curtailment by offering fast automated control actions. The authors of [13] show that a curtailment strategy based on power flow sensitivities can reduce the amount of power adjustments compared to established principles of access in the United Kingdom. The substitution of DG curtailment by fast-reacting curative congestion management measures is investigated in [5]. The authors show that capacities of the transmission network can be utilized more efficiently, if fast-reacting measures, such as phase shifting transformers, are implemented. Reference [14] proposes a congestion management regime including multiple voltage levels simultaneously. The results indicate optimization potentials regarding the coordination between grid operators of different voltage levels. In [15], potentials for reducing the demand for redispatch and DG curtailment in the transmission network through dynamic line rating are depicted.

The above articles analyze selected aspects and their influence on DG curtailment. However, to the best of the authors' knowledge, neither a comparative study taking into account multiple operational aspects simultaneously nor the validation of curtailment simulations based on real grid data have been carried out yet. One of the main contributions of this paper is thus the development of a curtailment simulation framework and its application to the model of a real 110 kV distribution network from a region located in Germany. To validate the simulated amount of DG curtailment, recent best

practice approaches are first implemented into the framework and the results derived from load flow simulations are compared to curtailment measures from real grid operation. Another main contribution of this work is the proposal of three novel operational concepts to improve grid capacity utilization in critical operating states. These concepts include increasing the grid operator's ability to control DG units by implementing smaller curtailment level increments, improving DG selection methods with a special focus on increasing the coordination between different grid operators and adapting the deterministic n-1 security criterion to maximize DG integration. Furthermore, combinations of the proposed concepts are investigated to demonstrate possible interdependencies. The concepts are implemented into the simulation framework and their potential to reduce the incidental amount of renewable energy curtailment compared to the best practice is quantified. Hence, by combining the proposal of different operational concepts and their implementation into the validated model of a real distribution network, this work extends the existing research in the field by quantifying the influence of several operational aspects on DG curtailment and by depicting potentials to maximize DG integration into power systems by enhancing the utilization of existing transmission capacities.

The remainder of the paper is structured as follows. Section 2 introduces the simulation framework and discusses different operational aspects influencing DG curtailment. The current best practice regarding these aspects in grid operation and concepts to improve the practical implementation are discussed. Section 3 includes a description of the 110 kV distribution grid model and the validation based on the simulation of best practice curtailment as a reference scenario. Furthermore, scenarios for the implementation of the proposed concepts are defined and simulation results for each of the scenarios are presented, summarized, and discussed. Section 4 concludes the most relevant findings of the paper.

2. DG Curtailment Simulation Framework

The process of DG curtailment is influenced by different operational aspects. This section describes the consideration of different aspects in the developed simulation framework. Because the model of a real distribution network of a region located in Germany is investigated as a case study in this paper, recent best practice approaches applied there are described as an exemplary specification of the considered aspects. Furthermore, inefficiencies of these approaches are discussed and used to derive concepts to improve the practical implementation of DG curtailment.

2.1. DG Controllability

Grid operators can request the reduction of power generation of DG units but are not allowed to directly control these. Instead, generation units receive curtailment requests and are required to realize the requested power output reduction. The maximum permitted power injection $P_{inj,max}$ of a DG unit requested by a grid operator can be formulated as:

$$P_{inj,max} = l_{curt} \cdot P_{nom} \text{ with } l_{curt} \in \Omega_{curt} \tag{1}$$

where P_{nom} describes the nominal capacity of the DG unit and l_{curt} the requested percentage level included in the feasible set of all possible curtailment levels Ω_{curt}. Recently, the established granularity of curtailment levels is four discrete output levels [1]:

$$\Omega_{curt,established} = [1,\ 0.6,\ 0.3,\ 0]$$

Here, the curtailment level of 1 is used to cancel previously requested commands and allow the maximum possible feed-in again. The ability of grid operators to request the most efficient amount of DG curtailment is thus limited due to their limited control opportunities. As a consequence, the practically curtailed power feed-in can exceed the theoretically necessary amount of power reductions to solve congestions in certain situations, which can result in an inefficient utilization of transmission capacities [1]. Therefore, implementing an extended feasible set of curtailment levels

with smaller increments can potentially enable the request of more efficient measures and reduce the amount of incidental renewable energy curtailment compared to the best practice.

2.2. DG Selection Procedure

In addition to requesting the most suitable curtailment level of a DG unit, usually multiple generation units in different locations can potentially terminate grid congestions. Thus, grid operators have to select which DG units to curtail. This selection process has to satisfy all technical constraints, reach the practical minimum of curtailment, and avoid discrimination of specific generation units [1]. However, several studies have shown that minimizing curtailment and sharing the amount of power adjustments between multiple DGs equally are contrary objectives and a trade-off between both aspects has to be found [16,17].

2.2.1. DG Selection Methods

The recent best practice in Germany is to curtail DGs iteratively based on their sensitivity to congested grid components [18]. Following this curtailment strategy, the most sensitive unit is curtailed first. If congestions remain after completely reducing the power output of the first unit, the second most sensitive unit is selected, etc.

The sensitivities can either be derived from simplified DC load flow models or from nonlinear AC models. The advantage of DC models is the independence of the recent grid state. Hence, these sensitivities can be calculated once and used permanently. In contrast, the AC formulation has a higher accuracy but requires separate calculation of sensitivity values for each grid state [19] In this work, the sensitivities are derived from the AC load flow model and calculated for each grid state separately. Sensitivities enable the approximation of the relation between changes in real and reactive branch power flows and changes in nodal real and reactive power injections as follows [20]:

$$\begin{bmatrix} \Delta\mathbf{P}_{\text{branch}} \\ \Delta\mathbf{Q}_{\text{branch}} \end{bmatrix} = \mathbf{M} \cdot \begin{bmatrix} \Delta\mathbf{P}_{\text{inj}} \\ \Delta\mathbf{Q}_{\text{inj}} \end{bmatrix} \tag{2}$$

where $\Delta\mathbf{P}_{\text{branch}}$ and $\Delta\mathbf{Q}_{\text{branch}}$ are the vectors of real and reactive power flow changes over all considered grid components, such as lines or transformers, $\Delta\mathbf{P}_{\text{inj}}$ and $\Delta\mathbf{Q}_{\text{inj}}$ are the vectors of changes in nodal real and reactive power injections, and $\mathbf{M}$ is the sensitivity matrix of the system. Each value of $\mathbf{M}$ approximates the effect of a change in power injection in a certain node in the network on a certain grid component for one specific power flow solution. Accordingly, power flow sensitivities can be used to determine the most sensitive DG unit to certain congested grid components.

However, the iterative selection scheme in combination with discrete curtailment level increments minimizes the number of necessary curtailment requests but does not necessarily lead to the minimum possible amount of curtailed power. This is due to the fact that the most sensitive unit can, e.g., be a large wind farm and only be curtailed in relatively large discrete steps, whereas smaller units with smaller possible curtailment levels with an equally large sensitivity are not considered.

To address this issue and enable the request of more efficient curtailment measures, the problem of selecting DG units can also be implemented in the simulation framework as an optimization problem aiming at minimizing the total amount of power reductions [20]:

$$\min_{x} f(x) = \sum_{i=1}^{n_u} \Delta P_i \tag{3}$$

where n_u describes the total number of available DG units and ΔP_i the curtailed power of unit *i*, which amounts to:

$$\Delta P_i = P_{i,init} - P_{inj,max} \tag{4}$$

where $P_{i,init}$ describes the initial power infeed and $P_{inj,max}$ the requested maximum power injection from Equation (1). Accordingly, the decision variables are discrete due to the discrete curtailment level increments which results in a mixed integer programming problem. Real power flow restrictions are displayed by the addition of constraints for each grid component:

$$P_{comp,init} + \Delta P_{comp} \leq P_{comp,max} \tag{5}$$

where $P_{comp,init}$ describes the real power flow over the considered grid component in the initial grid state, ΔP_{comp} the change in the real power flow due to DG curtailment, and $P_{comp,max}$ the maximum permitted power flow over the grid component. The power flow change can be written in terms of the power flow sensitivities of each DG unit on the respective grid component:

$$\Delta P_{comp} = \sum_{i=1}^{n_u} \frac{\partial P_{comp}}{\partial P_i} \cdot \Delta P_i \tag{6}$$

This optimization approach solely minimizes the amount of curtailed power, whereas the number of curtailment requests is not directly considered in the objective function. On the contrary, the best practice iterative approach curtails the least number of DGs and neglects the amount of reduced power output. However, grid operators might practically want to reach a certain objective, such as minimizing curtailment, with a limited number of control actions [21]. Therefore, a hybrid approach is also proposed as a candidate selection method in this paper, which aims at reducing the resulting renewable energy curtailment while limiting the complexity of the practical implementation by limiting the number of curtailment requests. The three considered selection methods are compared schematically regarding the amount of curtailment and the number of requests in Figure 1.

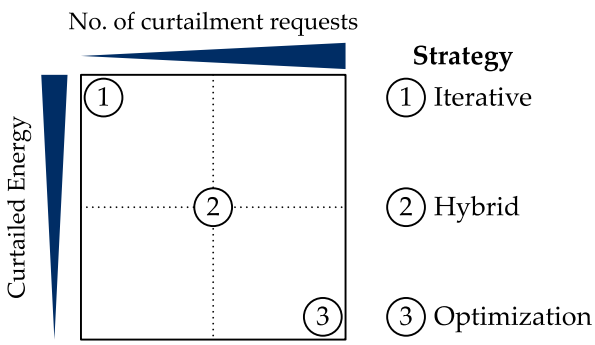


Figure 1. Schematic comparison of distributed generator (DG) selection methods regarding the resulting amount of curtailed energy and number of curtailment requests.

The hybrid selection method takes the number of curtailment requests into account by implementing a penalty term for each curtailment level leading to adjustments compared to the initial grid state ($\Delta P_i > 0$) in the optimization objective (Equation (3)). This can be interpreted as minimizing the total costs of curtailment consisting of a variable part depending on the amount of curtailment and a fixed part for each measure. The variable costs describe the financial reimbursement of curtailed DGs whereas the fixed proportion represents organizational expenses of grid operators (e.g., costs of billing curtailment). The optimization objective is thus adapted as follows:

$$\begin{gathered} \min_x f(x) = \sum_{i=1}^{n_u} \Delta P_i \cdot c_{var} \cdot \Delta t + p_c(\Delta P_i) \\ \text{with } p_c = \begin{cases} 0 \text{ if } \Delta P_i = 0 \\ c_{fix} \text{ else} \end{cases} \end{gathered} \tag{7}$$

The variable costs c_{var} are estimated based on the total amount of curtailed energy in Germany in 2017 and the respective amount of financial reimbursements, which amount to 610 M€ for 5518 GWh of curtailed energy [11], resulting in variable costs of 110 €/MWh. The penalty term p_c is set to 0 if no curtailment is requested and to a fixed cost parameter for curtailment requests. This fixed cost parameter c_{fix} directly influences the solution of the optimization problem. The higher this parameter, the higher the solution would prioritize the number of curtailment requests towards the amount of curtailed energy and vice versa. Due to the available data set in this work, the time interval Δt is set to 15 min or 0.25 h, respectively.

2.2.2. Influence of Grid Operator Coordination

Another issue reducing the efficiency of requested curtailment measures is the separate assessment of different power system levels. DG units can affect load flow situations both on the local distribution grid level and the superordinate transmission level. Consequently, DG curtailment is requested both by DSOs for preventing congestions at the distribution grid level and by TSOs to support grid operation at the superordinate transmission level in the course of an operative cascade [18]. TSO and DSO are only responsible for their own grid and request curtailment measures independently. Practically, measures requested by the TSO can also resolve congestions at the distribution level and vice versa. However, the separate security assessment and derivation of suitable curtailment measures carried out by each grid operator independently can cause redundant requests. Hence, this work proposes a coordinated curtailment procedure, which aims at finding the global optimal amount of DG curtailment. Therefore, grid restrictions at multiple system levels are considered simultaneously. Figure 2 visualizes the comparison of the established operative cascade and the proposed curtailment framework in this work.

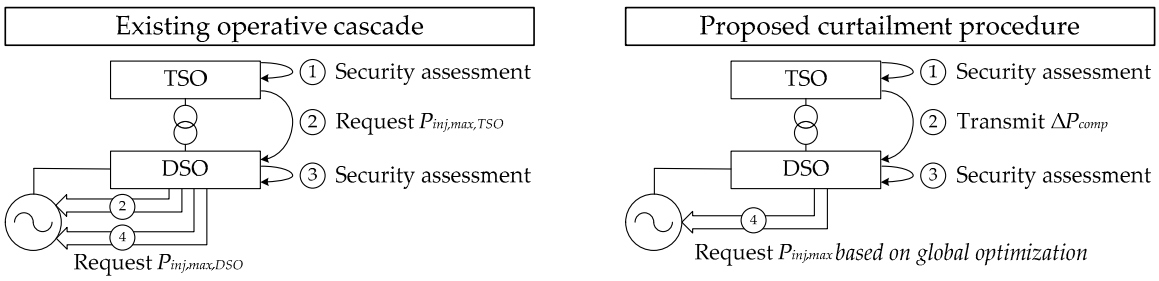


Figure 2. Comparison of established operative cascade and proposed curtailment procedure.

Following the existing operative cascade (left side of Figure 2), in the first step, the TSO assesses security criteria in its responsibility area (Step 1). If congestions, e.g., overloadings of transformers linking the transmission and distribution system, are identified, the TSO is allowed to send curtailment requests to the respective DSO. The DSO is then responsible for forwarding these signals to the respective DG units (Step 2). Additionally, the DSO determines the security state in its own responsibility area (Step 3), which can lead to additional curtailment requests (Step 4).

To avoid redundant or unnecessary curtailment requests, the proposed procedure aims at finding the global optimal amount of DG curtailment (right side of Figure 2). Therefore, grid restrictions of multiple system levels are considered simultaneously. Consequently, the TSO does not request DG curtailment directly but rather transmits the necessary power adjustments on all congested grid components ΔP_{comp} to the DSO (Step 2). These are added to the optimization problem as constraints and complemented by additional security constraints due to distribution network restrictions (Step 3). As a consequence, the optimization problem can be solved once considering all necessary security constraints simultaneously (Step 4). The operative cascade is also extensible for multiple grid operators on the distribution grid level by adding additional hierarchy levels. Because this work focuses on the 110 kV distribution level, subordinate grid levels are not represented in detail and the operational cascade only consists of two system levels.

2.3. Operational Security Assessment

The first step of the curtailment process is the security assessment carried out by the respective grid operator (Figure 2). Accordingly, the necessity and the extent of practical DG curtailment measures are also strongly influenced by the way power system security is assessed. This is done based on load flow calculation of the undisturbed base case and several credible contingency conditions [22]. Contingencies include the outage of a grid component or generation unit. The European Network of Transmission System Operators for Electricity (ENTSO-E) defines five different steady-state security states, namely normal, alert, emergency, blackout, and restoration [23]. The monitored security parameters contain the thermal loading of grid components, such as transmission lines and transformers, and the nodal voltages in the network.

The normal state is also referred to as n-1-secure and is reached if all parameters are within allowed operational limits both in the base case and in any contingency state. In this case, no correcting congestion management measures are necessary. The alert state is reached if at least one of the monitored parameters exceeds security limits in a certain contingency event. This state is also referred to as n-secure, since no limit violations are present in the undisturbed base case [24]. In the alert state, preventive congestion management measures are activated with the aim to return the system to a n-1 secure grid operation. This guarantees an a priori security margin for contingency events, which, however, leads to an inefficient utilization of transmission capacities in the undisturbed grid state since the considered contingencies are possible but not certain events. The emergency state is reached if operational limit violations occur in the undisturbed base case. Then, curative congestion management measures have to be realized. These include fast-reacting measures, which terminate congestions as quickly as possible. On the other hand, these enhance the efficiency of grid capacity utilization in the base case since they decrease preventive security margins [25].

Recently, best practice is to apply DG curtailment as a preventive congestion management measure [5]. Accordingly, it is activated in the alert state to maintain a security margin for possible fault situations. Hence, the utilization of grid components in the base case can be increased by increasing the loadability of grid components in contingency events and, thus, the amount of preventive renewable energy curtailment can be reduced [25].

The implementation of this aspect into the developed curtailment simulation framework can be realized by adapting the network security constraints in Equation (5). A distinction can be made between the maximum permissible active power transfer over grid components in the undisturbed grid state (n-0) and in possible contingency states (n-1):

$$P_{comp,init,n-0} + \Delta P_{comp,n-0} \leq P_{comp,max,n-0} \tag{8}$$

$$P_{comp,init,n-1} + \Delta P_{comp,n-1} \leq P_{comp,max,n-1} \tag{9}$$

Due to the uncertain occurrence of contingency events, the increase of the maximum permissible real power flow in n-1 events $P_{comp,max,n\text{-}1}$ above the physical limit of the respective grid component is not necessarily accompanied by actual overloadings.

2.4. Dynamic Line Rating

The developed simulation framework furthermore considers changes in the power transfer capability of overhead transmission lines dependent on environmental factors. The factor limiting the transmission capacity of overhead lines is usually the sag of the line, which results from its temperature [26]. However, this is not only dependent on the transmitted current but rather on several environmental factors such as the ambient temperature, wind speed, and solar radiation [27]. The transmission capacity of overhead lines is thus dynamically changing with variations in these factors. Generally, the rated current of overhead lines is determined by assuming normative values with an ambient temperature of 35 °C, a wind speed of 0.6 m/s, and solar radiation of 900 W/m^2 [28].

Particularly in times of high wind occurrence accompanied by a high amount of DG feed-in, the demand for congestion management measures can be reduced due to higher admissible currents on transmission lines resulting from additional cooling effects [27].

The application of dynamic line rating is already well established in practice. Therefore, it is not considered as a novel operational concept in this work but rather integrated into the simulation environment to increase the accuracy of simulation results in comparison to real data from grid operation practice because dynamic line rating has a significant impact on the amount of incidental DG curtailment. Based on a meteorological dataset, the maximum transferable current of a transmission line is calculated dynamically using the approach proposed by the Institute of Electrical and Electronics Engineers (IEEE) [29]. Thus, the maximum real power transfer capabilities in Equations (5), (8), and (9) change dynamically.

3. Implementation and Simulation Results

The developed simulation framework is applied to the model of a real 110 kV distribution network of a region located in Germany, which is characterized by a high share of installed DG capacities. Firstly, the model and data sources are described. Then, best practice curtailment approaches are implemented as a reference simulation scenario to validate the model regarding its capability to reproduce historical curtailment measures based on load flow simulations. Finally, different scenarios including the proposed novel concepts are defined and implemented, and the resulting reduction potential compared to the reference scenario is quantified and discussed.

3.1. Grid Simulation Model and Data Sources

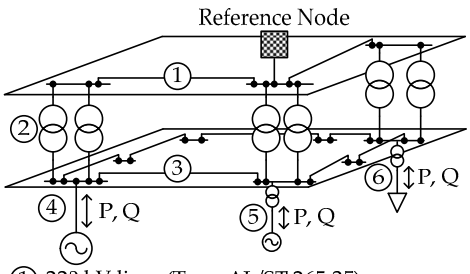
The model of a real 110 kV high voltage (HV) distribution system with 100 nodes and a ring topology located in Germany is used as a case study in this paper. Grid topology data of the 110 kV level are provided by the respective grid operator and further extended by a simplified representation of the superordinate transmission system. Accordingly, the power flows at the interconnection points between transmission and distribution system are also modelled to simulate possible congestions of transformers operated by the TSO. The investigated 110 kV system is supplied by three interconnection points and operated by the DSO.

The amount of curtailment due to congestions on the subordinate medium voltage (MV) and low voltage (LV) levels is negligibly small, which can be derived from a dataset including historical curtailment requests in the region. Thus, grid restrictions on the MV and LV level are not considered. Instead, DG units and loads on the MV and LV level are modelled in aggregate at the interconnection point to the HV network. Historical measurements of active and reactive power flows of all HV/MV transformers with a resolution of 15 min are available, which enable time series load flow simulations. Since these measurements are aggregated and the wind feed-in needs to be known separately to determine curtailment potentials, the method presented in [30] is used to disaggregate the measured time series into aggregated power injections of wind energy generators and the remaining part. Consequently, the simulation of curtailment is limited to wind turbines whereas other DG technologies are neglected. This assumption is expected as reasonable since FIM is mainly carried out using wind turbines [11]. Additionally, the time series are distorted by historical curtailment measures since the feed-in of DGs is reduced in these situations. The disaggregation enables the simulation of times with historical curtailment measures since the potential DG feed-in can be estimated based on meteorological data. A clear sky model provides the solar radiation [31] whereas the wind speed and ambient temperature are provided by the COSMO-DE analysis of the DWD (German Meteorological Service) [32]. These are geographically interpolated to the coordinates of all MV grid districts. Measured time series of wind farms directly connected to the 110 kV level are not available. Therefore, these are created synthetically by using the meteorological data set and the performance curve of a typical wind turbine [33]. The meteorological data set is also used to implement dynamic line rating for the

respective 110 kV transmission lines. For this, each transmission line is assigned to the substation it has the shortest geographical distance to.

The balance of the total real and reactive power within power flow simulations in the region is ensured by the reference node on the 220 kV level. The parameters of transmission lines on the 110 kV level are provided by the respective grid operator (GO). Furthermore, the line lengths of the 220 kV lines are derived from a publicly available GIS database and the electrical parameters are extracted from a typical AL/ST 265/35 220 kV overhead line model [34]. Capacities of 220 kV/110 kV transformers are also given through grid operator information, whereas the short-circuit voltage for power flow calculations is specified to 13% based on [35]. A schematic graphical representation of the model is given by Table 1 including an overview of all numbered model objects and the respective data sources.

Table 1. Schematic visualization of grid simulation model including the data sources of different model parameters.



1 220 kV lines (Type AL/ST 265-35)
2 220 kV/110 kV Transformers
3 110 kV lines
4 DG units on 110kV level
5 Aggregated DG units on MV/LV level
6 Aggregated Loads on MV/LV level

Objects	Parameter	Source
1	Line length Electrical parameters	GIS [34]
2	Capacity Short-circuit voltage	GO [35]
3	Line length Electrical parameters	GO
4	Installed capacity Wind speed Performance curve	[36] [32] [33]
5 6	Active and reactive power time series	GO

3.2. Validation of Simulated Curtailment Demand

The aim of the model validation is to assess the extent to which the developed simulation framework is capable of displaying realistic curtailment measures. Therefore, the recent best practice approaches for DG curtailment are implemented into the framework and the simulated curtailment measures are compared to historical measures, which are derived from published data by the respective grid operators in the model region.

Firstly, the best practice scenario setup is implemented into the simulation framework. The feasible set of curtailment levels is considered as:

$$\Omega_{\text{curt}} = [1,\ 0.6,\ 0.3,\ 0]$$

Furthermore, the iterative curtailment method is implemented and the curtailment requests by TSO and DSO are derived independently. In addition, the maximum loading of grid components in contingency situations is set to 100%. In the following, this scenario configuration is also considered as the reference scenario to evaluate the effectiveness of the proposed concepts.

The published data set of historical curtailment measures includes starting time, level (1, 0.6, 0.3, 0), ending time, and the receiving substation of each request. Due to the frequent occurrence of curtailment requests in the historical data set and the availability of comprehensive time series data, February 2016 was selected as the investigated time period in this work.

Hence, the historical curtailment of DG units is determined using the respective time series and the historical data set with a resolution of 15 min. For the same time horizon, the incidental curtailment using the best practice approaches is simulated. Therefore, in each time step, a contingency analysis is executed to assess the security state of the network. In the alert state, DG curtailment is requested as a preventive

congestion management measure. In case of multiple critical contingencies, grid operators usually initiate countermeasures ordered by the severity of operational limit violations [22]. Subsequently, the amount of curtailment is determined for the most severe contingency at first. This is iteratively repeated until all congestions in each possible n-1 event are terminated.

Firstly, according to the cascading grid operation approach (Figure 2), congestions on the TSO level are identified by performing a contingency analysis of all 220/110 kV transformers in the grid area. For all insecure grid states, the resulting amount of DG curtailment is derived by the simulation framework. Since most curtailment measures contained in the historical data set result from congestions of transformers connecting the transmission and distribution system it is assumed that the TSO requests FIM measures only to prevent overloadings of transformers. Thus, congestions of 220 kV transmission lines are not considered in this work. After deriving curtailment requests by the TSO, another contingency analysis is executed to determine the security state of the 110 kV system and derive curtailment requests by the DSO if necessary. Although the curtailment demand is determined for each installed DG unit individually, simulation results are validated for the total amount of curtailment in the investigated region to assess the overall amount of incidental renewable energy curtailment.

3.2.1. Validation Metrics

In the first step of the validation process, the accordance of simulated curtailment with the historical measures in each of the 15-min intervals is analyzed. Therefore, each simulation step can be assigned to one of the four binary states visualized in Table 2. In each time step, it is examined if the historical data set contains any curtailment requests and if curtailment requests are simulated based on the best practice approach. Consequently, four different combinations (a, b, c, d) of these aspects are possible [37].

Table 2. Depiction of different binary states to assess time steps resulting from combinations of the presence or absence of simulated and historical curtailment measures.

	Simulated Curtailment	
Historical Curtailment	**True**	**False**
True	a	b
False	c	d

To increase the comparability of the simulation results achieved in this work, these are put in relation to the study of [2] as a reference. There, the authors developed a congestion forecast model based on autonomous neural networks for a German transmission network and validated it based on historical data about congestion management measures. Although neither these measures are quantified nor multiple system levels are considered in [2], the results can be compared to the simulations carried out in this work regarding the ability to represent historical congestion situations. The precision (p), recall (r), and f1-score (f) are used as similarity indices between simulation and historical values in [2], which are defined as follows:

$$p = \frac{a}{a + c} \tag{10}$$

$$r = \frac{a}{a + b} \tag{11}$$

$$f = 2 \cdot \frac{p \cdot r}{p + r} \tag{12}$$

For each of those indices, a value of 1 indicates total similarity. Additionally, in this work the mean absolute error (MAE) and the root mean square error (RMSE) are used as error metrics to assess the accuracy of curtailment simulations, which are defined as follows [38]:

$$\mathrm{MAE} = \frac{1}{n} \cdot \sum_{k=1}^{n} |e_i| = \frac{1}{n} \cdot \sum_{k=1}^{n} \left| P_{curt,historic} - P_{curt,simulated} \right| \tag{13}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n} \cdot \sum_{k=1}^{n} |e_i|^2} = \sqrt{\frac{1}{n} \cdot \sum_{k=1}^{n} \left| P_{curt,historic} - P_{curt,simulated} \right|^2} \tag{14}$$

where n describes the number of simulated time steps, $P_{curt,historic}$ the amount of power reduction in the historical data set, and $P_{curt,simulated}$ the simulated power curtailment per time step.

Due to the independent simulation of curtailment requests by the TSO and the DSO, the similarity indices and error metrics are calculated separately for both grid operators. In addition, the aggregated results, defined as the sum of TSO and DSO curtailment requests, are determined. Table 3 depicts the resulting similarity indices from reference [2] compared to those achieved in this paper. Furthermore, the resulting MAE and RMSE from this work are depicted. In order to visualize the significance of the absolute values for the error metrics, the maximum amount of simulated power curtailment is also depicted.

Table 3. Resulting similarity and error metrics between historical and simulated DG curtailment in comparison to results published in [2].

	[2]	This Work		
		DSO	**TSO**	**Aggregated**
Precision p	0.699	0.462	0.812	0.930
Recall r	0.636	0.263	0.748	0.760
f1-score f	0.648	0.335	0.779	0.837
Maximum curtailment [MW]	/	162.844	389.393	389.393
MAE [MW]	/	7.892	19.985	22.484
RMSE [MW]	/	26.353	51.396	51.948

According to Table 3, regarding all similarity values, the simulation of TSO curtailment is more accurate compared to [2], whereas DSO measures are depicted less accurately. The results also show that the aggregated consideration has the highest values in all similarity indices. Both error metrics have the lowest values for the DSO curtailment and the highest values for the aggregated consideration.

Consequently, the similarity metrics indicate a lack of accuracy regarding the simulation of curtailment requests by the DSO. This is due to several reasons. In particular, the recall r of only 26.3% indicates a poor model performance. Since this index is dependent on the inaccurate state b, it can be concluded that a large number of historical DSO requests do not appear in the simulation results, because the corresponding congestions are already resolved by the prior determined TSO curtailment demand. In 86% of the times assigned to state b, TSO requests are simulated. Hence, congestions in the distribution network are often already resolved and no additional DSO curtailment is necessary. On the contrary, 58% of times assigned to state c are accompanied by an underestimation of TSO curtailment requests. Consequently, the precision p is also influenced by this dependency but to a smaller extent. Accordingly, this index indicates a larger similarity of 46.2%. The MAE values are relatively small compared to the maximum occurring power reductions in all three cases. The RMSE values are considerably larger than the MAE values. Hence, it can be concluded that the curtailment simulation values occasionally include larger deviations from the historical values, since the RMSE is more sensitive to large errors than the MAE [38]. However, both error metrics are relatively small compared to the maximum occurring values. The differences between simulation results and historical

data are further visualized by the time series comparison of requests by the TSO, DSO and the aggregated amount of DG curtailment in Figure 3. The time series confirm the high degree of temporal coincidence between simulation and historical values. Occasionally, larger deviations are apparent, which contribute to the larger RMSE values.

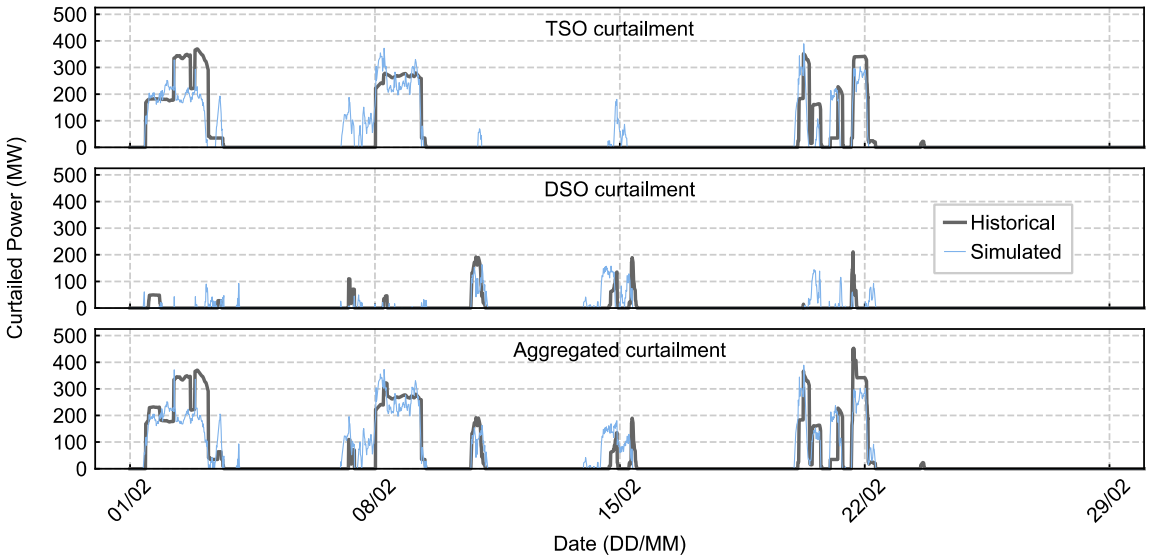


Figure 3. Time series comparison of simulated and historical curtailment measures requested by the transmission system operators (TSO) (**top**), distribution system operators (DSO) (**middle**) and aggregated (**bottom**).

Overall, the simulation of curtailment measures requested by the DSO is highly influenced by the simulation of the TSO demand beforehand, which also contains errors, as can be seen in Table 3. Nevertheless, the aggregated results gain the highest similarity values and only slightly higher values in the error metrics. This confirms that some measures historically requested by the DSO are mistakenly simulated as measures by the TSO and vice versa. The relatively low values of MAE and RMSE and the graphical time series comparison in Figure 3 confirm the accuracy of simulated DG curtailment, particularly considering the aggregated results.

Possible sources of errors decreasing the accuracy of curtailment simulations are the meteorological data which affect both the wind power time series and the dynamic line rating approach. As stated in [39], the quality of the dynamic line rating approaches could be improved by further increasing the maximum geographical resolution of 2.8 km of established meteorological models, which are also used in this work. This is especially relevant for the 110 kV lines and, thus, for the curtailment requests by the DSO. Additionally, due to the available data basis, the simulation was carried out for 15-min time intervals. However, grid security is typically assessed more frequently (e.g., in intervals of 2 [40] or 5 [41] min) by state estimation algorithms. Therefore, the practical security assessment fluctuates more than in the simulations, which can also affect the derivation of curtailment measures.

3.2.2. Comparison of Historical and Simulated Renewable Energy Curtailment

In addition, the total amount of renewable energy curtailment in the considered time horizon is derived from the data of simulated and historical curtailed power per time step. The resulting amounts of energy curtailment requested by TSO, DSO, and aggregated are depicted in Figure 4.

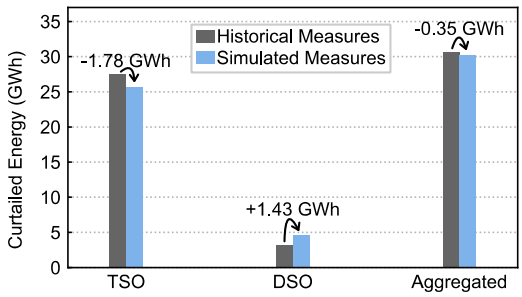


Figure 4. Comparison of renewable energy curtailment requested by the TSO, DSO, and aggregated.

The curtailed energy due to requests by the TSO is slightly underestimated by 1.78 GWh (6.5%), whereas the demand from the DSO is overestimated by 1.43 GWh (45.6%). Consequently, the combined energy amount is underestimated by 0.35 GWh or 1.1%. Accordingly, the model is able to project the historical curtailment measures regarding the total amount of curtailed energy very well. The share of TSO requests in the aggregated amount is comparably large in the simulation (84.89%) and the historical (89.74%) dataset. Consequently, most curtailment requests are due to congestions of transformers linking the distribution and transmission system.

Overall, the similarity measures, time series analysis, and evaluation of the curtailed energy indicate the capability of the simulation framework to represent the demand and number of curtailment measures in the investigated region to a reasonable extent. Despite inaccuracies regarding the allocation of curtailment measures to the requesting grid operator, the aggregated simulation results are particularly promising. Therefore, the developed simulation framework is assumed to achieve reasonable results regarding the simulation of DG curtailment. The resulting amount of renewable energy curtailment of 30.27 GWh in the reference scenario is thus further used to assess the extent to which the proposed operational concepts can increase grid capacity utilization and, thereby, decrease the incidental amount of DG curtailment.

3.3. Scenarios for the Implementation of Novel Operational Concepts

Section 2 discusses relevant aspects influencing the demand for DG curtailment including the description of recent best practice approaches and possible concepts to improve the practical implementation on a theoretical basis. Based on different scenarios, these concepts are implemented into the simulation framework to quantify their benefit in terms of maximizing the integration of renewable energy generation into the investigated 110 kV distribution network. The concepts include increasing the DG controllability by extending the feasible set of curtailment levels. In addition, the implementation of the proposed novel DG selection procedures is investigated. These include the coordination of curtailment requests between TSO and DSO by implementing both the optimization (Equation (3)) and the hybrid selection method (Equation (7)) into the simulation framework. Finally, the concept of improving the utilization of transmission capacities by increasing the maximum permissible loading of grid components in possible contingency events is considered. However, the implementation of one of these concepts does not exclude the coincident implementation of the others. Instead, combinations can be also realized to improve the DG curtailment process regarding different aspects simultaneously. Table 4 gives an overview of the investigated scenarios regarding the considered adaptations compared to the best practice reference scenario.

Table 4. Overview of investigated scenarios and adaptations regarding the specification of curtailment level increments, DG selection method, and maximum permissible loading in contingency states compared to best practice approaches.

Scenario Description	Specification of Aspect		
	Feasible Set of Curtailment Levels Ω_{curt}	**DG Selection Method and Grid Operator Coordination**	**Maximum Permissible Loading in n-1 Events**
Best practice reference scenario	[1,0.6,0.3,0]	Iterative selection method, independent curtailment requests by TSO and DSO	100%
	Adaptations compared to best practice approaches		
Scenario 1: Extended feasible set	X		
Scenario 2: Coordinated DG selection methods	X	X	
Scenario 3: Increased loadability in contingency events		X	X

Firstly, the reference scenario includes four discrete curtailment levels, the iterative selection scheme accompanied by independent curtailment request of TSO and DSO, and a maximum loadability of grid components of 100% in contingency events. The first scenario quantifies the benefit of decreasing curtailment level increments and thereby enabling the grid operator to control DG units to a larger extent. The DG selection procedure and maximum permissible loading in contingency events remain unmodified in comparison to the reference scenario. The second scenario supplements the larger control opportunities by also implementing the optimization and hybrid approaches as candidate DG selection methods and thereby improving the coordination between TSO and DSO. Finally, the last scenario quantifies reduction potentials of DG curtailment dependent on increasing the maximum loadability of grid components in n-1 events. This scenario also considers the different DG selection methods. In the following, simulation results for each of the described scenarios are presented.

3.4. Curtailment Reduction Potentials of Proposed Concepts

3.4.1. Scenario 1: Extended Feasible Set of Curtailment Levels

Smaller curtailment level increments enable more efficient requests due to the enhanced DG control capability of grid operators. Consequently, feasible sets of curtailment levels with smaller increments compared to the best practice approach are implemented into the simulation framework to quantify the benefit of this concept. The incremental sizes investigated in this scenario are 10% and 1% related to the nominal capacity of DG units. Table 5 depicts the resulting amount of DG energy curtailment within the considered time horizon of one month requested by DSO, TSO, and the aggregated sum of both in comparison to the reference scenario with only four discrete levels.

Table 5. Resulting renewable energy curtailment for different incremental sizes of curtailment levels.

Incremental Size of Curtailment Levels	Energy Curtailment [GWh]		
	DSO	**TSO**	**Aggregated**
Reference scenario ([1,0.6,0.3,0])	4.57	25.7	30.27
10%	4.16	25.19	29.35
1%	3.99	24.98	28.97

Curtailment requested by the DSO can be reduced by 0.41 GWh (9%) for 10% and 0.58 GWh (12.7%) for 1% increments. Moreover, TSO curtailment can be reduced by 0.51 GWh (2%) and 0.72 GWh (2.8%). Accordingly, the aggregated savings amount to 0.92 GWh (3%) and 1.3 GWh (4.3%) for 10%

and 1% increments, respectively. The results show that the reduction of the total amount of curtailment is comparable between DSO and TSO. Consequently, the relative savings achievable by the DSO are distinctly higher. Due to the iterative selection scheme applied in this scenario, the benefit of smaller curtailment level increments is limited to the least sensitive DG unit affected by the respective request, because each of the other affected units is fully curtailed. Hence, the relative reduction of curtailed energy is reduced significantly only in the case of less severe congestions that induce a small amount of total power curtailment.

This effect is illustrated in Figure 5, which shows the relative reduction of the aggregated amount of DG curtailment requested by TSO and DSO gained by 10% and 1% increments per time step depending on the respective amount of total power reduction. The relative savings are related to the best practice increments. It becomes clear that the highest relative savings are achieved at the less severe congestions. Smaller increments tend to only have minor advantages in situations with large amounts of power reductions. As depicted by Table 5, the relative reduction potential is thus considerably lower for TSO requests, since these exhibit larger amounts of power adjustments compared to DSO curtailment.

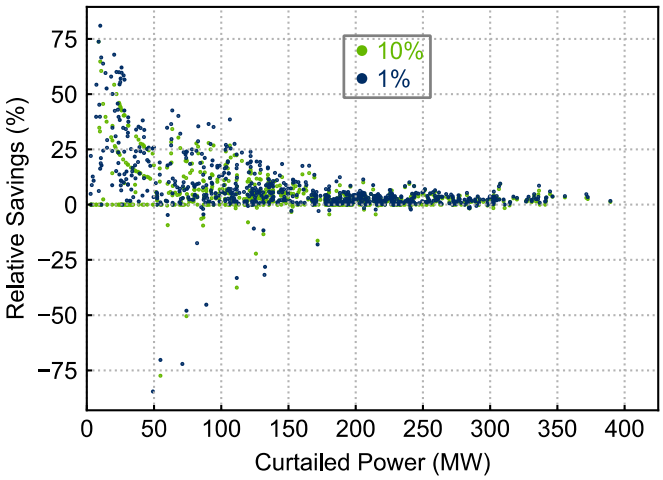


Figure 5. Relative reduction of curtailed DG power feed-in achieved by 10% and 1% increments in comparison to established curtailment levels.

Furthermore, a few measures show negative savings for 10% and 1% increments in Figure 5. This is due to the fact that TSO curtailment also reduces congestions at the distribution level. Therefore, the avoidance of TSO requests can inevitably lead to a higher amount of curtailment demand at the distribution grid level. Consequently, the aggregated amount resulting from smaller increments can even exceed the demand induced by larger increments in certain situations.

In total, the advantage of decreasing the curtailment level increments is its easy implementation into existing grid control strategies, since modern communication standards and technologies already enable a finer granularity in DG controllability compared to FIM [20]. However, the simulation results in this scenario imply that the potential to reduce the curtailed energy is limited to a few percent due to the frequent occurrence of severe congestions in real grid operation practice, especially in combination with the iterative DG selection approach. Therefore, the benefit of this concept is also assessed in combination with implementing the novel DG selection methods in the following scenario.

3.4.2. Scenario 2: Coordinated DG Selection Methods

In this scenario, the optimization approach (Equation (3)) and the hybrid approach (Equation (7)) are implemented as candidate DG selection methods to increase the coordination between TSO and DSO. The benefit of this concept is assessed based on both the potential to reduce the resulting amount of renewable energy curtailment and the complexity of its practical implementation compared to the best practice iterative approach. Therefore, in addition to the resulting amount of DG curtailment,

the number of necessary control signals is also considered to evaluate the communication demand associated with the implementation of this concept.

To implement the hybrid approach (Equation (7)), firstly a suitable choice for the fixed cost parameter c_{fix} in the objective function has to be determined. Therefore, this parameter is varied iteratively between 100 € and 500 € in steps of 100 € and analyzed regarding its influence on the curtailed energy and the number of requested measures. Both variables are depicted in Table 6 dependent on the respective fixed cost parameter. In addition, the results obtained from the reference scenario are shown. As expected, the lowest fixed cost parameter (100 €) causes the lowest amount of curtailed energy but the largest number of measures. In contrast, the highest fixed cost parameter of 500 € prioritizes the number of measures over the amount of curtailed energy. Compared to the reference case, an increase in the number of curtailment measures for all parameters is present, whereas the amount of curtailed energy is lower. For the further analyses in this work, the parameter is set to a value of 300 €, since this causes a considerable reduction of curtailed energy (2.79 GWh) while increasing the number of curtailment measures acceptably (49.43%) compared to the iterative approach.

Table 6. Renewable energy curtailment and number of curtailment requests for different fix cost parameter specifications.

		Curtailed Energy [GWh]	Curtailment Requests [#]
Reference Scenario		**30.27**	**437**
c_{fix} [€]	100	27.46	989
	200	27.48	738
	300	27.49	653
	400	27.77	542
	500	27.87	497

The three different DG selection methods are compared regarding the incidental amount of renewable energy curtailment and the number of resulting curtailment requests. In addition, the approaches are combined with the concept of smaller curtailment level increments to show possible interdependencies between both concepts. Therefore, nine different scenario specifications are investigated. The resulting energy curtailment and the number of measures are visualized in Figure 6. The different increments are represented by varying colors, and the number and the amount of curtailment are reflected by different markers ('o','x'), respectively.

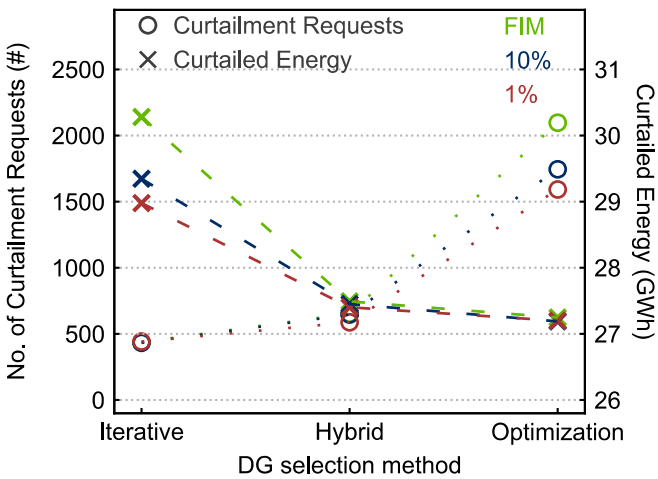


Figure 6. Resulting renewable energy curtailment and number of curtailment requests for different DG selection methods and incremental sizes of curtailment levels.

The iterative approach yields the least number of measures and the highest amount of curtailed energy. Decreasing the curtailment increments mainly reduces the curtailed energy (Section 3.4.1.), whereas the number of measures nearly remains constant. In contrast, the implementation of the optimization approach reduces the amount of curtailed energy by up to 3 GWh (10%) at the expense of 1660 additional curtailment requests. In contrast to the iterative approach, the energy amount remains constant with decreasing increments whereas the number of measures can be reduced considerably. This is due to the fact that smaller increments result in a higher flexibility regarding the controllability of DGs. Therefore, it is less probable that curtailment measures are firstly cancelled and, subsequently, reactivated if congestions return. Smaller increments allow the grid operator to carefully return the DGs feed-in to the initial value while monitoring the operational security limits of the network. Finally, the hybrid approach nearly obtains the same amount of curtailed energy compared to the optimization approach (dashed trend line) and a similar number of curtailment measures compared to the iterative approach (dotted trend line). Moreover, the dependence of this approach on the incremental size is relatively small.

Overall, the hybrid approach yields the best trade-off between the amount of curtailed energy and the complexity of its practical implementation. Combining this strategy with smaller increments only has a minor effect on both of these aspects. However, compared to the iterative approach, the curtailed energy can be reduced by 2.78 GWh at the expanse of 216 additional curtailment measures. Considering the average financial reimbursement of DG operators, reducing curtailment by 2.78 GWh could save 305,800 € of compensation payments within the investigated time period of one month. Concurrently, 1444 measures can be avoided compared to the optimization approach, which reduces the communication demand and the complexity of the implementation into grid operation significantly. This is realized at the expense of increasing the amount of curtailed energy by only 0.24 GWh.

3.4.3. Scenario 3: Increased Loadability in Contingency Events

Increasing the loadability of grid components in contingency events requires the availability of fast-reacting curative congestion management measures, such as fast power flow controlling devices, to terminate the occurring overloading in case of n-1 events as soon as possible. In this work, these measures are not explicitly investigated. Rather, the focus is on analyzing the resulting demand for preventive curtailment measures in the alert security state, if grid components can be loaded more heavily in case of contingency events.

This concept is implemented into the simulation framework by increasing the maximum permissible real power flow $P_{comp,max,n\text{-}1}$ in the security constraints (Equation (9)). Therefore, the maximum thermal loading of grid components is enhanced iteratively in steps of 5% until a maximum value of 130% related to the physical limit of grid components in this scenario. Hence, a value of 130% assumes that the loading of grid components in any contingency situation is preventively reduced to a maximum value of 130%. If this contingency actually occurred during grid operation, curative measures would have to ensure the return of the thermal loading to a value below 100% as quickly as possible. Concurrently, a maximum thermal loading of grid components of 100% in the base case is assured and, thus, the system remains in the alert state and does not reach the emergency state. Furthermore, the concept is applied for the iterative, optimization, and hybrid DG selection methods. The resulting amount of renewable energy curtailment for different maximum loading values and the different selection methods is depicted in Figure 7.

The results clearly illustrate the potential to reduce the incidental DG curtailment significantly by increasing the thermal loadability of grid components in n-1 situations. By enhancing the thermal loadability to 130%, the curtailed energy amounts to only 1.56 GWh, which is 5.2% of the initial value. According to Figure 7, the differences between different DG selection methods decrease as the loadability is increased. Hence, the potential to reduce DG curtailment by implementing novel selection methods is lowered due to the massive reductions obtained by increasing the loadability of grid components in contingency events.

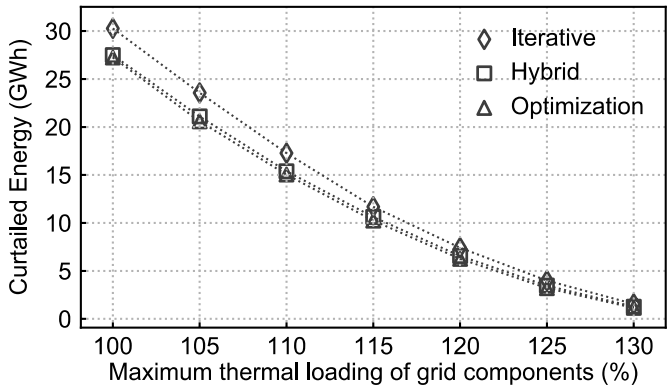


Figure 7. Resulting renewable energy curtailment for different maximum permissible grid component loadings in contingency events and different DG selection methods.

In addition to curative congestion management measures, another possibility to increase the loadability of grid components in contingency events is to consider their thermal inertia, as presented in [15]. Using more detailed thermal models of components, the temperature rise in contingency situations can be simulated dynamically and, thus, a critical time can be derived until the maximum temperature of transmission lines or transformers is reached to derive timely congestion management measures.

3.4.4. Summary and Discussion

To summarize the presented simulation results from the investigated scenarios, Table 7 presents the curtailment reduction potentials of the proposed concepts and evaluates the complexity of implementing these concepts into grid operation practice. The potential to reduce the incidental amount of DG curtailment by implementing smaller curtailment level increments of 10% and 1% was proven to be small due to the frequent occurrence of severe congestions. However, the implementation of this concept can be realized without large expanses since modern communication standards and technologies already enable a finer granularity in DG controllability compared to best practice [20]. Furthermore, simulation results show that the amount of DG curtailment can be reduced by implementing novel DG selection methods. The hybrid approach was proven to be the most suitable approach for the practical implementation since it nearly reaches the same reduction of renewable energy curtailment (9.48%) compared to the optimization approach (10.14%), while reducing the complexity of operational implementation by reducing the number of curtailment requests significantly. The coordinated curtailment procedure requires an extended data exchange between different grid operators regarding the demand for power flow adjustments and power flow sensitivities considering multiple system levels. Due to the low complexity of their practical implementation, both of the aforementioned concepts could be realized in the near term to maximize the integration of DG units into power systems. However, in the long-term perspective the concept of utilizing existing grid capacities by allowing heavier loadings of grid components in uncertain contingency events should be intensified since it clearly shows the highest potential to reduce incidental renewable energy curtailment, by up to 94.8%. On the contrary, this concept requires the implementation of curative congestion management measures or dynamic thermal models of components into grid operation. Therefore, future research should address the question of whether investments in novel curative technologies can be justified by their potential to reduce the amount of renewable energy curtailment quantified in this work.

Table 7. Overview of resulting renewable energy curtailment of proposed concepts and challenges regarding the practical implementation.

Proposed Concept	Minimum Resulting Renewable Energy Curtailment [GWh]	Challenges Regarding Practical Implementation
Best practice	30.27	/
Increased DG controllability	28.97	Adjustment of applied ICT standards
Improved DG selection scheme	27.20 (Optimization approach) 27.40 (Hybrid approach)	Extended data exchange between grid operators
Increased loadability in contingency events	1.56	Implementation of curative congestion management measuresImplementation of dynamic thermal grid component models

4. Conclusions

The on-going integration of DGs into the energy system causes an increase in curtailment measures executed by grid operators due to limited transmission capacities. To address this problem, this paper presents a simulation framework for optimizing the practical implementation of DG curtailment based on load flow analysis. The framework proved to be sufficient for simulating the curtailment demand in the investigated region in Germany, although the allocation of curtailment measures between DSO and TSO shows some inaccuracies. The framework is further used to analyze the ability of three operational concepts and combinations of these to reduce renewable energy curtailment. Firstly, an enhancement of DG controllability is investigated. Furthermore, novel DG selection methods are proposed that enable a simultaneous consideration of multiple voltage levels. Additionally, an extension of the deterministic n-1 criterion is considered by enhancing the maximum thermal loading of grid components in contingency events.

The simulation results obtained indicate that the amount of renewable energy curtailment can be reduced both by implementing smaller curtailment level increments by up to 4.3% and by establishing coordinated novel DG selection methods by up to 10%. To limit the complexity of the practical implementation, the hybrid approach proves to be superior to solely minimizing the amount of power adjustments. Both concepts could be a temporary solution to optimize the curtailment process since the effort for their realization is rather small. However, the concept of increasing the utilization of transmission capacities by enhancing operational limits in contingency situations has clearly proven to be the most efficient concept to reduce preventive DG curtailment. Enhancing the maximum permissible loadings of grid components to 130% reduces the amount of renewable energy curtailment by up to 94.8% and, thus, nearly leads to a complete prevention of these congestion management measures. Concurrently, this is also the most challenging concept regarding its implementation. Therefore, future research should address possibilities to extend operational limits, such as considering the thermal inertia of grid components or establishing fast-reacting, curative congestion management measures, and compare the additional costs of these measures with their benefit regarding the reduction of renewable energy curtailment.

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