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Curative System Operation in the 110 kV Distribution Grid

Opportunities for Unlocking and Using the Potential for Higher Utilization

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Abstract. The energy transition poses significant challenges for the electrical distribution grid. This paper examines curative system operation in the 110 kV distribution grid that aims to tackle some of these challenges. Unlike preventive system operation, which avoids potential violations of operating thresholds during normal operation before they occur, curative system operation aims to maintain the grid within permissible thresholds only *after* a critical event through prepared, targeted measures. This paper analyses the complex requirements and challenges in implementing curative measures, particularly in comparison to existing approaches and concerning the high node density and the multitude of possible measures involving distributed generators and other customer facilities in the high-voltage distribution grid. By defining relevant thresholds and considering influencing factors, a unified understanding of curative system operation in the distribution grid is established. The paper demonstrates how curative system operation approaches can contribute to ensuring system security and describes the advantages of their utilization. Finally, perspectives for future research in the area of curative system operation in the 110 kV distribution grid are outlined.

Keywords: Distribution Grid, Curative System Operation, Congestion Management, High Voltage Level

1. Introduction

Decarbonization and the ongoing electrification of our energy supply present significant challenges to the power grid, particularly the distribution grid. Efficient utilization of electrical grids is of central importance to ensure an affordable, secure, and reliable energy supply during the transformation towards a climate-neutral energy system. One component that enables higher utilization of electrical grids while maintaining high system reliability is curative system operation. The key difference between traditional preventive system operation and curative system operation lies in the handling of potential failures. In preventive system operation, a safety reserve is considered during normal operation (N-0 case, also referred to as N-1-secure operation) based on the N-1 principle, ensuring that even in the event of a grid asset failure (N-1 case, no longer N-1-secure operation due to the failure), all remaining assets in the grid remain within their permissible operating thresholds. This prevents cascading failures due to further tripping of grid protection equipment. In curative system operation, curative actions are taken only after an event occurs (e.g., an N-1 case) to keep the remaining operational resources within their permissible operating threshold (see Figure 1). For this, the permanent admissible transmission loading (PATL) and temporary admissible transmission loading (TATL) are relevant, which are described in the following section [1].

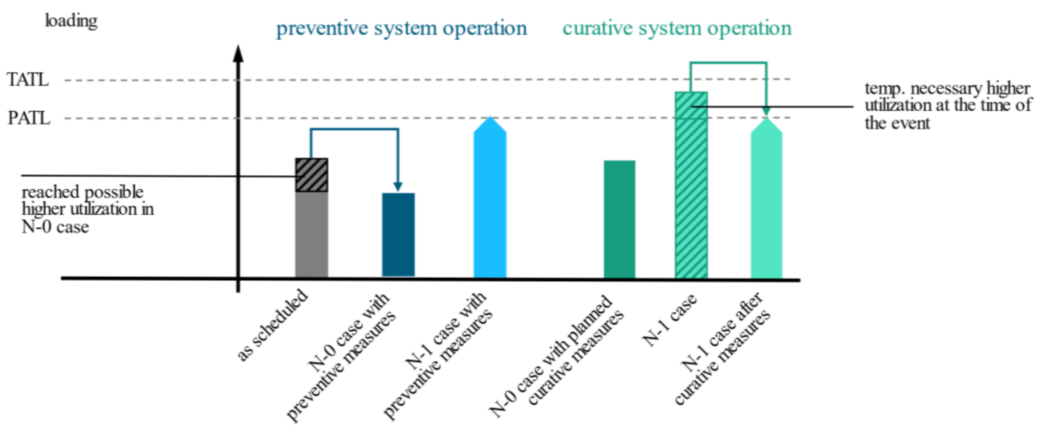

Figure 1. *Possibility of increased utilization of grid resources during normal operation by curative measures for specific event variants (illustrated by the example of N-0/N-1) (based on [2]).*

Curative measures must be reliably available and quickly deployable. In this way, the necessary safety reserve regarding the operational thresholds of the grid is reduced, allowing for increased utilization during normal operation. By increasing usable capacities, the need for grid expansion can be delayed or even reduced, the frequency of redispatch measures and associated costs can be lowered, and the integration of distributed generators and other customer facilities into the power grid can be accelerated. In this publication, customer installations refer to consuming and generating installations. Curative system operation approaches have long been discussed in the scientific literature (see, e.g., [3-5]) and are increasingly being applied in transmission grids, enabled by digitalization and automation (see, e.g., [6-10]). Potential approaches in transmission grids include the adjustment of active power setpoints of voltage source converters (VSC) in high-voltage direct current (HVDC) systems, adjustment of active power exchange to distribution systems and fast-reacting battery storages (so-called grid boosters) [6]. In high-voltage distribution grids (110 kV level), curative system operation approaches also have many potential applications, which not are used yet. The paper at hand addresses this gap and tries to discuss relevant differences to previous approaches as well as structural and technical differences in the voltage levels. The large number of directly connected and potentially controllable customer installations creates diverse flexibility potentials that can be utilized by curative measures. The large number of these customer installations makes curative system operation complex, as a single measure may be insufficient to alleviate a congestion, necessitating a combination of several curative interventions. This, along with sometimes short allowable response times, creates a demand for a high degree of automation. If a customer installation is to be activated as part of a curative measure, the cooperation of at least the distribution system operator (DSO) and the operator of customer installations and coordination is required regarding communication pathways, execution responsibilities, and action times. The interaction of multiple actors should ideally follow existing protocols and specifications. Ultimately, the impacts on other processes must also be considered. These challenges require innovative approaches for the optimal design of curative system operation in the 110 kV distribution grid.

This paper examines the use of curative system operation approaches in the high-voltage distribution grid. The starting point for the development and analysis of curative system operation approaches in the distribution grid is a unified understanding of curative measures and their application in the distribution grid. Subsequently, curative system operation in the distribution grid will be presented in terms of concept, realization, and exemplary application, followed by a definition of relevant terms and dependencies to establish a common understanding.

2. Curative Measures in the Distribution Grid

2.1 Threshold Concept

The permissible operating thresholds of the individual components of a power grid must be adhered to at all times. In quasi-stationary operation, this specifically includes permissible current flows, voltage bands, and short-circuit power of the grid. For the high-voltage level, VDE AR-N 4121 must be applied by the grid operators. Considering the energy transition and the associated higher power flows in the distribution grid, the permissible threshold of overhead lines, cables, and transformers are increasingly causing grid congestions [1]. Thus, they are becoming a focal point of operational planning and grid management. In the threshold concept of the transmission system operators, the following two threshold definitions are used for grid operation, which can also be applied to curative system operation in the distribution grid:

- Permanent Admissible Transmission Loading (PATL): Refers to the current with which a circuit or circuit section can be permanently loaded.
- Temporary Admissible Transmission Loading (TATL): Refers to the current with which a circuit or circuit section may be temporarily loaded for a specific time interval.

Various factors can influence the choice of operational thresholds PATL and TATL, with the ultimately applicable value being derived from the minimum of the available thresholds. A detailed examination of the individual factors can be found in Chapter 4.

2.2 Conceptualization

Figure 2 shows (a) the comparison of preventive and curative system operation for an outage with threshold violation (event) and (b) the corresponding temperature profile for the presented system operation approaches. The default scenario is without measures ("no measure"). In the case of high initial utilization, the outage leads to an exceedance of the permanently or temporarily permissible threshold (PATL or TATL), resulting in inadmissible system states in the event of a disturbance at time t_e.

In preventive system operation, in the event of a grid component outage, the maximum loadings are kept below the PATL value ("preventive"), thus ensuring the avoidance of the otherwise resulting emergency state. Therefore, the power grid is in a normal state before the occurrence of the disturbance at time t_e and in a threatened (but permissible) state after the disturbance occurs. The curative system operation approach also has a preventive component, which ensures that the TATL value is not exceeded in any remaining grid component at the time of disturbance. The prepared and activated curative measures, which must be deployed within a specific time window ("impact window of curative measures" from t_e to t_{e+cur}), bring the grid into a state where all PATL thresholds are also maintained by utilizing available temperature reserves (the difference between $T_{is,cur}$ (t) and T_{max}) ("curative"). This avoids the emergency state, and similarly to preventive system operation, only the threatened state is established. Since the curative measure is implemented only upon the occurrence of a disturbance, the possibility of increased utilization arises from the difference between the permissible current I_{is} (t) in the case of purely preventive system operation and the permissible current loading in the case of curative system operation. After the completion of the curative measure, due to the occurrence of the event, there is no longer a N-1-secure system state, similar to preventive system operation (threatened state according to [11]).

Following the deployment of the curative measure, a further measure must be identified and applied, to return to a N-1-secure state and thus to the normal state, analogous to preventive system operation. This typically involves classical measures of congestion management, just as they would be implemented in preventive system operation after an actual event occurrence (and the associated loss of N-1 security). Only when using curative measures with limited effectiveness (e.g., in the case of feeding in/out from a storage system) is the further measure linked to the possible duration of the curative measure and may thus be subject to a time requirement. After restoring the original state and re-evaluating necessary preventive and curative measures, the utilization will approximately return to the initial level.

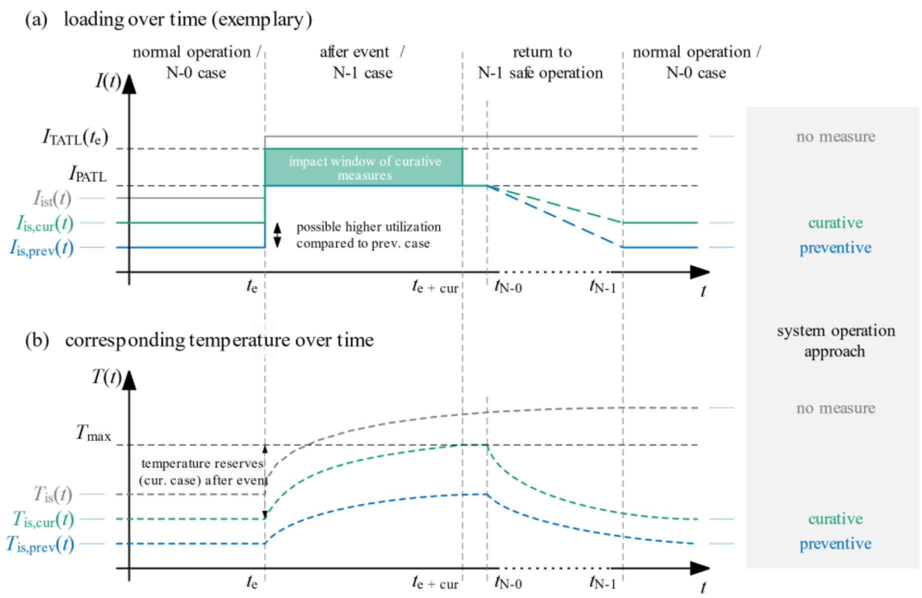

Figure 2. *Conceptual representation of the deployment of curative measures over time (based on [2, 7]) (a) and the resulting temperature profiles (b).*

The representations illustrate the deployment of curative measures to address loading-related congestions. Additionally, compliance with other system thresholds can also be addressed through curative system operation (e.g., voltage band violations, operationally addressable stability reserves).

2.3 Implementation of Curative Measures

As a concrete example, the following section describes a congestion on a classic 110 kV double circuit in terms of the technical implementation of curative measures, which focuses on generation plants as examples of customer installations. Figure 3 conceptually illustrates an exemplary configuration in the 110 kV distribution grid. The double circuit connects two grid areas with significant power exchange. Since generation plants are typically not connected to the grid in a N-1-secure manner, the failure of the line alone leads to a reduction in available generation capacity along the failed line(s), as the two wind farms illustrated on the right side of Figure 3 are also disconnected from the grid. (This already represents a complication compared to the pure implementation of curative measures but is a common scenario in the 110 kV high-voltage grid.) Nevertheless, a congestion arises at point (2) of the remaining line, meaning that the reduction in generation capacity of the wind farms still connected to the grid is an effective measure of congestion management and must thus be reduced in curative operational mode after the failure.

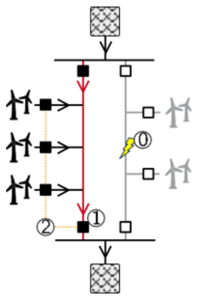

Figure 3. *Application example of a double circuit with failure variant (0), resulting threshold violation (1), and control command for congestion elimination (2) [12].*

There are generally two different options for implementing this, each with its own advantages and disadvantages:

- Control signal for power reduction via remote controllability of the generation plants (central approach, e.g., through the grid control system).
- Disconnection of the wind farms by opening the circuit breaker at the grid connection point via special protection schemes (decentralized approach, e.g., through existing or additional field devices).

The implementation via control signals allows for a reduction of generation capacity to a specified setpoint, so that plants could still feed reduced energy into the grid depending on the severity of the congestion, and after the congestion situation ends, they can quickly return to full operational readiness. In contrast, this requires more elaborate signal chains from the detection of the congestion through the algorithmic determination of control commands (e.g., in the grid control system) to signal transmission and implementation in the plant.

Disconnection of the plant via circuit breakers could also be carried out directly through field control devices as part of a decentralized approach with shorter implementation times, if generation plants (or other customer facilities) with direct influence on the congestion situation are available. This would have the advantage that operational resources could tend to be utilized higher temporarily, as the curative measure realized would take effect significantly faster, and the temporary higher utilization would therefore be shorter. A reduction via switching commands could also occur sequentially to ensure a more precise adjustment of the remaining permissible generation capacity. However, the adjustment of such disconnection automatics requires rule-based, robust triggering criteria that cannot be generalized across different failure variants and usage scenarios in more complex grids. Similarly, disconnection via circuit breakers also means that plants are no longer available for providing additional or other system services (e.g., for voltage support).

Considering the mentioned disadvantages, the decentralized and centralized approaches can also be combined, thus leveraging the benefits of both concepts. Considering the permissible time windows, a suitable implementation could therefore include the centralized approach as the main measure and the decentralized approach as a redundancy measure. In terms of maximizing the integration of distributed generators into the 110 kV distribution grids, it is necessary to weigh which concept allows for the greatest possible power intake into the grid.

Figure 4 illustrates, in this context, in step (2) the control signal-based power reduction and, as step (3), the rapid (left) or cascading disconnection (right) of the generation plants implemented here as a redundancy measure.

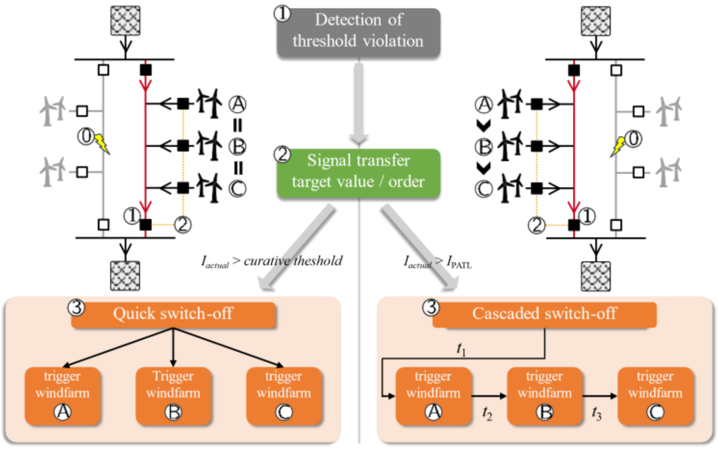

Figure 4. *Possible process implementation of curative system operation upon detection of threshold violations due to an event occurrence (1) using setpoint specifications (2) or protection systems (3) (based on [12]).*

For the deployment of curative measures (here: the reduction of feed-in power to variably specified setpoints within the curative time or effectiveness window), the information exchange occurs via the existing remote-control technology between the grid operator control centre and the customer installations. This can be expanded with additional data points for curative setpoints, activation and triggering, feedback, and expected forecast information from the connected plant. By prioritizing curative setpoints over redispatch, the reduction in generation capacity occurs independently of these. The expansion with new data points can ensure clear documentation. Similarly, this implementation approach allows for the specification of separate characteristic curves for reduction or subsequent power increase by the grid operator when necessary. Additionally, this implementation approach provides the possibility for overbuilt plants (i.e., installed capacity is greater than the agreed feed-in capacity) or plants with battery storage to not only reduce the feed-in power but also to increase it. However, for this application case, the technical limits of the plant and its grid connection must still be adhered to. Using additional "plant-specific forecast information", a targeted forecast can be made for the grid connection point of a plant regarding the expected flexibilities or power reserves and thus about the duration of the anticipated power reduction or additional power provision. The accurate recording of the time periods of a deployment and the reduced power amounts are of significant importance for the economic evaluation of the customer installation, as a widespread implementation of curative measures for connected users can only be achieved with a suitable cost-benefit factor or incentive system.

3. Influencing Factors on the Possibility of Higher Utilisation

The implementation of curative system operation in distribution grids first requires an assessment of specific grid operating conditions during congestions based on the cause of the congestion and various additional criteria. These criteria include but are not limited to:

- Type of asset (transformer, line, etc.) which constitutes the congestion,
- Degree of temporarily increased utilization (difference between component loading in the base case and in the most critical failure variant).
- Higher utilization of components using dynamic temperature monitoring of affected components.

3.1 Type of Asset

The type of asset which constitutes a congestion in the grid is particularly relevant for determining the temporary overload capacity of the circuit, e.g., the thermal behaviour of transformers and lines must be considered differently. Similarly, all other relevant components of a circuit (e.g., converters, trigger values of protection functions, conductor clamps, conductors inside of a station, disconnectors, and circuit breakers) which are affected by the source of the congestion (e.g. current) must be considered.

3.2 Temporary Higher Utilization

The potential of curative system operation approaches is greater the larger the difference in the component load between the present base case (N-0 case or normal operation) and the most critically considered event variant (e.g., a N-1 case). If the permissible component temperature defines the PATL, then with complete utilization of the PATL potential, there is no longer any potential for higher utilization in normal operation. Similarly, higher utilization through curative measures means that further opportunities for curative actions diminish, leading to saturation effects regarding possible efficiency gains. Principally, the TATL must also be adhered to after an event occurs, even when using curative measures. Therefore, only preventive measures are applicable, meaning that even in curative system operation, a preventive measure may be needed to be implemented. The value of possible higher utilization is dependent on the preloading I_{is} (t_e) at the time of the event occurrence (t_e in Figure 2) as well as the effectiveness duration of the chosen curative measure (time difference t_e to t_{e+cur} in Figure 2) and the possible maximum component temperature T_{max}.

3.3 Dynamic Temperature Monitoring

Interactions with approaches to dynamic temperature monitoring must also be considered when evaluating curative potential. Both measures do not necessarily exclude each other and can be used in combination. However, this requires more comprehensive adjustments to operational concepts, such as protection settings, as illustrated in Figure 5.

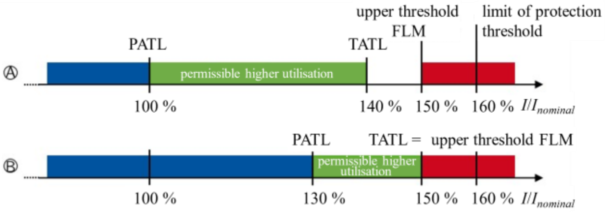

Figure 5. *Interactions between DLR and Curative System Management (based on [12]).*

For example, if dynamic line rating (DLR) is used for higher utilization on a route, the potential for curative measures is lower with an unchanged protection concept: In Case A without DLR, a load range of up to 40% could be utilized curatively, while in Case B, this is only 20%. This is because, when combining DLR and curative approaches, higher utilization of lines can be achieved that could trigger protections and thus lead to cascading failures (see Section 4.2). For this case, new protection concepts would need to be implemented, increasing the operational effort for implementation. Accordingly, the utilized protection concept is also relevant. The most used protection scheme in 110kV grids is distance protection. It relies on self-sufficient protection relays which measure current and voltage and calculate the impedance of transmission lines. In case of emergency (e.g. short-circuit), different relays react within a different time horizon and subsequently trip the faulted line selectively. In case of higher utilization by curative system operation, it must be ensured that protection relays do not cause any false tripping due to higher currents. The interaction between overhead line rating as another method for higher grid utilization and protection schemes is analysed e.g. in [13].

4. Limits in Operation of the High-Voltage Distribution Grid

Various factors can influence the choice of the operating thresholds PATL and TATL, with the ultimately applicable value deriving from the minimum of the available limit values:

- Thermal limits,
- Pickup thresholds of grid protection,
- System limitations and other external constraints.

4.1 Thermal Thresholds

Every component of a power grid has thermal limits that must not be exceeded to avoid risking damage or destruction [11]. Furthermore, for overhead lines, the thermal limits are not only defined by the temperature beyond which the equipment is thermally harmed, but also by the conductor temperature beyond which the line sags so much that sufficient safety clearance can no longer be guaranteed. Besides external factors, such as ambient temperature, solar radiation, and wind speed, resistive losses caused by the flow of current through a conductor particularly influence the temperature of a conductor. In response to sudden changes in influencing factors, such as current, the conductor temperature rises or falls according to the heat energy supplied or dissipated over time, until a thermal equilibrium is established, which can also be seen by comparing subfigure (a) and (b) of Figure 2. A prerequisite for circuits and circuit sections to be temporarily loaded up to their thermal TATL is the ensured availability of a curative measure package that can be activated in the event of a grid disturbance to return the grid to its permanently permissible thermal thresholds within the TATL period. The time interval considered in determining the TATL depends on the technically possible or regulatory prescribed activation and implementation speeds.

4.2 Pickup Thresholds of Grid Protection

The primary task of grid protection in high-voltage distribution grids is short-circuit protection [14]. The types of protective functions (e.g., distance protection) and settings must be carefully chosen by grid operators to ensure that short circuits in the grid are reliably detected and selectively disconnected. Overload protection is typically not used in high-voltage distribution grids. To guarantee safe and selective clearing of short-circuits, distance protection with current or impedance based pickup thresholds is widely used. This is further supplemented by emergency overcurrent protection that ensures protection tripping even in the event of faulty impedance measurement. Under unfavourable operating voltages, high load currents can cause the measured impedance entering the pickup zone of distance protection devices, or it can cause the current falling below any current-based pickup thresholds. The corresponding current is referred to as the protection limit. The PATL and TATL values resulting from the protection limit share the same value.

4.3 System and Other External Limitations

In addition to limits which restrict the permissible loading of circuits or circuit sections from thermal or grid protection perspectives, systemic limits can represent additional factors in determining PATL and TATL. Systemic limits may arise for reasons of grid stability, power plant stability, or voltage control. Existing permissions and emission control measures, e.g. due to the influence on neighbouring pipeline grids, can represent external limiting factors for the permissible current loading of a circuit or circuit section. The PATL and TATL resulting from systemic or external limitations typically share the same value.

4.4 Relevant Time Intervals in the Distribution Grid

Energy flows in the distribution grid are characterized by increasingly volatile generation and demand. Load peaks often occur over periods of only a few hours, while the average loading of the components over weeks is often very low. The effects of this are described hereafter.

4.5 Grid Assets

For components with high thermal inertia, such as transformers, temporary increased load is possible even without curative measures. In contrast, conductors (inside and outside of stations) reach their thermal equilibrium in periods of a few minutes [15]. Switchgear and secondary technology (e.g., current transformers) are also to be considered as additional congestion-determining elements. Current operating specifications do not provide for overload capacity or allow very little of it. However, during standardization, particularly in new installations, devices are often used whose maximum current-carrying capacity exceeds that of the conductor wires, thus not representing a congestion. If the switchgear is the congestion element in the circuit, replacement of the component is essential. Further relevant time intervals of grid assets include those related to protection systems. While these affect grid operation, their interaction with curative system operation is limited as it is generally active in less critical operating states as outlined in Chapter 0. Typical response times of protection systems are limited by the normatively defined maximum short-circuit durations for installations (1 second) and overhead lines (0.5 seconds according to DIN EN 50341-1). Time delays for distance protection devices are usually less than 0.5 seconds. Emergency overcurrent time protection functions are typically triggered after about 0.8 seconds. Thus, considering the switchgear response time, a so-called "safe disconnection" is ensured within the permissible short-circuit durations.

4.6 Control and Regulation of Facilities

Relevant time intervals for curative system operation approaches can also be derived from operational processes. The current standard for the control of decentralized generation plants with control options connected at medium or low voltage is data transmission via mobile or operational radio. Access times typically amount to several minutes, with availability varying in the range of 50-90% of the plants. Control connections are characterized by significantly higher availability and shorter transmission times. However, even for these plants, the power gradients according to VDE AR-N 4120 are limited, and setpoint adjustments are only implemented within minutes. During activation, the grid operator is supported by various systems, but the verification, confirmation, and issuance of control commands is carried out by the grid operator, typically within a timeframe of several minutes.

4.7 Processes of Congestion Management

In addition, redispatch calls should be announced at each full quarter-hour before activation to enable market interaction for cost reduction. Overall, in preventive system operation, the time from detecting the congestion to adjusting the setpoints of customer installations is about 30-45 minutes [16]. The existing operational and control processes are adequate for this purpose.

There was no motivation for further acceleration in preventive system operation. The introduction of curative system operation thus presents new requirements for operational processes.

5. Incentive Mechanisms and Integration of Customer Installations

For operators of customer installations, which include distributed generators or flexibilities such as battery storage systems and electrolysers, participation in curative system operation can be beneficial and financially attractive for various reasons. However, this must be reassessed for each project. A significant advantage of participating in curative system operation lies in the possibility of achieving a timely realization of a grid connection point in an area that may be economically unsuitable when considering preventive system operation. Costs for connecting to higher voltage levels or for longer cable runs could be saved. Therefore, faster and more resource-efficient project realization can be ensured. Higher utilization of existing grid connection points is also possible during the expansion or repowering of plants. From both ecological and economic perspectives, participation in curative system operation can be advantageous. With further expansion and rising costs due to redispatch interventions, it may no longer be possible for grid operators to compensate all losses for redispatch interventions in the future. Curative controllable generation plants can feed into the connected grid for longer periods without their output being reduced due to redispatch interventions. Incentive systems could also be considered to temporarily provide additional value in situations of congestion or higher power demand. In cases of higher installed power capacity, this could involve the short-term provision of additional capacity above the normal contractual connection capacity.

6. Summary & Outlook

This paper highlights the potentials and challenges associated with transferring the concept of curative system operation from the transmission system to the 110 kV distribution grid. The concept of using the TATL in addition to the PATL in curative system operation to increase grid utilization is elaborated. Two possible curative measures are presented to illustrate this: remotely controlling the setpoints of distributed generators via control signals and disconnecting distributed generators using circuit breakers. Furthermore, influencing factors on the possibility of higher utilization as well as relevant thresholds of system operation in the 110 kV distribution grid are presented. In addition, time intervals that are relevant for the implementation of curative measures are evaluated. This is crucial as curative measures need to reduce asset loading from temporary higher loading (up to TATL) to values below PATL as fast as possible. Finally, possible incentives and incentive mechanisms for operators of customer installations to partake in curative system operation are discussed. The paper shows that curative system operation can be transferred to the 110 kV distribution grid and that a promising potential for higher utilization of the existing grid is offered once all identified challenges are considered.

The research project *kurSyV* (Curative System Operation in the Distribution Grid, German: *kur*ative *Sys*temführung im *V*erteilnetz) investigates methods for curative system operation in the high-voltage distribution grid. It aims at developing practical approaches based on concrete real-world examples, and verifying the approaches in laboratory and field tests. Both the specific grid-side requirements in the 110kV level as well as the customer-side flexibility potentials available in this voltage level are addressed. Specifically, standardized solution concepts for the application of curative measures are developed (e.g., based on typical grid topologies of 110kV grids), expansion needs in monitoring and control technology are identified (e.g., new algorithms to monitor available flexibility potentials of customer installations in the field, to automatically pre-evaluating the potential utilization of such flexibilities as curative measures in network security calculations, or to automatic trigger curative actions following a critical network contingency), and the interaction between curative system operation and grid planning is evaluated. The goal is to derive specific criteria and potentials based on which the most advantageous concept can be selected for particular grid situations. This also includes an estimation of when which concept should be used depending on the conditions in a grid area, e.g.

which concepts are most fitting for areas with high wind penetration and comparatively low load. Therefore, it should be ensured that the implementation of curative measures can be utilized modularly for various application cases in the 110 kV level in the future. Based on this, effective and quickly implementable best-practice solutions for grid operation and planning, utilizing the flexibilities available in the distribution grid, should be identified. The developed implementation options will be analysed during the project regarding their applicability and practical relevance. Additionally, incentive systems will be further developed in collaboration with operator of customer installations to make the provision of grid-oriented flexibility attractive for operators. By facilitating higher utilization of grid assets, methods for curative system operation have the potential to improve the integration of renewable energy generation plants and make a significant contribution to the energy transition. The expansion of the distribution grid, i.e. building new grid assets such as overhead lines, is very cost- and time-intensive. By increasing the potential utilization of the existing grid, the energy transition can be accelerated, and grid structures can be utilized more efficiently through the flexible deployment of customer installations. For flexibility management, along with the determination and assessment of measures to integrate high shares of renewable energy into the operational planning process of the distribution grid, dynamic aspects will increasingly need to be examined alongside stationary effects in the future. Considering the temporal temperature profile of a conductor during a curative measure enables more efficient utilization of an asset within its physical system limits. Besides overhead lines, this concept is generally also transferable to other asset types.

Data availability statement

There is no data available in relation to this paper.

Underlying and related material

There is no underlying and related material for this paper.

Author contributions

All authors were involved equally in writing the paper (original draft as well as review and editing). The paper was conceptualized by Denis Mende.

Competing interests

The authors declare that they have no competing interests.

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