Requirements of curative system operation on the behavior of the protection system in an extensive sub transmission grid

1st Franz Jani
Chair of Electrical Power Systems
Dresden University of Technology
Dresden, Germany
franz.jani@tu-dresden.de

2nd Oliver Groß
Chair of Electrical Power Systems
Dresden University of Technology
Dresden, Germany
ol.gross@gmx.net

3rd Peter Schegner
Chair of Electrical Power Systems
Dresden University of Technology
Dresden, Germany
peter.schegner@tu-dresden.de

4th Martin Wolter
Chair of Electrical Power Systems
Dresden University of Technology
Dresden, Germany
martin.wolter@tu-dresden.de

***Abstract*—Curative system operation temporary overloads of grid components to increase grid utilization and facilitate the integration of distributed energy resources. However, short-term overloads may trigger undesired protection system reaction or trips, potentially causing cascading outages. This work investigates the adaptation of protection systems in a realistic 110-kV test grid to ensure reliable fault detection while enabling curative operation. Using steady-state and root mean square simulations in PowerFactory, state-of-the-art protection settings are evaluated alongside adaptations with extended back-up times and increased pickup thresholds. Results show that extending the directional and non-directional back-up times effectively prevents unwanted tripping during distributed energy resource curtailment without compromising fault detection reliability and equipment, or thermal damage. The study provides guidance for protection system adaptations and identifies limitations for further research in curative system operation.**

***Index Terms*—curative system operation, sub transmission grids, protection systems, temporary overloads**

I. Introduction

The ongoing energy transition in Germany has led to a significant increase in installed generation capacity. This development is driven by the shift from centralized power plants to a decentralized generation structure with a high share of renewable energy sources, as well as by the electrification of sectors such as heating and mobility [1]. As a result, the grid infrastructure must be expanded to ensure a secure and reliable power supply. However, grid expansion is lagging behind the rising power demand [2], resulting in higher utilization of existing grid assets. To prevent component overloads, preventive system operation is currently applied. The (n-1)-criterion is central to this approach, requiring that the outage of any single grid component must not cause overloads in the remaining components. While this ensures high operational security, it may lead to underutilization of the existing grid infrastructure. In contrast, curative system operation refers to an approach that allows short-term overloads of grid components in the event of an outage, provided that corrective actions can be applied in time to relieve the system and prevent permanent damage to the equipment [3] [4]. This approach can increase the utilization of existing grid assets, reduce the need for grid expansion, and facilitate the integration of renewable energy sources. A suitable explanation of the difference between preventive and curative system operation are two parallel overhead lines. In preventive operation, both lines are operated below their permanent admissible transmission load (PATL) [4] [5] so that, in the event of a line outage, the remaining line can carry the entire load without exceeding its limits. In curative operation, both lines may be loaded close to their PATL. If one line trips, the other may temporarily exceed its PATL but remain below its temporary admissible transmission load (TATL) [4] [5]. Curative actions must then be initiated promptly to prevent thermal overload and equipment damage. The key distinction lies in timing: preventive measures are applied before a contingency occurs, while curative actions are executed afterward to restore secure operation. The PATL and TATL define the curative potential of a grid component and are determined by the most restrictive component characteristics, external conditions, and system constraints [6]. One critical constraint is that the protection system operates as intended. Research on curative system operation has so far focused mainly on transmission grids, with some work addressing distribution grids. The InnoSys2030 [6] project investigates curative operation regarding system control, stability, protection, and cybersecurity. In terms of protection, it proposes adaptive protection schemes to meet curative operation requirements. Building on this, [7] analyzes the effects on distance protection and suggests methods to avoid unwanted tripping caused by impedance shifts during high-current conditions. However, no practical case study was presented.

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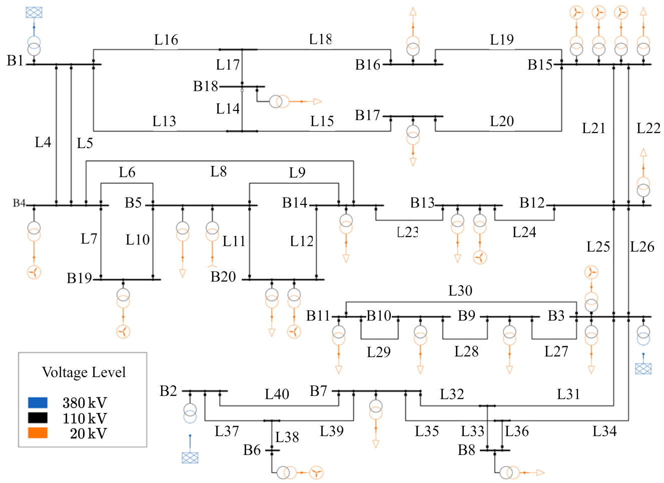

Fig. 1. 110 kV Test Grid

TABLE I
OPERATING CASES

Case	Amount of used DERs	f_{Load}
1	10	0.25
2	10	1.00
3	10	4.00
4	9	$\{0.25, 5, 4, 6, 0.25, 0.25, 0.25, 0.25, 0.25, 0.25, 0.25, 0.25, 1\}$

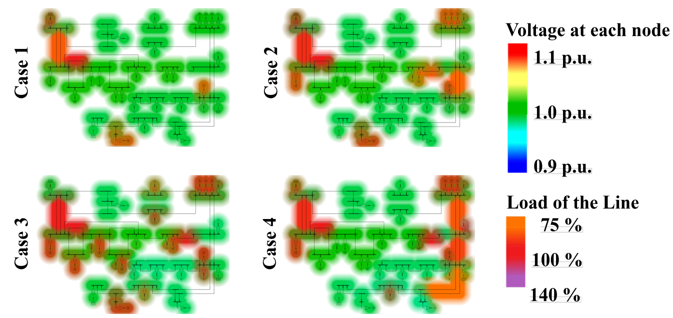

Fig. 2. Visualization of the four operating cases (utilization of the lines and voltage levels of each node)

Other studies focus on optimizing curative measures such as redispatch, load shedding, or grid reconfiguration [8]. This paper investigates the implications of curative system operation on the protection system in a 110-kV test grid modeled in PowerFactory. It analyzes line loading after a line outage, the behavior of the existing line protection, and curative actions implemented via distributed energy resources (DER) using optimal power flow. Finally, 2 approaches for adapting the protection system is proposed and validated by simulation.

II. Modelling

This section outlines the modeling approach adopted for this study, covering the test grid, the representation of curative system operation and its associated time constraints, as well as the protection system configuration.

A. 110 kV Test Grid

The investigations are carried out on a 110-kV test grid, which is shown in Fig. 1. The grid consists of 25 nodes, 35 lines, 10 DERs, and 15 loads. All specific parameters of the grid are provided in [9] and [10]. There are connections to three separate upstream independent networks, but no interconnections exist between them; hence, any mutual influence, such as through loop flows, was not considered. The difference to the grid in [9] and [10] is the modification of the nominal power of the DERs and loads to create a more heavily utilized grid. Each DER has a nominal power of $S_{\mathrm{DER}} = 100\,\mathrm{MVA}$. In four different cases, the load situation is varied by scaling the nominal power of all loads with the factor f_{Load}, as shown in Table I, while the corresponding DER feed-in power is determined by an initial optimal power flow algorithm performed for each case as described in Section III B. Case 1 represents a scenario with a high load concentrated on a single double line, whereas Case 4 corresponds to a situation where all double lines experience heavy loading. Cases 2 and 3 represent intermediate situations with gradually increasing load distribution and DER utilization. The purpose of these scenarios is to compare the effects of highly localized loading with those of widespread high utilization across the entire grid. This is modeled by using only 9 of the 10 DERs in combination with a distributed scaling factor. For each case, varying load factors (LFA) are applied, reflecting the equipmement loading as a percentage of the PATL (LFA = 80%, 90%, 100% PATL) For the purpose of illustration the four cases are visualized in Fig. 2.

B. Protection System

The protection system consists of a distance protection unit at each line end, equipped with four forward-looking zones and one reverse-looking zone. The considered pickup methods are overcurrent (I-pickup) and voltage-dependent overcurrent (U/I-pickup), as these are commonly applied in sub-transmission networks. The key settings relevant to this work are summarized in Table II. Due to the high grid utilization, only the pickup value $I_{>}$ is included in Table II, while other configuration parameters can be found in [9].

C. Time constraints

If a line outage occurs, other lines may become overloaded. In such cases, a curative measure must be initiated to relieve the affected components. The duration of this process is constrained by several time factors: the time required to decide which curative measure to apply, the dissemination of this information to all involved DERs, and finally, the execution time for the DERs to implement the curtailment. The first two time factors are assumed to all together take $\Delta t_{\mathrm{Signal}} + \Delta t_{\mathrm{M}} = 1\,\mathrm{s}$. The time required for the DERs to adjust their output Δt_{dP} is defined by their active power gradient $\frac{\mathrm{dP}}{\mathrm{dt}}$ after the German standard VDE-TAR4120 [11] or the requirements made up by the distribution grid operator TAB-Avacon [12]. These data can be found in Tab. III.

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TABLE II

LINE PROTECTION SETTINGS

Setting	I and U/I pickup
$I_>$	$1.4 \cdot I_\mathrm{r}$
t_dir	$2.8\,\mathrm{s}$
$t_\mathrm{non\,dir}$	$4.7\,\mathrm{s}$

TABLE III

DER CURTAILMENT TIMES

Standard	Active Power Gradient $\frac{\mathrm{d}P}{\mathrm{d}t}$	Δt_dP
VDE-TAR4120 (min.)	$0.33\,\%\,P_\mathrm{inst}/\mathrm{s}$	303 s
VDE-TAR4120 (max.)	$0.66\,\%\,P_\mathrm{inst}/\mathrm{s}$	151 s
TAB-Avacon (min.)	$2.00\,\%\,P_\mathrm{inst}/\mathrm{s}$	50 s
TAB-Avacon (max.)	$5.00\,\%\,P_\mathrm{inst}/\mathrm{s}$	20 s

Therefore, the total time available to relieve an overloaded line is given by:

$$t_\mathrm{Cur} = \Delta t_\mathrm{Signal} + \Delta t_\mathrm{Cur} + \Delta t_\mathrm{dP} = 21\,\mathrm{s} \ldots 304\,\mathrm{s} \qquad (1)$$

III. SIMULATION-BASED ANALYSIS

This section presents a simulation-based analysis of the 110 kV test grid in PowerFactory. The study focuses on the impact of line outages on the loading of remaining lines and on the response of the protection system. First, an (n-1) contingency analysis is performed to assess the grid utilization under (n-1) conditions. Subsequently, an optimal power flow (using the Interior Point method [13]) is applied to determine curative measures for relieving overloaded lines through DER curtailment. Finally, the protection system response is assessed for the state of the art and both proposed methods.

A. *(n-1)-contingency analysis*

In a first step, a comprehensive (n-1)-contingency analysis is performed for all four operating cases and the three PATL levels. Each scenario sequentially disconnects every line, recording the loading of the remaining ones. This allows for the identification of lines that become overloaded due to the outage of a specific line. The results of this analysis are summarized in Fig. 3, which shows the number of overloads occurring in the grid for case 4 as a heatmap. A line outage is represented through an red cross inside the corresponding cell. A utilization above the PATL is indicated by a black frame. The figure reveals that, in case of a line outage of a double line, the parallel line becomes overloaded (L04/05, L21/22, L25/26, L31/34). Additionally, other lines in the grid also experience overloads (L06 after an outage of L24). If we consider now the reaction of the protection system to these overloads, it becomes evident that unwanted tripping occurs in several scenarios. Fig. 4 illustrates the (n-2) up to (n-4) state. Because an outage of L26 up to L40 has no effect on the protection system, these lines are not shown in Fig. 4. Starting from the outage of one system of the double circuit line L04/L05, the remaining system becomes overloaded and is subsequently disconnected after exceeding its protection threshold. This leads to severe overloading of lines L23 and

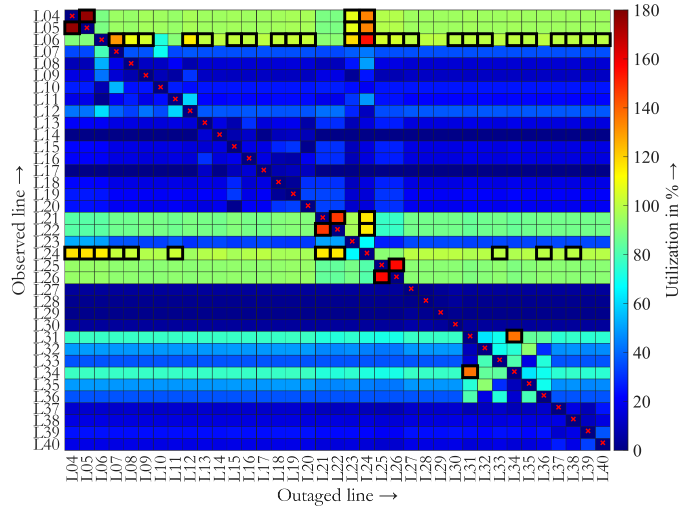

Fig. 3. (n-1)-contingency analysis results for case 4

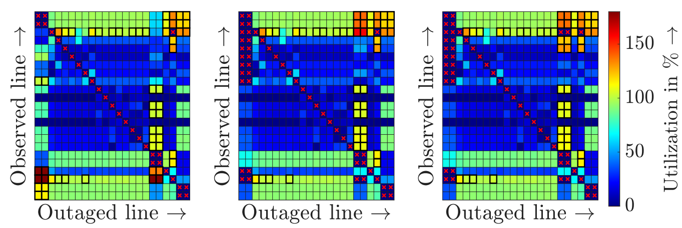

Fig. 4. (n-2)- to (n-4)-state after response of the protection system (case 4)

L24, which are also tripped. Consequently, an entire grid section between lines L06 and L12 becomes isolated from the rest of the grid, resulting in a large-scale supply interruption. This case illustrates the potential consequences of an inadequately coordinated protection system during curative grid operation. To prevent such cascading failures and ensure supply security, appropriate protection coordination and curative measures are required. In Fig. 5 the utilization of every line is illstrated.

B. *Implementation of curative measures*

Following the contingency analysis, the required curative actions, such as DER curtailment, are identified to manage congestion after a line outage. Using AC optimal power flow (OPF), individual optimal active power setpoints are calculated for each DER while ensuring that operational security limits are respected. In this work, the integrated OPF module of PowerFactory is used, which solves a nonlinear AC-OPF problem using the Interior-Point method [13]. The objective function minimizes deviations of the DER active power setpoints, subject to constraints on the active and reactive power limits of DERs, node voltage limits, and line utilization limits according to PATL values. The optimization is performed for all grid switching states, incorporating scenario-specific line loading constraints. To prevent unnecessary curtailment in scenarios where no limits are violated, the penalty weighting factor is set to $\mu_\mathrm{min} = 10^{-5}$, allowing the solver to terminate at the initial point if all constraints are satisfied.

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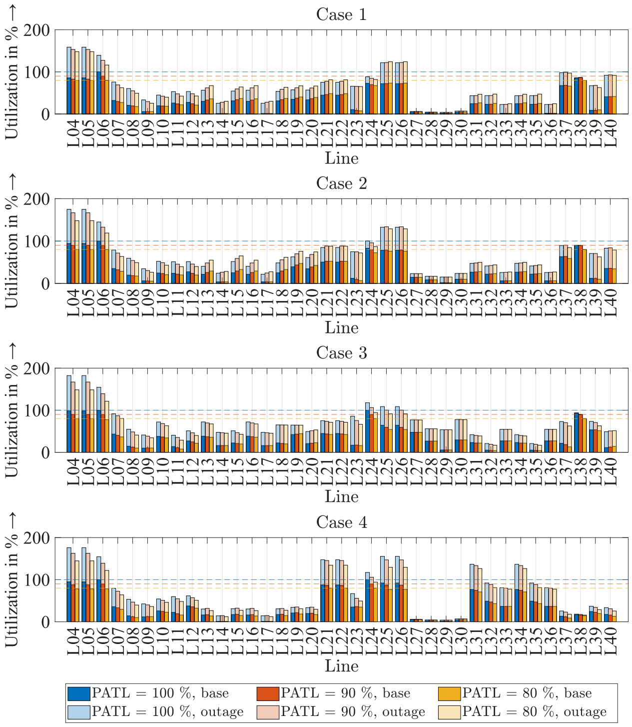

Fig. 5. Maximum utilization of each line at (n-1)-state

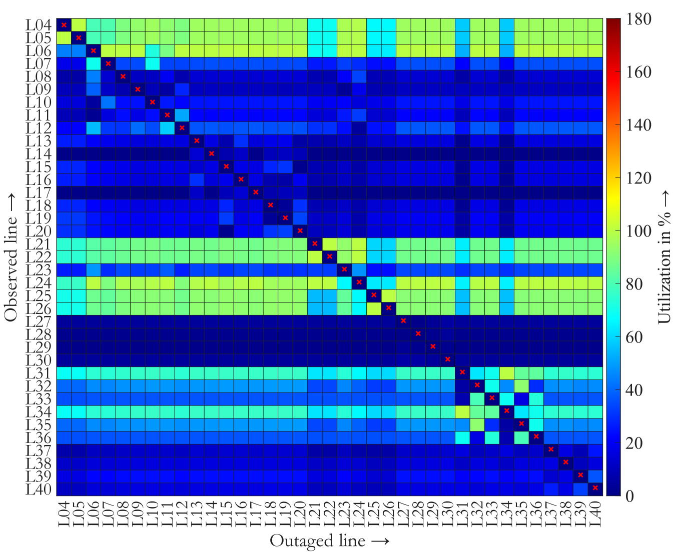

Fig. 6. Maximum utilization of each line at (n-1)-state after curative DER curtailment

The resulting utilization in (n-1)-state after curative DER curtailment is shown in Fig. 6. All lines are relieved below their PATL. Using the new DER setpoints and the active power gradients $\frac{\mathrm{d}P}{\mathrm{d}t}$ from Table III, the curative DER curtailment time is calculated. The results are summarized in Fig. 7. First to acknowledge is the trivial correlation between the active power gradient $\frac{\mathrm{d}P}{\mathrm{d}t}$ and the time required for curative DER curtailment. There is also a correlation between the different cases and the maximum value of Δt_{dP}. Cases with a

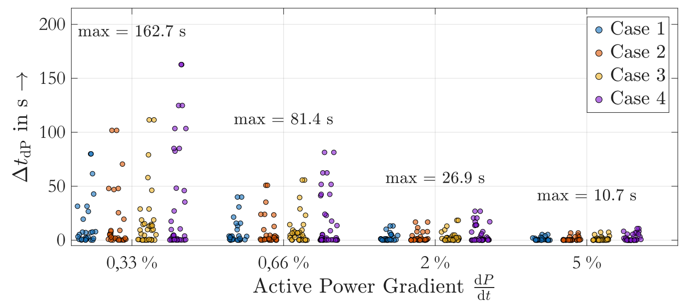

Fig. 7. time required for curative DER curtailment in every case

concentrated high utilization require significantly less time for curative DER curtailment compared to cases with a widespread high utilization. Case 4 is also an exception, because only 9 of the 10 DERs are used. Therefore, less curative potential is available. In all cases, the calculated values of Δt_{dP} remain below the corresponding maximum values given in Table III, since a complete curtailment of a DER is not required in any case. For all active power gradients $\frac{\mathrm{d}P}{\mathrm{d}t}$, it can be observed that the maximum time required for curative DER curtailment is considerably shorter than the maximum times listed in Tab. III, since a full curtailment of a DER is never necessary.

C. Validation through RMS-Simulation

RMS simulations in PowerFactory validate the steady-state analysis and protection system response. Fig. 8 illustrates the response of the protection system after a line outage of L05 for case 4 with a LFA of 100 % PATL and a $\frac{\mathrm{dP}}{\mathrm{dt}} = 5\% \frac{P_{\mathrm{inst}}}{\mathrm{s}}$. At $t = 1\,\mathrm{s}$, the line outage occurs. The current in the parallel line L04 exceeds the pickup threshold of its protection system. At $t = 2\,\mathrm{s}$, the required curative actions for all DERs are computed, transmitted, and the corresponding curtailment begins. At approximately $t = 3.8\,\mathrm{s}$, the protection system of L04 operates in directional back-up time mode ($t_{\mathrm{dir}} = 2.8\,\mathrm{s}$), resulting in the tripping of L04. This, in turn, causes a severe overload of lines L23 and L24, which subsequently trip after their respective directional back-up time delays. Consequently, a large section of the grid becomes isolated from the rest of the system, leading to a significant supply interruption. The RMS simulation confirms the steady-state results and highlights the need to adapt the protection system to avoid unwanted tripping.

D. Adaptation of the Protection System

Two main approaches can adapt the protection system to curative operation requirements without major concept changes. The first approach is to allow a pickup but increase the directional and non-directional back-up time delays to values exceeding the maximum duration of the curative action ($t_{\mathrm{dir}} = t_{\mathrm{non\,dir}} = 12\,\mathrm{s}$). The underlying assumption is that an actual fault will be detected either by one of the zones of the distance protection relay or by a redundant protection unit of another line. Therefore, the increased delay time does not compromise the reliability of fault detection.

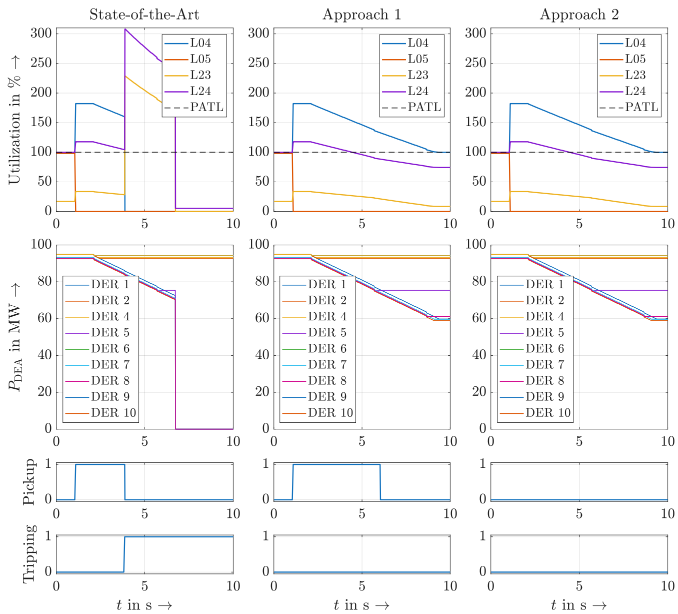

Fig. 8. RMS simulation results of the protection system response after the line outage of L05 (case 4, PATL 100%, $\frac{\mathrm{d}P}{\mathrm{d}t} = 5\% \frac{P_{\mathrm{inst}}}{\mathrm{s}}$). Left: state-of-the-art protection settings. Middle: adapted protection settings with extended back-up times. Right: adapted protection settings with increased pickup threshold.

The second approach aims to prevent the pickup of the protection system during curative operation by increasing the pickup threshold. This ensures that no pickup occurs within the curative time frame. However, this method may reduce the sensitivity of the protection system and its ability to detect faults in low-utilization cases. Alternatively, this approach can be realized through advanced pickup methods, such as impedance-based pickup or adaptive protection schemes, where the threshold is dynamically adjusted online according to the current operating conditions of the grid. As [6] mentioned, impedance-based pickup methods are particularly suitable under extreme high load conditions, but require further investigations. Fig. 8 shows that both adaptation approaches are effective for the outage of line L05. In approach 1, the pickup of the distance protection system becomes visible. Interestingly, this pickup remains active for only about $\Delta t \approx 5\,\mathrm{s}$. Therefore, for each specific case, it should be carefully assessed which duration is actually required to adjust the directional and non-directional back-up time delays appropriately.

IV. Conclusion

This work investigated the requirements and challenges of implementing curative system operation in sub transmission grids, with a particular focus on the response of protection systems under temporary overload conditions. Using a 110 kV test grid, both steady-state and RMS-simulations were conducted to analyze the effects of line outages on the loading lines and the behavior of conventional distance protection units. The results demonstrate that, without adaptation, state-of-the-art protection settings may lead to unwanted tripping during the curative DER curtailment period, potentially causing cascading outages and significant supply interruptions. Two main adaptation strategies were examined: extending the directional and non-directional back-up time delays, and increasing the pickup thresholds of protection units. Among the evaluated measures, extending back-up time delays proved most effective in preventing undesired tripping while maintaining reliable fault detection. Increasing the pickup threshold is an alternative but may reduce sensitivity under low-loading conditions. The results emphasize the need to coordinate curative DER actions with protection settings to ensure secure operation during contingencies. In addition, sufficiently high DER active power gradients are required; future work should therefore determine suitable gradients alongside optimized directional and non-directional back-up delay settings.

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