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Improving Frequency Defence Schemes for Critical System Conditions in the Continental European Power System

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SUMMARY

As the electricity sector transitions towards a low-carbon future, an increasing proportion of synchronous generation in the power system is replaced with inverter-based resources (IBRs). The result is a reduction in the available rotational inertia in the grid, depleting its ability to withstand and arrest frequency changes following disturbances. Consequently, disturbances such as a loss of generation or load have an increasingly larger impact on the system, resulting in higher frequency deviations and increased rate of change of frequency (RoCoF).

On two occasions in 2021, the Continental Europe Synchronous Area (CESA) experienced system-splitting events caused by cascading trips of several transmission system protection elements. In both cases, system defence plans were activated to preserve the integrity of the overall system [1, 2]. The amount of disconnected load was limited on both occasions, however, should similar events occur in the future with even lower rotational inertia in the grid, the impact could be more severe. This raises the question of whether the existing defence measures are sufficient to maintain system integrity and stable system operation.

Currently in CESA, containment of system frequency excursions following a severe loss of generation is achieved through low-frequency demand disconnection (LFDD) at a frequency below 49Hz. Due to the reduction in traditional synchronous generation and system inertia, the frequency stability of the system is expected to deteriorate, leading to an elevated impact of major disturbances, a rising probability of forced disconnections at frequencies below 49 Hz, and the potential for cascading loss of generation and blackout events.

The objective of this research is to explore the potential impact of reduced system inertia and increased penetration of renewable generation on the performance of the traditional LFDD scheme. In conjunction, additional proactive measures are proposed and investigated with the aim to reduce the probability of LFDD activations, by taking actions at frequency thresholds between 50 and 49Hz, as well as to improve the performance of the LFDD scheme in the event that disconnections are required. As a test case, the LFDD scheme as currently applied by one of the distribution system operators in the Netherlands is considered.

This project is therefore categorised in three primary research directions: (i) Exploring the effect of increased IBR on frequency deviation and LFDD performance following contingency events (ii) improving selection criteria for LFDD load shedding locations, and (iii) improving LFDD performance using alternative load shedding schemes.

Key topics explored in this research include: (i) the use of system strength and real-time DER generation as input parameters to load bus selection criteria for LFDD, and (ii) proactive RoCoF-based disconnection of pre-determined consumers above 49Hz. The findings of this study indicate that adapting the LFDD implementation based on the local system strength and the level of active DER generation at LFDD buses can improve frequency response and reduce instability following LFDD switching operations. Furthermore, proactive RoCoF-based load disconnection above 49Hz proves effective in reducing frequency deviation during the most severe events while avoiding over-shedding for smaller contingencies.

This research provides insights for power grid operators and policymakers in Continental Europe. It aims to enhance grid resilience and reduce the risk of potential blackouts amid the increasing integration of inverter-based generation. Through further investigation, validation and implementation of these strategies, IBR-dominated power systems are expected to better cope with large disturbances.

KEYWORDS
Energy Transition, Low Frequency Demand Disconnection, Low-Inertia, RoCoF, System Defence.

1. INTRODUCTION

The predicted growth in penetration of renewable energy sources (RES) and inverter-based resources (IBRs) on the power grid is set to have an increasing effect on power system dynamics [3,4]. The effects of this change can be seen in many areas of power system dynamics such as voltage control, system protection, congestion management, grid stability, and system inertia [5, 6, 7]. Higher frequency deviation and rate of change of frequency (RoCoF) values will be seen for low inertia systems in response to an imbalance in comparison with a traditional system [8]. As a result of higher RoCoF values following a disturbance, the system frequency is more likely to breach safe thresholds before control measures can react and restore balance [9].

Given the anticipated increase in IBRs in the Central European Synchronous Area (CESA), existing system defence measures may be insufficient to arrest frequency decline should a severe contingency occur in the future. In addition, the uncontrolled disconnection of distributed resources in response to a frequency decline event introduces further risks to system stability. To enable the continued addition of non-synchronous generation to the power system, research is ongoing into possible solutions such as synchronous condensers with flywheels, Voltage Source Converters (VSC) with regulating capacities, grid forming converter technology, constant verification and tuning of load shedding plans, inclusion of renewables in fast regulation and system support, etc. [10,11].

The purpose of this research is to investigate, firstly, the effect of increased penetration of renewable energy on post-contingency power system dynamics and, subsequently, the corresponding effect on the performance of the existing underfrequency system defence measures. Findings from this initial research phase are used to guide investigation into potential improvements to existing defence measures to enable a more robust response to contingency events and reduce the risk of cascading disconnections and blackouts in the future power system.

This paper is organised as follows: Section 2 describes the method used to model the existing Dutch LFDD scheme on a template network and assess the effect of increased IBR penetration on LFDD performance. In the third section, the effect of IBR penetration on the performance of the traditional LFDD scheme in the template model is described. Following this, modelling method and results for the evaluation of four proposed improvements to traditional LFDD schemes are presented. Finally, the main outcomes are summarised and possible continuations of this research are defined.

2. MODELLING METHODOLOGY

Modelling and simulations in this analysis are performed using DIgSILENT PowerFactory 2022 SP4. Grid modelling and simulations for this project are performed on the New England 39 Bus template network available in PowerFactory. The system frequency is set to 50Hz for all simulations. Seven different operating scenarios are created for the analyses. In each sequentially higher IBR penetration scenario, one extra synchronous generator is replaced by a non-synchronous generator, as shown in Table 1. As the penetration of non-synchronous generation increases, total system inertia decreases. Frequency deviation and the performance of the LFDD scheme in all scenarios are evaluated based on a series of large power unbalance events.

Western Electricity Coordinating Council (WECC) type 4B template wind turbine generators [12] are used to replace the synchronous generators in this model. The power balance on the network was maintained for each scenario by matching the active power dispatch and MVA rating of the WECC template generators with the synchronous generator being replaced. No changes were made to other wind generator functions such as protection, electrical control, or the generator-converter model.

To quantify the penetration of renewable energy on the network, the System Non-Synchronous Penetration (SNSP) is used [9]. This parameter was introduced by the Irish Transmission System Operator, Eirgrid, and is used to represent the amount of non-synchronous generation on the system at any instant. SNSP is given by the equation below where the total non-synchronous generation is expressed as a percentage of the total load on the network.

$$SNSP = \frac{NonSync\ Gen}{Total\ Load}$$

It is important to note that this index is relative to the load present on the 39 Bus test grid and does not take into account the load associated with G01, which represents the connection to the rest of the transmission system outside the 39 bus grid.
In a system with synchronous condensers and large amounts of import/export, the equation would need to be altered to reflect these exchanges. As there are no synchronous condensers in this system, the SNSP parameter is taken as an effective method of highlighting the relative level of inertia on the grid in each operating scenario.
Contingency events were created by sequentially turning on static loads connected to Bus 39 of the system. Each load has an active power demand of 500MW and a time delay of 300ms was used between switching of sequential loads. Switching on loads sequentially at this location simulates the loss of generation at a distant point in the network, resulting in an active power deficit on the test network. Three contingency event sizes were used in the analysis of the existing Dutch LFDD scheme. These events were of magnitude 500MW, 1000MW and 1500MW respectively. The total load on the test network is 6100MW.

Table 1: Scenarios used in this project combined with associated inertia values

Scenario	Active Sync Gens	Active IBR Gens	SNSP	System Inertia – H [s]
Full Sync Gen	10	0	0%	4.77
Scenario 1	9	1	9%	4.62
Scenario 2	8	2	20%	4.45
Scenario 3	7	3	33%	4.24
Scenario 4	6	4	43%	4.08
Scenario 5	5	5	53%	3.87
Scenario 6	4	6	66%	3.61

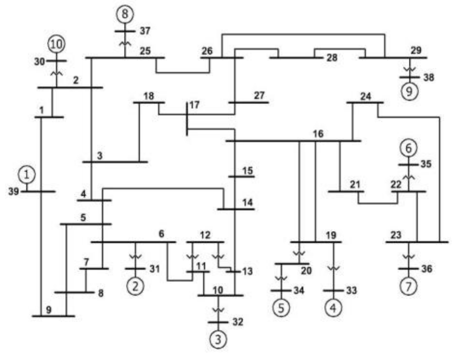

Figure 1: New England 39 Bus Test Network

In the analysis of the existing Dutch LFDD scheme, two separate LFDD schemes were developed based on the Dutch grid code requirement for 6 load shedding thresholds with 7.5% of the peak system load in each threshold. A breakdown of the threshold (step) settings in the two LFDD schemes is presented in Table 2. The frequency threshold for disconnection of step 1 is 49Hz with 0.2Hz gap between each sequential threshold. The final threshold where the demand is disconnected is at 48Hz.

Table 2: Traditional LFDD Schemes Developed for Analysis

	% of Total Load						
Step No	**Step 1**	**Step 2**	**Step 3**	**Step 4**	**Step 5**	**Step 6**	**Total**
LFDD Scheme 1	8.6	7.2	8.2	10	5.4	5.1	45.1
LFDD Scheme 2	6.9	7.1	8.6	7.9	8	8.2	46.6

It should be noted that graphical and tabular results for each simulation are ordered based on the minimum frequency, where the scenario with the minimum frequency value (worst case) appears at the bottom of the legend and is shown as a red line in the corresponding graph.

3. EFFECT OF IBR PENETRATION ON LFDD PERFORMANCE

In Figure 2 the response of the network with LFDD active is shown for a contingency event of 1000MW and 1500MW. The load shedding amount in each renewable energy penetration scenario is also presented. Load shedding amount is dependent on the minimum frequency value seen in each system configuration.
The effect of higher IBR penetration and lower system inertia can be seen by observing the difference in load shedding amount between operating scenarios. In lower inertia scenarios, the frequency nadir is

deeper, causing more load to be shed. In response to the 1000MW contingency, the result of breaching the second LFDD threshold of 48.8Hz and shedding an extra 7.5% of peak load is a more rapid return towards the nominal frequency. In scenarios with lower system inertia, earlier activation of the LFDD scheme can be seen than in scenarios with more synchronous generation active. This is understandable due to the increased RoCoF also seen in low inertia scenarios. Scenarios with SNSP greater than 20% see step 2 breached in 9s. The same threshold is breached almost two seconds later in the scenario with 9% SNSP.

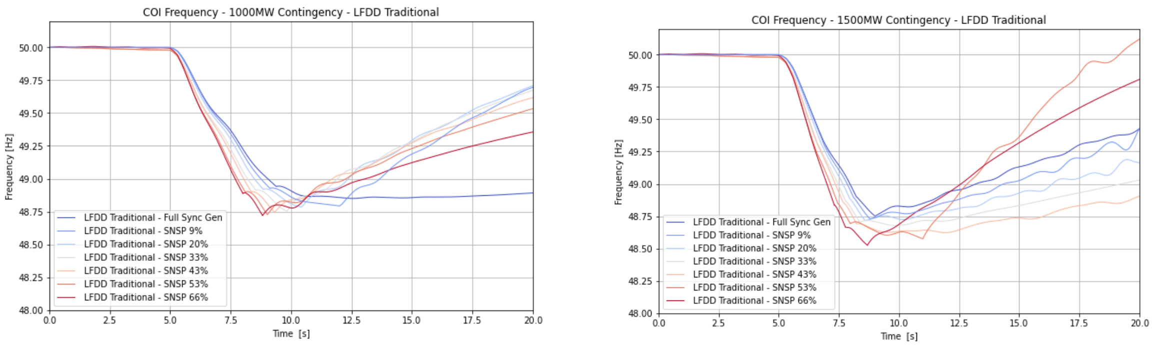

Figure 2: Effect of IBR penetration on frequency response and load shedding amount.

Table 3: Minimum Frequency and RoCoF and Load Shedding Amount for Traditional LFDD Scheme

Event Size	1000MW			1500MW		
	Min Frequency	Min RoCoF	Load Shed	Min Frequency	Min RoCoF	Load Shed
Scenario	[Hz]	[Hz/s]	[MW]	[Hz]	[Hz/s]	[MW]
Full Sync Gen	48.85	-0.371	522	48.75	-0.471	964
SNSP 9%	48.79	-0.373	964	48.72	-0.571	964
SNSP 20%	48.79	-0.396	964	48.72	-0.511	964
SNSP 33%	48.75	-0.463	964	48.68	-0.564	964
SNSP 43%	48.74	-0.422	964	48.63	-0.577	964
SNSP 53%	48.73	-0.469	964	48.58	-0.628	1464
SNSP 66%	48.72	-0.484	964	48.52	-0.688	1464

Shedding more load for the same contingency event could result in an overshoot of frequency as the system recovers. This is apparent in response to the 1500MW event as the slope of the frequency for the SNSP 66% and SNSP 53% scenarios does not lessen as the frequency reaches 50Hz. They also highlight the effect of the fixed thresholds used in the traditional LFDD scheme. In some cases, in response to the 1500MW contingency, the frequency breaches the 48.6Hz threshold of step 3 by a small margin and still the full 7.5% of the load in this threshold is shed. It is possible that the system could recover without shedding the whole of the added 7.5% total load in step 3 during an event such as this. Although the existing LFDD scheme does successfully stop frequency decline for this test network, several areas for improvement have been identified in relation to load bus selection and the ability of the LFDD scheme to adapt to lower inertia scenarios.

4. IMPROVEMENT TO LFDD: LOAD SELECTION CRITERIA – ACTIVE DER GENERATION

To analyse the effect on system dynamics of disconnecting distributed energy resources (DERs) during LFDD, six DER units are added to the test grid. The aim of this section is to understand the effect of unintentionally disconnecting active DER generation during LFDD switching operations. Therefore, six DER units are added to the model at the bus locations that were already included in the LFDD scheme. The utilized LFDD scheme is a traditional LFDD scheme based on the Dutch grid code.

The active power output of the DER was varied between 25%, 50%, and 75% of the load connected at the same bus, as outlined in Table 4. Simulations were carried out for various contingency event sizes to assess the impact of disconnecting active DERs on the performance of the LFDD scheme. Each simulation (a combination of a certain contingency event size and DER generation percentage) was carried out for all IBR penetration scenarios. Thus, allowing the effect of reduced inertia on system resilience to tripping DERs to be examined.

Table 4: DER Generation Overview

Bus No.	Load Active Power (MW)	DER Active Power (25% Load) (MW)	DER Active Power (50% Load) (MW)	DER Active Power (75% Load) (MW)
3	322	80.5	161	241.5
4	500	125	250	375
8	522	130.5	261	391.5
16	329	82.3	164.5	246.8
18	158	39.5	79	118.5
29	283.5	70.9	141.8	212.6
Total	2114.5	528.6	1057.3	1585.9

The effect of shedding different amounts of active DER generation on LFDD performance is presented in Figure 3. As all DERs are connected at buses that are included in the LFDD scheme, should LFDD switching operations take place, one or more DERs will be disconnected at the same time as the corresponding load. Frequency plots are presented for each IBR penetration scenario and DER generation level. It can be seen in Figure 3 that a small percentage of DER generation (25% of the associated load) can affect the restoration of system frequency following LFDD. Disconnecting active DER generation prevents the power balance from being effectively restored as the LFDD scheme is not disconnecting the pre-estimated amount of load. The effect of a small amount of active DER generation being disconnected can be seen as the frequency in all scenarios is slower to recover towards nominal values than in the case of no DER generation.
Increasing the DER generation to 50% of the associated load results in further degradation of LFDD performance. In this case, the power balance is not restored and therefore the system frequency does not recover within the simulation time frame.

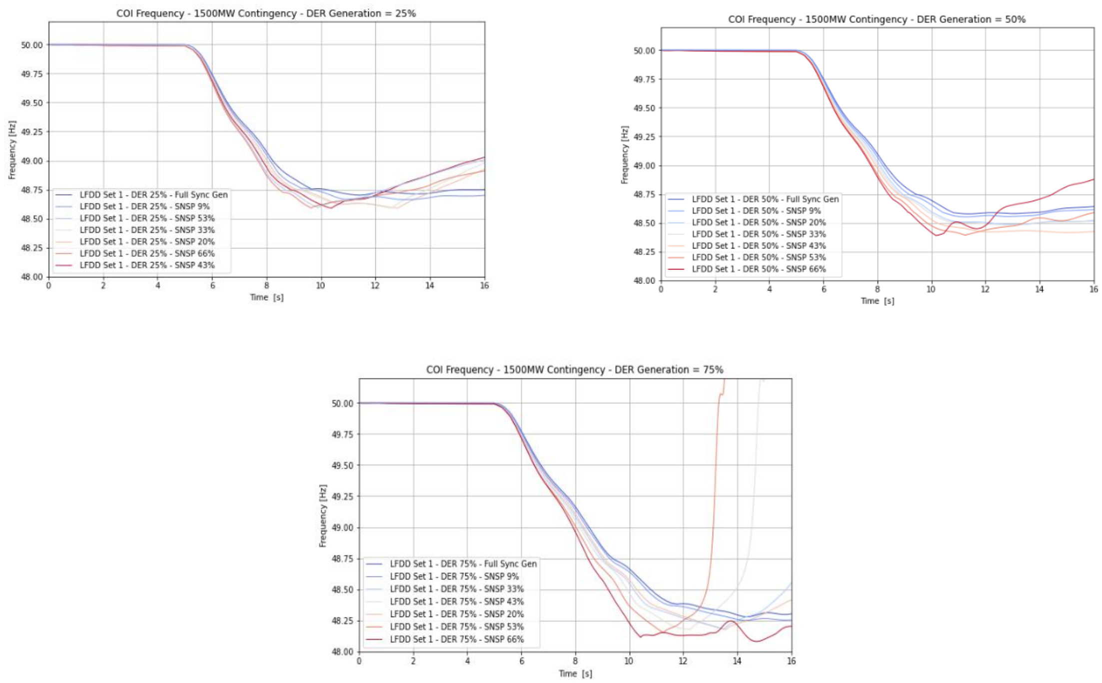

Figure 3: Effect of disconnecting active DER generation on frequency response to LFDD

The sensitivity of a system with higher IBR penetration levels to shedding active DER disconnection is evident as the frequency plot for the SNSP 66% case displays a continued downward trend following LFDD activation while the frequency decline is successfully halted in higher inertia scenarios for the same event. Substantial degradation of LFDD performance, particularly in scenarios with higher IBR penetration can be seen which shows the effect of DER generation at 75% of the associated load. In this case, the frequency nadir is lower for all scenarios and the LFDD scheme is ineffective in restoring power balance to the system. A DER generation level of 75% causes the system to split in low inertia scenarios following the LFDD actions. These figures highlight the potential for cascading disconnections and system collapse caused by unintentional shedding of active DER generation.

Including real-time DER generation data into load bus selection criteria for LFDD actions could ensure that LFDD actions only take place at locations with a DER penetration level below a pre-defined threshold. This could ensure a more robust system response to LFDD and ensure that the power balance is effectively restored to the system following LFDD.

5. IMPROVEMENT TO LFDD: LOAD SELECTION CRITERIA – SYSTEM STRENGTH

During a contingency event, sudden changes in loading conditions can have a more drastic effect on voltage and frequency at weaker locations in a system. This phenomenon could also be seen during the load-switching operations of LFDD. Consequently, it was decided to investigate the effect of system strength at locations where LFDD takes place to understand whether this parameter could be useful when deciding what locations should be included in an LFDD scheme for a particular network configuration.

Minimum short circuit power was calculated for each bus, according to the IEC60909 standard, and the results were used to develop LFDD schemes with system strength as a load selection criterion. The effect of system strength at LFDD load shedding locations on the performance of LFDD was analysed for two IBR penetration scenarios: Full Sync Gen and SNSP 66%. In this paper, the results are presented for the high IBR penetration scenario, SNSP 66%. Following the short circuit calculation mentioned above, load buses were ranked in descending order based on system strength. Two traditional LFDD schemes (7.5% peak load in each threshold setting) were developed based on the system strength calculations. One scheme was designed to include the loads at the strongest buses in the earliest LFDD threshold settings. The second scheme was designed to include the loads connected to the weakest buses in the network in the early LFDD threshold settings. The effect of shedding loads at weaker or stronger buses was analysed for contingency events of 1000MW and 1500MW. Frequency plots for all simulations are presented in Figure 4. It should be noted that no active IBR generation was present at any location included in the LFDD schemes for this analysis.

An increase in oscillations in the frequency response when shedding loads at weaker buses can be seen for the 1000MW event in Figure 4. Shedding loads at locations with higher network strength provides a smoother frequency recovery at all inertia levels. Although there are more oscillations in the frequency response, the frequency decline is still effectively halted when shedding load at weaker buses during this particular contingency event.

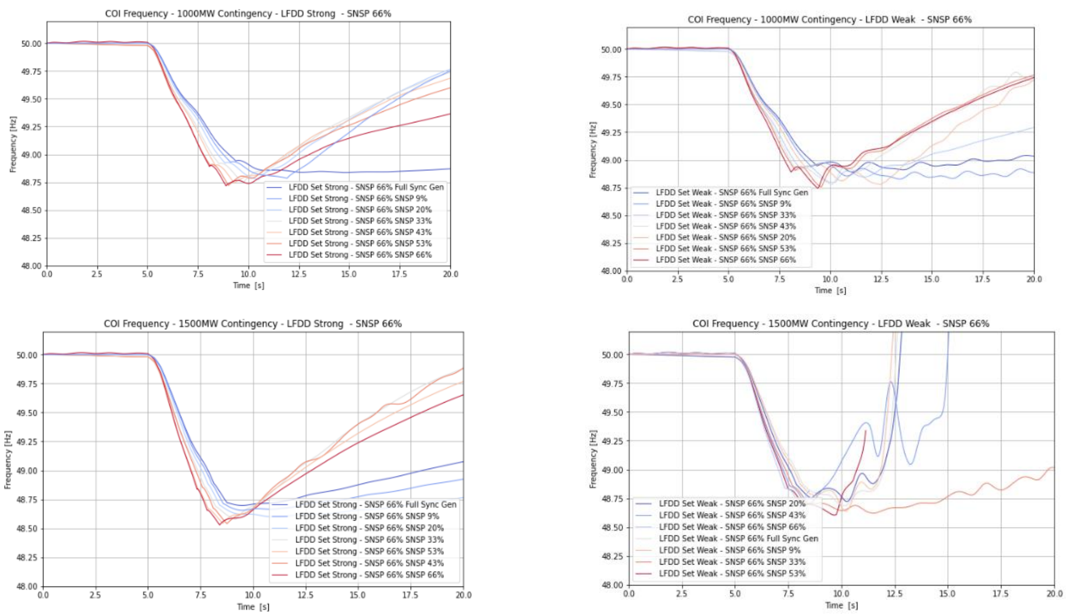

Figure 4: Effect of System Strength on LFDD Performance (left: strong buses, right: weak buses)

Increasing the contingency event size exaggerates the effect of system strength on the frequency recovery immediately after LFDD load-shedding actions. As shown in Figure 4, when the SNSP value is 66%, system splitting occurs in almost all IBR scenarios when the loads are shed at locations with low system strength. Conversely, shedding load at locations where network strength is higher can ensure a more stable response on this network and avoid the system splitting events even in a system with high SNSP.

It can be seen from the results presented in this section that shedding loads at stronger buses during LFDD actions can ensure a more stable frequency profile following LFDD. As expected, fewer frequency oscillations are observed during high inertia scenarios for all LFDD schemes and contingency event magnitudes. This suggests that accounting for system strength at LFDD locations is more important for lower inertia scenarios where the system is more vulnerable. LFDD switching actions inherently result in a disturbance on the network and may lead to unintended oscillations and instability if performed at weaker buses in the network. Giving priority to shedding load at the strongest buses based on calculations of system strength at the lowest inertia level could ensure a more stable response for the largest array of contingency event sizes and system inertia levels. Furthermore, utilizing more advanced system strength evaluation methods that could improve the LFDD selection criteria could be explored in future work [13, 14, 15].

6. IMPROVEMENT TO LFDD: PROACTIVE RoCoF-BASED DISCONNECTION

One aspect of this project is to investigate the possibility of taking action to arrest frequency deviation before the frequency has reached the 49Hz threshold to activate LFDD. As the existing Continental Europe Synchronous Area network does not regularly experience major frequency deviations, any additional measures which would activate before 49Hz should ideally only activate in cases where the frequency deviation is expected to be severe. In cases where the standard LFDD scheme is expected to be sufficient to allow the system to recover, no additional actions should take place before 49Hz.

The protection relay used for RoCoF-based disconnection is the standard F81R df/dt relay available in PowerFactory software. In each simulation case, one load, which is not already included in the LFDD scheme, is selected for additional RoCoF protection. In this section, the size of the load connected to the RoCoF relay was varied between 2.3-5.6% of the total system load, the RoCoF relay threshold setting was varied between 0.2-0.5Hz/s and the definite time delay for RoCoF-based protection was varied between 0.5-3s. The performance of LFDD in combination with each RoCoF relay setting configuration was analysed in response to the two most severe contingencies in this analysis: 1000MW and 1500MW. Each simulation was carried out for all inertia levels and the results were compared between different RoCoF relay settings and the existing Dutch LFDD scheme.

A comparison is made between the frequency response of the system with an added RoCoF-based relay which would disconnect a specified consumer before 49Hz, and the traditional LFDD scheme without the added RoCoF relay. As the goal behind the use of the added ROCOF relay is to improve system response under severe event conditions, simulations are presented for the 1500MW contingency event in Figure 5. Table 5 shows the minimum frequency and RoCoF values for all IBR penetration levels. Also included in the table is the trip time at which the RoCoF-based protection activates. In all simulations presented in this section, the RoCoF relay is set with a RoCoF threshold of 0.5Hz/s and a definite time delay of 0.5s. The RoCoF protection is added to load 27, which is equal to 4.6% of the peak load on the system.

Table 5: Min frequency and RoCoF values – effect of additional RoCoF protection

	Traditional LFDD		**With RoCoF Relay**		
Scenario	**Min Frequency [Hz]**	**Min RoCoF [Hz/s]**	**Min Frequency [Hz]**	**Min RoCoF [Hz/s]**	**RoCoF Relay Trip Time**
Full Sync Gen	48.75	-0.471	48.75	-0.471	No Trip
SNSP 9%	48.73	-0.493	48.73	-0.493	No Trip
SNSP 20%	48.72	-0.511	48.72	-0.511	No Trip
SNSP 33%	48.68	-0.564	48.73	-0.56	6.44s
SNSP 43%	48.62	-0.561	48.71	-0.561	6.43s
SNSP 53%	48.58	-0.628	48.74	-0.626	6.17s
SNSP 66%	48.52	-0.671	48.70	-0.671	6.2s

It can be seen from Table 5 that the RoCoF relay is activated in the four scenarios with the lowest inertia level. This is expected as these are the scenarios with higher RoCoF. In these simulations, the RoCoF relay was set with a threshold of 0.5Hz/s, a value which is not seen in the high inertia scenarios for an event of this magnitude.

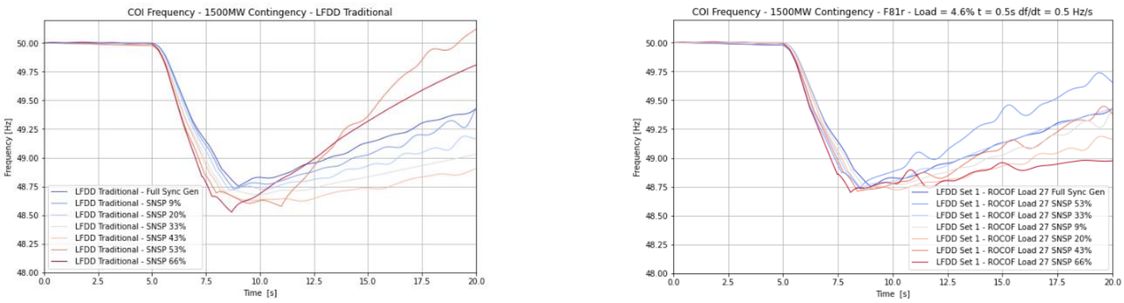

Figure 5: Effect of additional RoCoF based protection on frequency response

In scenarios where the RoCoF values experienced by the system are low the system frequency recovers effectively without activating the additional RoCoF protection. In low inertia scenarios, the RoCoF-based protection is activated and additional load is shed before the traditional scheme activates, limiting the frequency nadir in these scenarios. Additional protection based on RoCoF has the benefit of being selective and only operating in scenarios where an effective system recovery is not expected with the traditional scheme. Using RoCoF-based protection, additional load can be shed proactively in situations where a more severe frequency deviation is expected, due to low system inertia or high contingency event size.

Exploring the optimal ways to implement RoCoF-based schemes, whether using local or wide-area measurements [16], is an important future work direction.

7. IMPROVEMENT TO LFDD: ADAPTIVE LFDD SCHEME

Adaptive underfrequency load shedding schemes are designed to disconnect the appropriate amount of load to provide the desired frequency recovery response for all contingency event sizes and system inertia levels. These schemes typically make a real-time decision regarding where and how much load should be shed to provide the ideal frequency response.

It was decided to develop a simple, representative adaptive scheme for this project to compare the results of fixed LFDD schemes and an adaptive scheme that has no fixed thresholds or load-shedding amounts. Should the results of the adaptive scheme show a sufficient improvement in performance relative to the traditional LFDD scheme, proposals could be made for further research into this area to develop an adaptive scheme that could be implemented in a practical manner given the operational constraints of existing power systems.

Using an adaptive scheme with real-time power-deficit estimation could allow the load-shedding amount to be tailored to each specific event that occurs in the network. The adaptive scheme in this project calculates an estimated power deficit on the system based on ROCOF following an event and the system inertia at that instant according to the equation below [17]:

$$P_{imb}(MW) = \left(\frac{2. H_{sync}^{gen} . \frac{df}{dt}^{max}}{50} \right) . (P_{load})$$

A decision on the amount of load to shed is made based on a scaling factor applied to the calculated power deficit for each individual event and inertia level. In this analysis, three scaling factors are used. These factors are 50%, 75%, and 100% and define the percentage of calculated power deficit that the system will shed. In Figure 6, frequency plots are shown for a 1000MW contingency event on the system with 66% SNSP at that instant. Results are shown for the adaptive scheme using the three scaling factors. Also shown is the result for a traditional LFDD scheme for the same event. The calculated power deficit using the adaptive scheme is presented in Table 6. The frequency nadir, maximum ROCOF, and load shed amount are also presented for each adaptive scheme scaling factor and the traditional LFDD scheme. It can be seen both in the graph of frequency trajectory and from the minimum frequency results that the adaptive scheme is effective in reducing the frequency nadir in comparison with the traditional LFDD scheme. This effect is expected as the adaptive scheme is designed to begin shedding load when the frequency drops below 49.5Hz while the traditional LFDD does not activate until frequency reaches 49Hz.

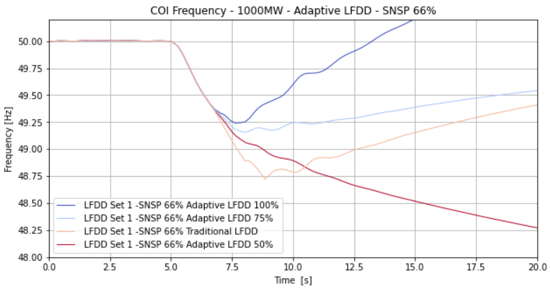

Figure 6: Frequency Plot - 1000MW Contingency - Traditional LFDD Vs Adaptive LFDD

Table 6: Results comparison Adaptive LFDD Vs Traditional LFDD

Scenario	Event Size (MW)	Estimated Power Deficit (MW)	Min Frequency [Hz]	Max RoCoF [Hz/s]	Load Shed (MW)
Adaptive LFDD 100%	1000	1140	49.241	-0.482	1140
Adaptive LFDD 75%	1000	1140	49.156	-0.482	855
Traditional LFDD	1000	N/A	48.721	-0.482	964
Adaptive LFDD 50%	1000	1140	48.271	-0.482	570

In the case of higher system inertia, shedding a smaller amount of load can be effective in arresting the frequency decline and beginning the recovery of the system. In the lower inertia system, as shown above, shedding 50% of the estimated power deficit is ineffective in stopping the frequency decline and the system does not recover from the contingency event. The varying responses of the high and low inertia systems suggest that a specific scaling factor could be used to determine the optimum amount of load to be shed based on inertia level. In case of large systems there may be a big difference in RoCoF throughout the system. When only considering the initial local RoCoF following an event, this could lead to inaccurate estimations of the power imbalance. Furthermore, the averaged RoCoF over a certain time-window might give a more accurate result.

Further information, details and more simulation results for all topics discussed in this paper, omitted here due to paper length limitations, can be accessed at [18]. The effect of changing the selection strategy of thresholds, amplitude of each step and number of steps in traditional LFDD schemes is also investigated in [18].

8. CONCLUSIONS AND RECOMMENDATIONS

The results of this work highlight the potential effects of increased penetration of IBRs and reduced rotational inertia on the system on the performance of the Dutch emergency load shedding scheme on a template network. Findings indicate that improving load selection criteria by adding parameters such as network strength and active DER generation at load-shedding locations can improve the robustness of the existing Dutch LFDD scheme. Alternative methods such as the addition of proactive RoCoF-based protection or implementation of an adaptive LFDD scheme can ensure frequency decline is halted successfully for large contingency events while avoiding over-shedding for smaller contingencies. Results indicate that improved performance of LFDD can be achieved within the constraints of the existing European grid code while some measures would require policy changes and widespread collaboration between TSOs, DSOs and connected parties before successful implementation.

Detailed investigation should be undertaken into the technical, legislative and organisational (over 25 TSOs and hundreds of DSOs in CESA) challenges associated with implementing any chosen improvement to LFDD in a real-world power system. It is important to understand which improvements can most readily be implemented given the technical and legislative constraints in the CESA today. Research should be divided into two sections: (i) improvements that could be implemented in a short timeframe (ii) improvements that require longer-term technical and legislative developments before implementation.

Detailed modelling of the networks downstream from substations with LFDD could provide more information regarding system response to LFDD switching actions. In this research, downstream networks from LFDD substations are represented as static loads. Detailed modelling of downstream DER generation and dynamic loads could provide further insight into the effect of both disconnections of active DERs and network strength on the overall performance of LFDD defence measures. In addition, the effect of changing SNSP levels caused by a generator trip on performance of LFDD defence measures should be investigated.

Furthermore, the impact of LFSM-U (of EV, electrolysers, BESS etc.) should also be taken into account.

Research could be undertaken into the inclusion of frequency threshold settings in combination with RoCoF threshold settings for relays associated with proactive disconnection. The addition of frequency thresholds would be useful in the event of a large contingency happening during a high inertia operating scenario. In this case, the measured RoCoF may not be high enough to trip the proactive disconnection but, due to the amount of generation loss, the frequency deviation may still breach desired thresholds. It is also important to establish the maximum operative RoCoF systems can successfully tolerate, considering technical capabilities of generators and protection devices. Entso-e currently assumes a threshold of 1 Hz/s [4], however, this value may evolve with the systems and require further research.

It may be useful to employ additional threshold settings or investigate the possibility of estimating power deficit and using this value to issue trip commands to proactive disconnection relays. The effectiveness of such schemes, especially on large networks, needs additional research.

Local implementation of an adaptive load shedding scheme, such as the one described in [19] could provide a promising pathway to introducing more intelligent load shedding schemes to the CESA. As the use of central controllers and complex communication is undesirable for emergency defence measures in a large-scale power system, local implementation of adaptive schemes could enable a sophisticated load-shedding scheme without diminishing security and robustness.

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