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Assessment of Low Frequency Demand Disconnection Impact on Network Operability

Behnam Feizifar[1*], Ibrahim Abdulhadi[1], Federico Coffele[1], Colin Scoble[2], Calum Jardine[3]
[1]PNDC, University of Strathclyde, Glasgow, United Kingdom
[2]UK Power Networks, Crawley, United Kingdom
[3]Scottish & Southern Electricity Networks, Perth, United Kingdom
[*]Email: behnam.feizifar@strath.ac.uk

Abstract

This paper presents an assessment of Low Frequency Demand Disconnection (LFDD) impact on network operability. One of the issues arising from LFDD relay operation is the disconnection of Distributed Generators (DGs) along with loads during disconnection of large numbers of Extra High Voltage (EHV) substations. This could compromise the effectiveness of LFDD schemes considering the increasing presence of DGs in distribution networks. Another issue is the loss of system earth (i.e. from 132/33 kV substations) from the point of view of connected DGs following LFDD operation that might occur in some areas within distribution grids due to back-feed current from 33/11 kV primary substations. A distribution network model experiencing the above issues has been used in the PowerFactory to simulate a number of operation and fault scenarios. Different types of DGs including Photovoltaic (PV), Battery Energy Storage System (BESS), Wind Generation (WG) and Synchronous Generation (SG) have been modelled. The results provide useful insights on the LFDD schemes impact on network operation with DGs interface protection based on ENA Engineering Recommendation G99 and how the LFDD schemes based on direction of current could influence the frequency response in the network. The results also show that the loss of system earth issue on the studied LFDD scenarios occurs when the network is operating in its minimum loading condition.

1. Introduction

LFDD schemes are deployed in UK distribution networks to arrest a fall in grid frequency by disconnecting pre-defined blocks of demand in up to 9 steps starting at 48.8Hz (as defined by The Grid Code clause CC.A.5.1) as specified in [1]. LFDD relays are typically installed in Grid Supply Points (GSPs) to maximise the amount of load disconnected. Although this approach has been so far successful in maintaining grid frequency stability during large historic disturbances, some of the recent events such as the 9th August 2019 LFDD operation in the UK shows the need for improvements in the scheme [2-4].

The increase in deployment of DG in distribution networks at voltage levels below where the LFDD relays are used is likely to influence the effectiveness of the scheme. On one hand, if the level of DG output is high when the LFDD relay is operated, the net amount of demand disconnected may be lower than expected. On the other hand, if the level of DG output is low the amount of demand disconnected may be higher than expected [5]. A study shows some of the issues impacting the LFDD protection performance with rising installed capacities of DG in the UK distribution networks. It is demonstrated that the effectiveness of the scheme is challenged with current and future expected DG deployed capacities and the risk of over demand disconnection due to the scheme's current settings is evaluated [6].

New LFDD schemes based on directional relays, power flow through feeders and DG measurements, which are designed to overcome the shortcomings of traditional LFDD scheme are proposed in [7] such that DG disconnection is minimized while disconnecting required amount of consumption. These LFDD schemes are compared in terms of frequency response, amount of consumption and DG disconnected during load shedding. Furthermore, another LFDD scheme has been proposed which considers power stability with economy in load shedding for a distribution grid with DGs such as Combined Heat and Power (CHP), wind and photovoltaic (PV) generations. The proposed strategy classifies loads into heavy and light groups, ranking is based on willingness to pay, frequency threshold and rate of change of frequency (RoCoF) [8]. Such approaches, although potentially beneficial, are not permitted by the UK Grid Code and would require a Code modification.

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The study presented in this paper analyses the impact of LFDD operation on different types of DGs including PV, Battery Energy Storage Systems (BESS), Wind Generation (WG) and Synchronous Generation (SG) connected to different buses in an active distribution grid. Also, two types of mixed DG scenarios including PV-WG and SG-BESS have been investigated by considering each DG type being connected to a separate bus in the network. In addition, a directional LFDD relay has been modelled in the PowerFactory and its performance has been compared with the static scheme.

2. DG Protection Interface Based on ENA ER G99

ENA ER G99 (hereinafter referred to as G99 for the sake of simplicity), contains recommended protection arrangements and settings that depend upon the particular DG installation and the requirements of the Distribution Network Operator (DNO) network. These individual requirements shall be ascertained in discussions with the DNO. To achieve the above-mentioned objectives, the protection shall include the detection of [9]:

- Under Voltage (UV) (1 stage);
- Over Voltage (OV) (2 stages);
- Under Frequency (UF) (2 stages);
- Over Frequency (OF) (1 stage);
- Loss of Mains (LoM).

Following the DNO connection study, the risk presented to the Distribution Network by the connection of a Power Generating Module may require additional protection to be installed and may include the detection of Neutral Voltage Displacement (NVD), Over Current, Earth Fault, and Reverse Power.

This additional protection may be installed and arranged to operate the DNO interface circuit breaker or any other circuit breakers, subject to the agreement of the DNO and the DG.

The protection functions required by DGs set the requirements for the connection of DGs in parallel with public distribution grids. The protection settings for long-term parallel operation are shown in Table 1. The settings noted in the high voltage (HV) protection column are used with the protection elements of U/O V, U/O F and RoCoF for the DG models.

Table 1. Protection settings for long-term parallel operation from G99 [9]

Protection Function	Type A, Type B and Type C Power Generating Modules	
	HV Protection	
	Trip Setting	Time Delay Setting
U/V	Vφ-φ - 20%	2.5 s
O/V st 1	Vφ-φ - 10%	1.0 s
O/V st 2	Vφ-φ + 13%	0.5 s
U/F st 1	47.5 Hz	20 s
U/F st 2	47.0 Hz	0.5 s
O/F	52.0 Hz	0.5 s
LoM (RoCoF)	1 Hz/s	0.5 s

Figure 1 shows a typical protection arrangement for an HV power generating module connected to a DNO's HV distribution grid designed for parallel operation only.

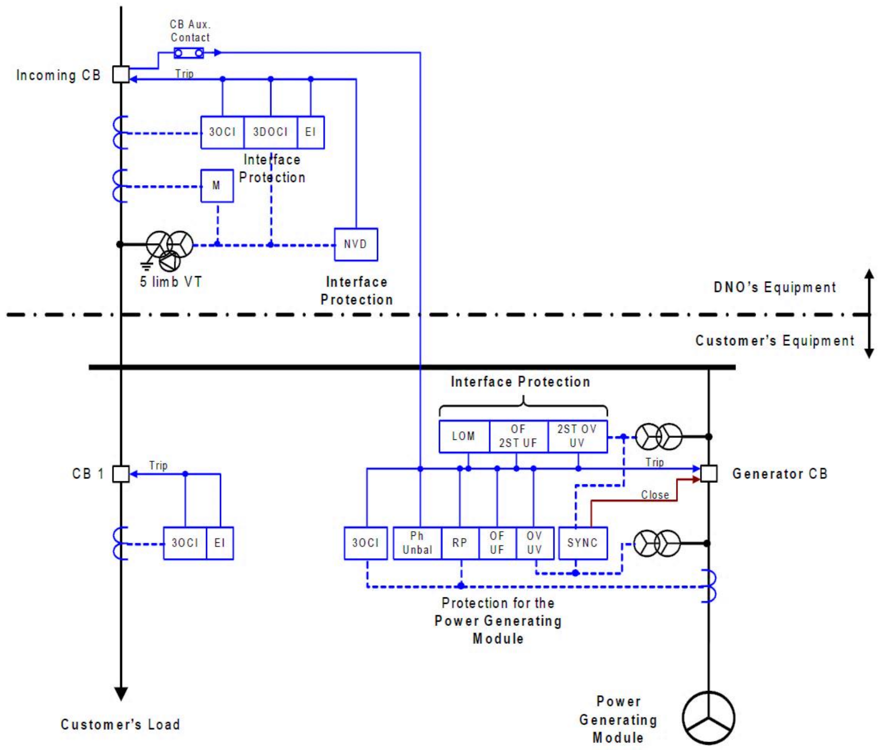

Figure 1. Typical protection arrangement for an HV power generating module for parallel operation only [9]

3. LFDD Schemes

3.1 Static-LFDD method

Static LFDD relays are deployed in selected incomers or feeders at 33 kV voltage levels based on the amount of installed loads. Generally a certain number of feeders are chosen considering the historical load data of these feeders such that their disconnection should remove the required amount of load. The Grid Code requires that these LFDD strategies should have the capability of disconnecting certain percent of demand based on the amount of frequency deviation as shown in Table 2 [1]. Generally these feeders are selected based on types of demand, network topology, and equal distribution of loads to be disconnected. This scheme is very simple and economical to implement, but it does not consider DG being connected to the feeders, which it may be disconnected affecting the total amount of load reduction. Consequently, frequency response may deteriorate resulting in the activation of further LFDD stages. [3].

Table 2. LFDD recommended stages based on Grid Code [1]

Block	Frequency (Hz)	% of Demand Disconnection
1	48.8	5
2	48.75	5
3	48.7	10
4	48.6	7.5
5	48.5	7.5
6	48.4	7.5
7	48.2	7.5
8	48.0	5
9	47.8	5

3.2 DIR-LFDD method

One of the major drawbacks of the static LFDD scheme is that it may disconnect a large amount of DG while disconnecting specific feeders. It is possible that at certain time of the day, generations from DG is higher than consumption for any of these feeders. Consequently, that specific feeder acts as a net generator instead of load. Disconnecting any such feeder can have detrimental effects on the system frequency. In order to prevent such scenarios, a directional current relay element can be incorporated along with the static relays. This relay checks whether the current flow is from distribution to transmission network. If the current is flowing from distribution network to transmission network then the relay is blocked from activation and the corresponding feeder is not disconnected [7].

4. Power Network Model

The power system model used in this paper includes the 132 kV grid feeding seven 132/33 kV substations, A Grid, B Grid, C Grid, D Grid, E Grid, F Grid, and G Grid as illustrated in Figure 2. The LFDD relay schemes (i.e., static and directional) will be modelled at four substations including A Grid, B Grid, C Grid and D Grid. It's been considered that the LFDD schemes can disconnect 33 kV outgoing feeders of these substations individually. In order to simulate the frequency response, the representative National Grid bus is fed from a down-scaled 800 MVA SG. This rated power (i.e., 800 MVA) was used to provide flexibility in demand disconnection to simulate frequency drops in the network. Two generator outage incidents have been simulated through losing two SGs with 110 MVA at 10 s and 50 MVA at 80 s. These outages simulate two frequency drop incidents which will be caught by different LFDD stages depending on the amount of frequency deviation.

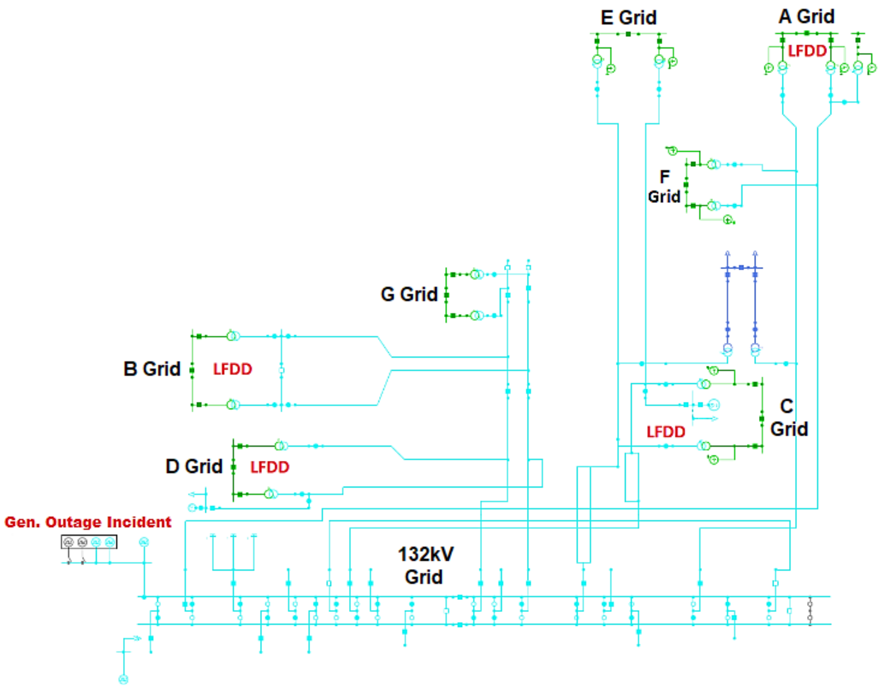

Figure 2. 132 kV Grid substations

5. Dynamic DG Models

Four dynamic DG models from the PowerFactory library have been used to study their impact on the LFDD operation. The DG models include PV, BESS, WG and SG connected to separate buses at the locations of interest in the 33 kV distribution grid. At DG1 bus, the PV, WG, SG and BESS were modelled utilising the existing dynamic models in the PowerFactory library by changing the apparent and active powers, series reactor short circuit impedance and copper loss as well as inertia constants for WG and SG as defined in Table 3.

Table 3. Parameters of DG models connected to DG1 Bus

DG Type	DG Model	Apparent Power	Active Power	Series Reactor S.C. Impedance	Series Reactor Copper Loss	Inertia Constant H
PV	Photovoltaic System_0.4 kV	16 MVA	15 MW	60%	10 kW	-
WG	IEC WT Control System Type 4B	16 MVA	15 MW	60%	10 kW	4 s
BESS	DIgSILENT BESS FrequencyCtrl 10 kV	16 MVA	15 MW	60%	10 kW	-
SG	General Power Plant Unit	16 MVA	15 MW	-	-	4 s

At DG2 bus, the PV, WG, SG and BESS were simulated using the existing dynamic models in the PowerFactory library by changing the apparent and active powers, series reactor short circuit impedance and copper loss as well as inertia constants for WG and SG as indicated in Table 4.

Table 4. Parameters of DG models connected to DG2 Bus

DG Type	DG Model	Apparent Power	Active Power	Series Reactor S.C. Impedance	Series Reactor Copper Loss	Inertia Constant H
PV	Photovoltaic System_0.4 kV	3 MVA	2.5 MW	60%	2 kW	-
WG	IEC WT Control System Type 4B	3 MVA	2.5 MW	60%	2 kW	2 s
BESS	DIgSILENT BESS FrequencyCtrl 10 kV	3 MVA	2.5 MW	60%	2 kW	-
SG	General Power Plant Unit	3 MVA	2.5 MW	-	-	2 s

6. LFDD Relay Models

The 9-stage LFDD relay model of this study was developed based on the 4-stage DSL model of ABB SPAF140C relay in the PowerFactory protection library. This is a secondary relay that is connected to the voltage transformers of the grid section to be protected. It incorporates one relay module: the combined frequency and RoCoF. It includes four protection stages, each of which with its own frequency function (f), RoCoF function (df/dt) and two adjustable operate times (t and t'). When the frequency limit of a stage is set below the rated frequency, the protection stage operates as an UF stage. Correspondingly, the stage has the function of an OF stage, when the frequency level is set above the rated frequency. The frequency setting cannot be the same as the rated frequency. The operation of the df/dt function of a protection stage is based on the same principle as the frequency function, which means that if a protection stage operates as an UF stage, the sign of the df/dt function is going to be negative. Then the function starts once the absolute value of the rate of frequency drop exceeds the df/dt limit. When required, the frequency function and the df/dt function can be combined so that the criteria for operation of both functions have to be fulfilled at the same time. Once a preset condition is fulfilled, the stage starts and, at the same time, it activates a timing circuit. When the stage times out, the relay produces a trip signal.

The original directional over-current (DOC) relay model in the PowerFactory protection library is equipped with three phase currents and three phase-to-phase voltages inputs. The phase directional generic relay is also provided with four directional stages and five control inputs for external control signals such as blocking signals. As part of the DOC relay modelling on 11 kV CB of 33/11 kV primary substations, 1st directional stage was used with the parameters indicated in Table 5. The extended 9-

stage LFDD relay model was then incorporated with a DOC element with the settings noted in Table 5 to develop a directional LFDD relay model as shown in Figure 3.

Table 5. DOC settings on primary substations and DIR-LFDD relay

DOC Parameters	DOC Settings on Primary Substation	DOC Settings on DIR-LFDD
Current	50% of I (Transformer LV Winding)	1% of I (Rated)
Curve	IDMT IEC Standard Inverse	IDMT IEC Standard Inverse
TMS	0.1	0.05
Angle	90-45°	90-45°

The LFDD recommended stages based on the Grid Code as shown in Table 2 were set in 9-stages of the relay. In addition, the RoCoF setting noted in Table 1 was used for these stages. The output of DOC element is connected to the output logic of LFDD relay stages using "AND" logic. This means whenever the measured frequency goes below a stage threshold and the direction of current signal is as set in the directional element for tripping, the directional LFDD relay issues a trip signal for that LFDD stage.

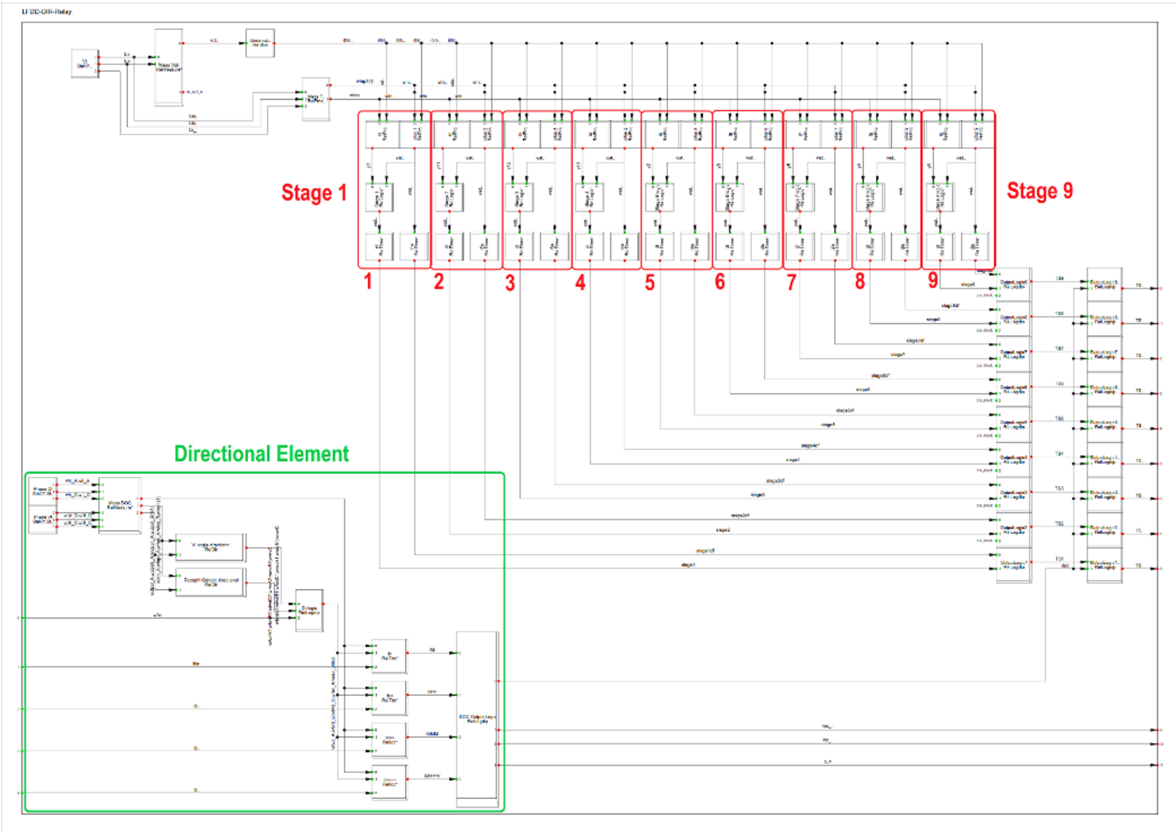

Figure 3. Developed 9-stage Directional-LFDD relay model in the PowerFactory

7. LFDD Operation Scenarios and Results

The impact of LFDD relays operation on network operability was studied using a number of operation and fault scenarios considering different types of DGs. These are designed based on LFDD schemes, connected DGs, minimum and maximum loading conditions, and network operation scenarios. Some of these scenarios are explained in the following sections.

7.1 Case 1: PV generations – Min loading – Static LFDD

This case study considers Static-LFDD scheme with minimum loading condition in the network. The LFDD stages have been implemented on the 33 kV outgoing feeders of four 132/33 kV substations including A Grid, B Grid, C Grid and D Grid. In this case, no DOC operation was observed on T2 CB of DG1 Primary substation as the current threshold was not exceeded by the minimum loading condition. No G99 protection operation was observed on the DG CBs of DG1 or DG2 Buses as well. Figure 4 depicts the status of A Grid and B Grid substations as well as DG1 and DG2 Buses following the LFDD operation.

In this case, the highlighted 33 kV part of the grid remains energised through 33/11 kV transformer T2 CB back-feed (i.e. through a 33 kV feeder coming from the C Grid 132/33 kV substation indicated by red arrows). The blue circles indicate 33/11 kV primary substations. This energised part of the network has already lost the earthing connection at 33 kV using an interconnected Star (Z) winding earthing transformer as shown earlier in Figure 2. This is unacceptable as the ESQCR requires that distribution networks are earthed at all times [10].

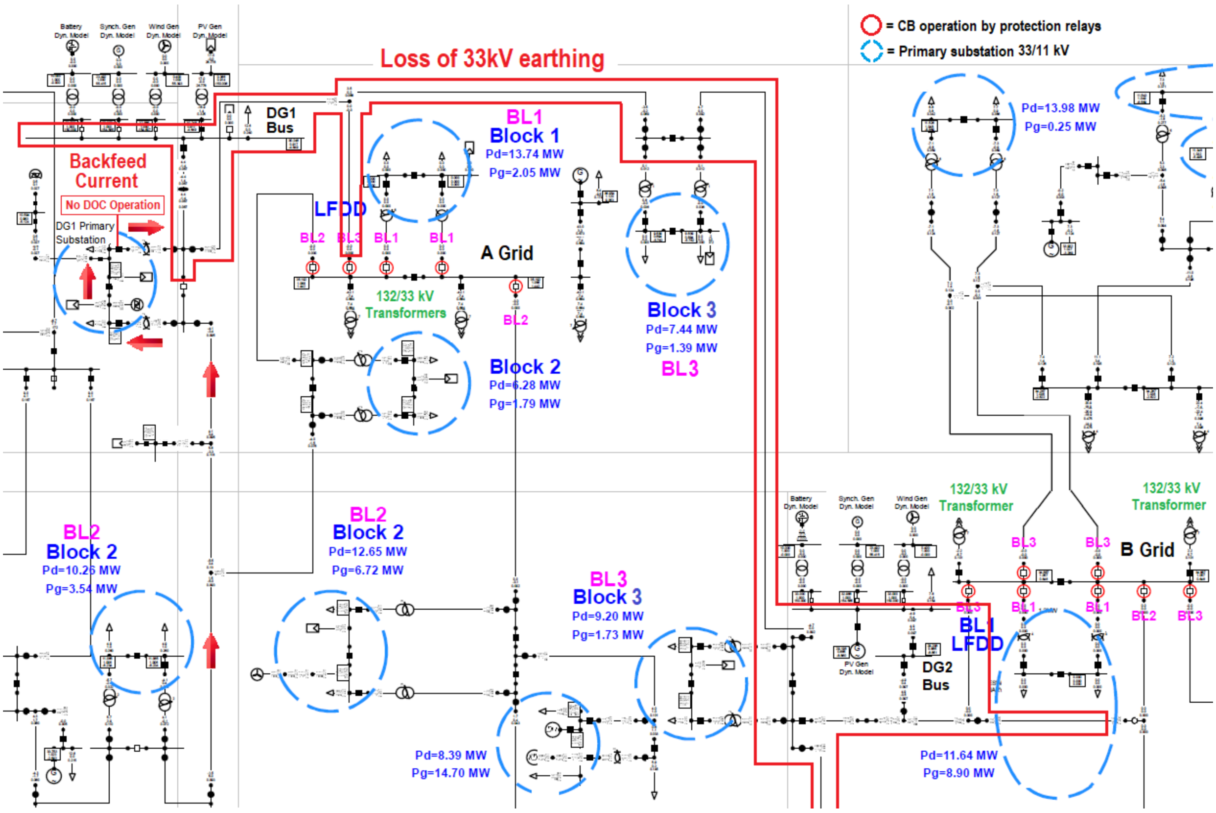

Figure 4. Loss of system earth at 33 kV during min loading static LFDD operation

Figure 5 shows the A Grid substation bus voltage and frequency related to the case where the static-LFDD is used and the network is operating on minimum loading condition with PVs connected to both DG1 and DG2 buses.

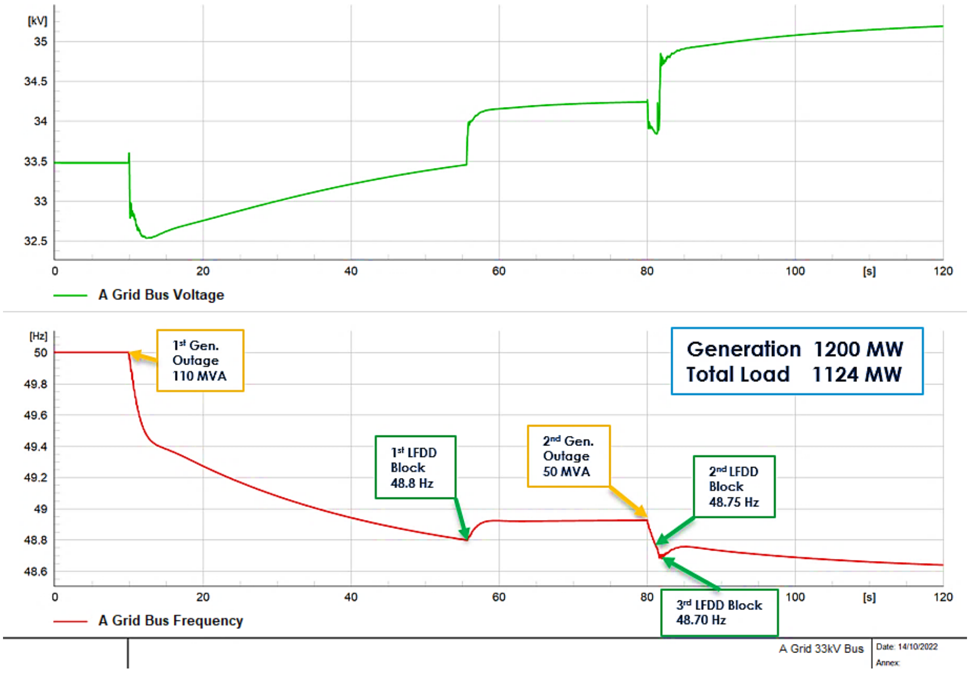

Figure 5. A Grid substation V-F during min load static LFDD operation

7.2 Case 2: PV generations – Max loading – Static LFDD

This case study includes Static-LFDD scheme with maximum loading condition in the network. In this case, by applying the maximum loading condition, the DOC relay operated at 87.4s on T2 CB of DG1 Primary substation as the current threshold setting was exceeded by the maximum loading condition (i.e. considering the DOC settings shown in Table 5). The G99 U/V protection also operated at 84.1s and 86.6s on the DG CBs of DG2 and DG1 Buses, respectively.

7.3 Case 3: PV generations – Min loading – Static LFDD – Earth Fault

This case study considers static-LFDD scheme and minimum loading condition followed by a phase-ground fault at 90s (i.e. 8s following the operation of third LFDD block) on one of the outgoing feeders of A Grid substation. In this case, the NVD protection relay on the 33 kV side of primary substation trips the primary T2 CB of DG1 Primary Substation at 95s considering the NVD protection settings indicated in Table 6. The G99 NVD protection was also operated at 95s on the DG CBs of DG1 and DG2 Buses. Figure 6 illustrates the status of A Grid substation and DG1 Bus following the earth fault. Figure 7 depicts the status of B Grid substation and DG2 Bus following the earth fault. Both NVD operations on the primary substation and DG buses were expected because of the presence of earth fault in that part of the network.

Table 6. NVD relay settings on primary substations

NVD Relay Parameters		Settings
(VN>1)	Voltage	5 kV
	Time	5 s
(VN>2)	Voltage	5 kV
	Time	10 s

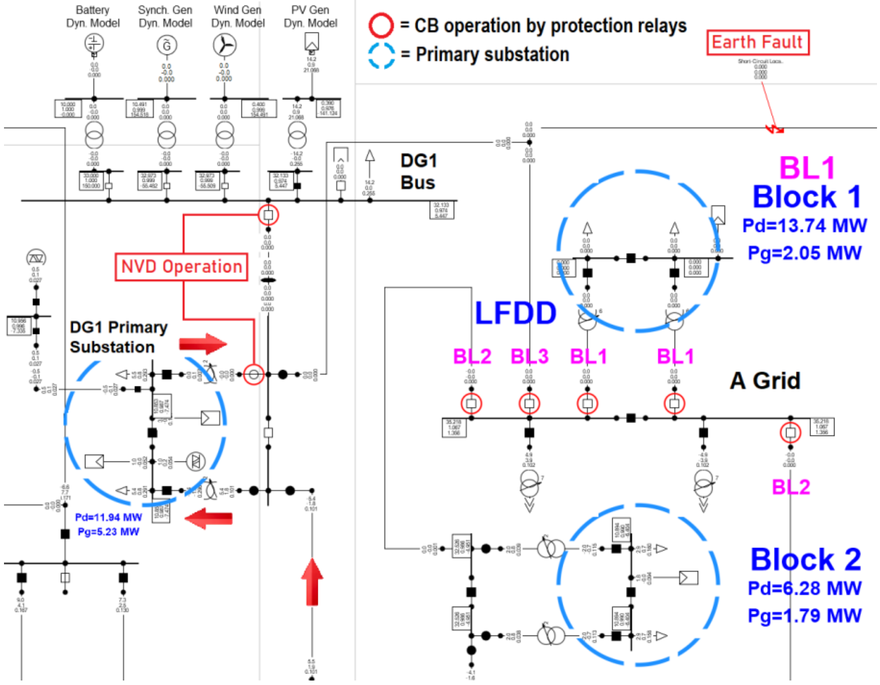

Figure 6. Back-feed earth fault current path through DG1 Primary Substation

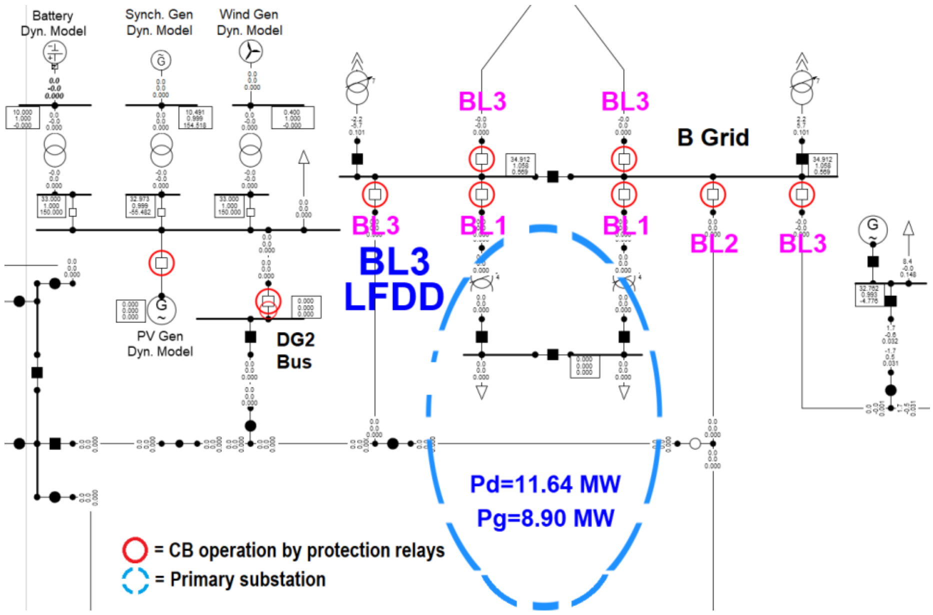

Figure 7. DG2 Bus status following the static-LFDD operation followed by an earth fault

7.4 Case 4: PV generations – Min loading – Static LFDD – Phase-Phase Fault

This case study considers static-LFDD scheme and minimum loading condition followed by a phase-phase fault at 90s (i.e. 8s following the operation of third LFDD block) on one of the outgoing feeders of A Grid substation. In this case, the DOC relay tripped the T2 CB of DG1 Primary Sub at 90.6s. The G99 U/V protection also operated at 92.5s on the DG CBs of DG1 and DG2 Buses. Figure 8 illustrates the status of A Grid substation and DG1 Bus following the phase fault. Figure 9 depicts the status of B Grid substation and DG2 Bus following the phase fault. Both the DOC and G99 U/V operations were expected because of the presence of phase fault in that part of the network.

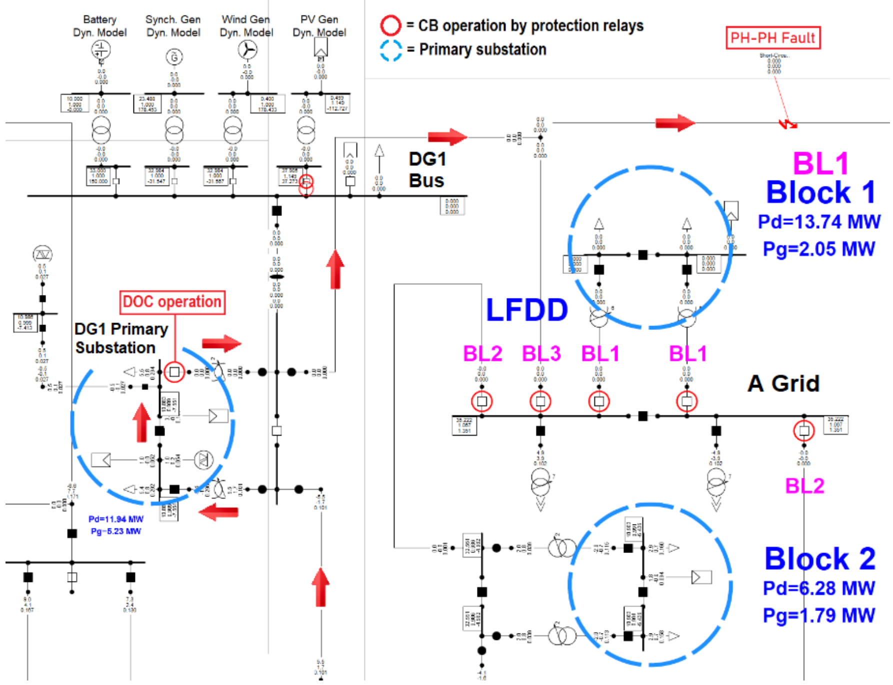

Figure 8. Back-feed phase fault current path through DG1 Primary Substation

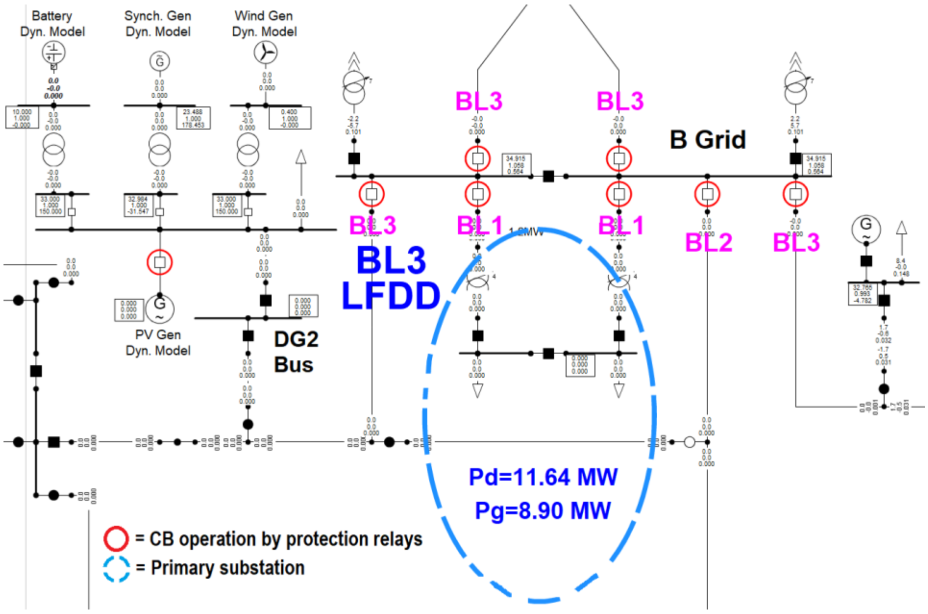

Figure 9. DG2 Bus status after the static-LFDD operation followed by a phase-phase fault

7.5 Case 5: PV generations – Min loading – DIR LFDD

This case study considers DIR-LFDD scheme with minimum loading condition in the network. In this case, by applying the minimum loading condition, no DOC operation was observed on T2 CB of DG1 Primary Substation as the current threshold setting was not exceeded by the minimum loading condition. Furthermore, no G99 operation was observed on the DG CBs of DG1 or DG2 Buses. In this case, a section of 33 kV network remains energised through 33/11 kV transformer T2 CB back-feed current (i.e. through a 33 kV feeder coming from the C Grid 132/33 kV substation) without earthing connection at 33 kV via an interconnected Star (Z) winding earthing transformer. This case demonstrates that DIR-LFDD could improve the frequency response of the network with the noted assumptions, i.e., a down-scaled generator model was used (i.e., 800 MVA) instead of National Grid Supply and frequency drop was simulated by generator outage incidents.

Figure 10 indicates the DIR-LFDD operation on the A Grid and B Grid substations. The 2nd block of LFDD was blocked on two feeders on the A Grid and B Grid substations indicated by green circles as the direction of current was reverse. Figure 11 shows the A Grid substation bus voltage and frequency related to the case where the DIR-LFDD is utilised and the network is operating on minimum loading condition with PVs connected to both DG1 and DG2 Buses.

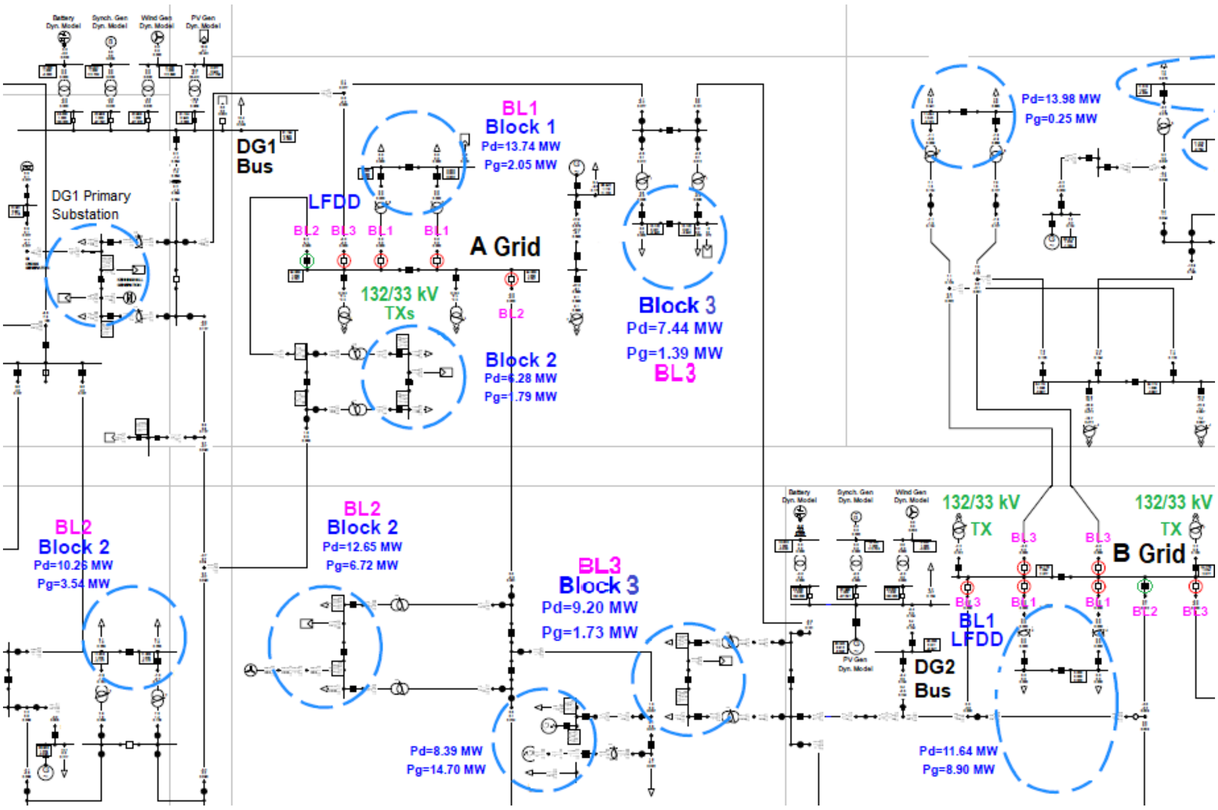

Figure 10. DIR-LFDD operation on the A Grid and B Grid substations

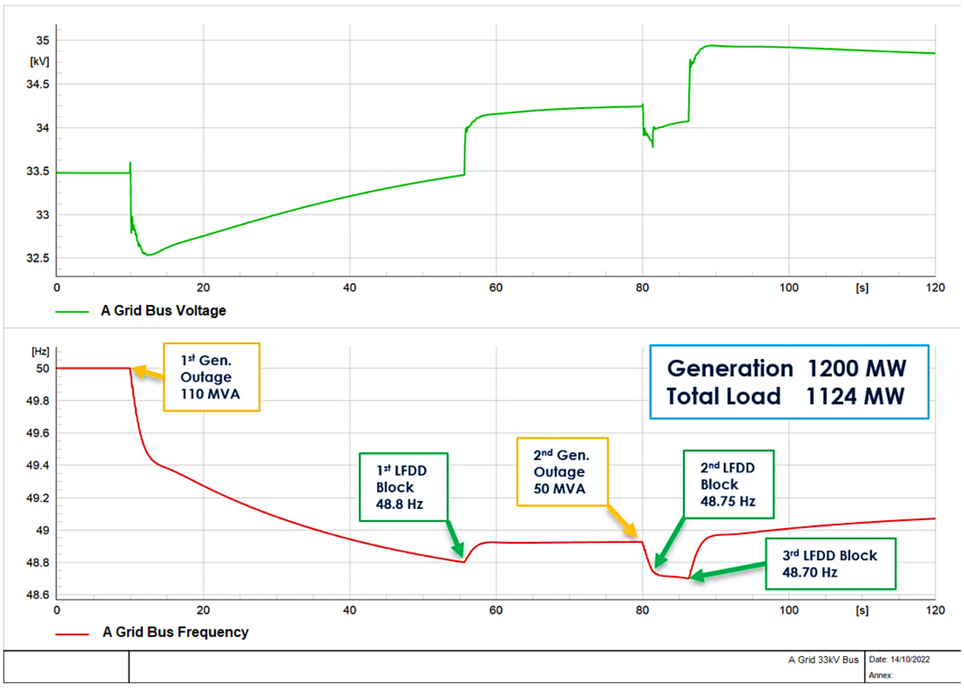

Figure 11. A Grid substation V-F during min load DIR-LFDD operation

7.6 Case 6: PV generations – Max loading – DIR LFDD

This case study considers DIR-LFDD scheme with maximum loading condition in the network. In this case, by applying the maximum loading condition, the DOC relay operated at 97.8s on T2 CB of DG1 Primary Substation. The G99 U/V protection was also operated at 88.2s and 100.3s on the DG CBs of DG2 and DG1 Buses, respectively. The DOC operation in this case was expected because the current threshold setting was exceeded by the maximum loading condition.

7.7 Case 7: BESS – Min-Max loadings – Static LFDD

Considering BESSs on DG1 and DG2 Buses, no G99 protection operation was observed on the DG CBs of DG1 and DG2 Buses during the minimum loading condition. However, the U/V protection operated the DG CBs of DG1 and DG2 Buses at 84.2s, following the Static-LFDD operation during the maximum loading of the network.

7.8 Case 8: WG – Min-Max loadings – Static LFDD

Considering WGs on DG1 and DG2 Buses during minimum loading condition, no G99 protection operation was observed on the DG CBs of DG1 and DG2 Buses. However, the U/V protection operated on the DG CBs of DG2 and DG1 Buses at 85.1s and 87.6s, respectively, following the Static-LFDD operation during the maximum loading of the network.

7.9 Case 9: SG – Min-Max loadings – Static LFDD

Considering SGs on DG1 and DG2 Buses during minimum loading condition, no G99 protection operation was observed on the DG CBs of DG1 and DG2 Buses. However, the U/V and U/F protection operated the DG CBs of DG1 and DG2 Buses at 85.7s, following the Static-LFDD operation during the maximum loading of the network.

7.10 Case 10: PV-WG – Min-Max loadings – Static LFDD

By considering a mix of DGs arrangement with PV and WG on DG1 and DG2 Buses with minimum loading, no G99 protection operation was observed on the DG CBs of DG1 and DG2 Buses. However, the U/V protection operated both the DG CBs of DG2 and DG1 Buses at 85.2s and 87.7s, respectively, following the Static-LFDD operation during the maximum loading of the network.

7.11 Case 11: BS-SG – Min-Max loadings – Static LFDD

By considering a mix of DGs arrangement with BS and SG connected to DG1 and DG2 Buses with minimum loading, no G99 protection operation was observed on the DG CBs of DG1 and DG2 Buses. However, the U/V and U/F protections operated at 84.5s and 86.2s on the DG CBs of DG2 and DG1 Buses following the Static-LFDD operation during the maximum loading of the network.

In relation to the above cases with the maximum loading conditions, the G99 U/V protection operated as a result of voltage suppression because of the loading conditions following the operation of LFDD. This is considered as an adverse effect of LFDD operation on DG as it disconnects additional generation over and above generation connected to LFDD feeders. With respect to the cases with minimum loading conditions, no G99 protection operation was observed as the DGs were able to provide enough support for that loading condition.

In reference [11], the authors have proposed a solution for detecting the loss of system earth for embedded generation based on neutral voltages and neutral currents which derives the earth impedance using the steady state zero sequence voltage and current signals measured from the DG terminals. This method could be further investigated to evaluate its performance in detecting the loss of system earth conditions described earlier.

8. Conclusions

An assessment of LFDD impact on network operability was carried out in this study. The issue arising from LFDD relays disconnecting a large numbers EHV substations which in return could disconnect DGs along with loads was addressed by a preliminary study of static and directional-based LFDD techniques and comparing the related results. This demonstrated that the directional LFDD relay implemented on the 33 kV outgoing feeders of 132/33 kV substations could improve the frequency response of the grid following a frequency disturbance with the mentioned assumptions. These results provide useful insights on how an LFDD scheme based on direction of current could improve the frequency response in a network.

It was observed that the LFDD operation impacted the DG interface protection based on G99 (i.e. operation of U/V, U/F or NVD) during the maximum loading condition in the network considering different operation scenarios. No G99 protection operation was observed during minimum loading condition following the LFDD operation. However, the G99 protection (U/V) operated during maximum loading conditions as a result of voltage suppression because of the loading conditions following the operation of LFDD. With the minimum loading condition, the loss of system earth issue was observed on the 33 kV feeders of the network. The reason was that the DOC protection of primary substation did not operate and the 33 kV feeders remained energised through the back-feed of 33/11 kV primary substation. This unwanted condition can be theoretically detected using a proposed protection algorithm reported in [11] based on neutral voltages and neutral currents that calculates the earth impedance for detecting the loss of system earth condition. The feasibility and performance evaluation of this earth impedance based method need further investigation.

It was verified that the NVD protection of primary substations (i.e. 33/11 kV substations) tripped for earth faults on the 33 kV feeders and the DOC protection element of primary substation also tripped for phase faults on the 33 kV feeders following the LFDD operation during both minimum and maximum loading conditions.

The future work could be focused on investigating the LFDD impact on additional network running arrangements and scenarios as well as identifying, modelling and testing complementary protection solutions to be deployed on the DG CBs that could be part of G99 protection which could detect the loss of system earth condition.

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[11] Redfern, M. A., Brown, D., and Bartlett, M. G.: 'Detecting Loss of Earth for Embedded Generation,” in Developments in Power System Protection, Amsterdam, Netherlands, 2001.