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Technical Report TA User Project

Distribution Network Oriented Demand Response (DiNODR)

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Abbreviations

A	Ampere
AC	Alternating Current
DAQ	Data Acquisition
DC	Direct Current
DER	Distributed Energy Resource
DG	Distributed Generation
DiNODR	Distribution Network Oriented Demand Response
DR	Demand Response
DTU	Technical University of Denmark
EPRI	Electric Power Research Institute
EU	European Union
IEC	International Electrotechnical Commission
kVA	Kilovolt-ampere
kVAr	Kilovolt-amperes Reactive
kW	Kilowatt
kWh	Kilowatt Hour
LV	Low Voltage
PV	Photovoltaic
RES	Renewable Energy Sources
TA	Transnational Access
ToU	Time-of-use
US	United States
V	Voltage

Executive Summary

Current demand response (DR) programs are designed for wholesale markets and utility level issues, neglecting local challenges that distribution network operators face in daily operation. Wide deployment of DR can even trigger local or regional problems in distribution networks, while providing services to wholesale markets for the favour of transmission grid. Therefore, it is important to consider distribution network operational state and constraints during demand response applications. Moreover, deployment of DR to specific parts of distribution networks can enable additional services and benefits.

DiNODR project focuses on distribution network oriented application of demand response. The project has three main objectives; namely, to develop distribution network centered DR approaches, to investigate distribution network threatening cases in wholesale market-driven DR applications and to design integrated programs comprising local level and utility level DR solutions. This project is one of the first efforts to field test distribution network centered demand response applications.

DiNODR project is aiming to contribute to this important area of study by developing a variety of device based DR methods, by evaluating the response performance of devices in a network and significantly by field testing of innovative DR methods on distribution networks.

In the first stage of the tests, technical issues that can arise in distribution networks were imitated using the test infrastructure and DR solutions were implemented using the available devices. The second stage was related to the impact of wholesale market or utility-driven DR actions on the local network. The last stage of the project was devoted to the development of coordinated DR programs that take into account the operational criterions and constraints of both transmission and distribution networks.

Field-tests with internal control options of domestic appliances in two houses with real residents showed that, 4 to 7 kW DR performance can be achieved per house, improving voltage profile by around 1.5%. The length of response depends on the participating appliances' operational constraints (temperature dead band limits, thermal insulation, program cycles and many more), while it may be possible to maintain a determined response level based on the coordination of available devices in the portfolio of an aggregator. DR actions for phase balancing and reconfiguration support have also promising results with location specific deployment. Considering that real LV networks have lines with rather smaller cross-sectional areas and more devices that can participate in DR actions, better performances can be achieved in typical LV networks.

Utility driven DR actions that conflict with the current state of the local network have particularly critical negative impact on customers located far from the substation. Therefore, during wide utility-driven DR deployments, it is vital to consider local network constraints.

The final stage of the tests showed that it is possible to deploy local network oriented DR and utility-driven DR actions with inverse targets on the same LV network simultaneously, with a proper grouping of loads that have minor impact on each other's buses. Real time transition from one target to another for a number of devices is also possible, in the case of insufficient response to mitigate a local problem. Voltage sensitivity matrix with less than 10 mV error rate can be derived by collecting 30 samples per step change in power of each of the buses, highlighting the interrelations between the buses in a local network.

The study is concluded by discussing open issues, while providing suggestions and possible directions for future research.

1 General Information of the User Project

Title	Distribution Network Oriented Demand Response
Acronym	DiNODR
Host Research Infrastructure	SYSLAB - Technical University of Denmark (DTU)
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2 Research Motivation

DiNODR project focuses on distribution network oriented application of demand response. The core motivators for this user project are,

- affection of distribution networks even at early stages of renewable integration,
- lack of locally specified demand management approaches to aid low voltage (LV) distribution network operation,
- lack of consideration of local network conditions during deployment of wholesale market-driven DR,
- absence of combined and simultaneous deployment approaches for local network oriented and wholesale market-driven DR events with conflicting requests.

2.1 Objectives

The project has three objectives:

- to validate promising localized and aggregated demand response approaches for distribution network services, including voltage profile improvement, overloading prevention, phase balancing and network reconfiguration support,
- to characterize the impact of utility-centered demand response actions on distribution networks,
- to validate simultaneous deployment options for two DR applications with opposite targets on the same LV distribution network.

2.2 Scope

The project mainly investigates aggregated use of residential flexible loads. In order to deploy real-time DR actions to reduce or increase demand, devices can be stopped (directly or by changing temperature set point for thermostatically controlled loads) using their existing control availabilities. The majority of new devices entering the market also allows remote and/or automated deployment of a number of the desired actions.

3 State-of-the-Art

The number of studies regarding the use of DR in distribution networks follows a rising trend particularly in recent years.

In [1] it is indicated that water heater consumption can be managed in response to changes in system frequency, outperforming any generation asset. Researchers in [2] described that active demand can postpone the need for reinforcements. Distribution line losses are reflected to a retail tariff structure and price-based demand flexibilities of consumers are modeled in [3]. A DR integrated distribution network planning study can be found in [4]. According to the analysis proposed in [5], critical peak pricing (CPP) is more effective than hourly pricing (HP) for distribution network based DR and network reconfiguration. It is because of the limited shifting flexibility of demand and the need for a considerable price difference between the nominal operation period and the shifted operation period. Use of DR in a distribution energy market based scenario is investigated in [6]. Distributed locational marginal prices are used without any additional incentives to reflect the locational state of a distribution network to customer tariffs. The services that DR can provide in distribution systems are described in [7] as coordinated voltage control and adaptive power factor control. The researchers in [8] introduced the contribution of DR to renewable hosting capacity and to reduction of losses in a distribution network. The work presented in [9] differs from many other studies in that it considers distribution network operational constraints for residential DR applications. Two important results of the study are the location effect (households far to the substation tend to reduce demand more) and rebound effect (a new peak can be faced with, due to reduced diversity of loads after a DR event ends). A similar approach can be found in [10], considering distribution grid topology in utility-driven DR actions. The study emphasizes that, the effect of DR events on the distribution network can be critical, after a certain threshold is reached. In another distinctive study, DR is preferred to prevent overloading of power sources in a DC distribution network [11]. A comprehensive discussion of future opportunities and challenges to use DR in distribution network operation is made in [12], determining the possible new use cases of DR (maximum capacity relief, emergency load transfer, steady state voltage management, power quality, phase balancing and outage recovery).

The related studies in the literature are mainly structured on assumed distribution network-centered DR performances of a house or a number of houses, neglecting individual performance of appliances. This limits the scenarios that can be investigated and prevents effective development and evaluation of innovative methods. Moreover, mostly a general DR method is considered for the loads, ignoring possible varieties in DR methods due to device-specific operational characteristics. It should also be noted that the existing distribution network-centered DR studies are based on simulations or numerical calculations, requiring field tests and demonstrations for further clarification of applicability.

4 Executed Tests and Experiments

The tests were categorized and executed as three main groups:

1- Localized and aggregated demand response approaches for distribution network services,
2- The impact of utility-centered demand response actions on distribution networks,
3- Simultaneous deployment options for two DR applications with opposite targets on the same LV distribution network.

The host research infrastructure is SYSLAB of Technical University of Denmark (DTU), Department of Electrical Engineering. It has a 400 V low voltage (LV) network with advanced monitoring, data acquisition and control options. The used assets are 2 wind turbines (10 kW and 11 kW), 3 PV plants (37 kW in total), 3 mobile controllable loads (up to 36 kW),1 stationary dump load (up to 75 kW), a controllable load that can have different set points up to 15 kW for each phase, and particularly two buildings (one office – FlexHouse-1 and a domestic house FlexHouse-3) with controllable loads. The house has real residents that live inside. FlexHouse-1 has heating system up to 10 kW in total, 5 air conditioners and lights up to 1.4 kW. FlexHouse-3 has two space heaters 1.3 kW in total, a 2.8 kW water heater, a washing machine, dishwasher, and a clothes dryer as flexible residential loads. The network has five substations together with configurable lines and busses that allows numerous test setups.

4.1 Test Plan

The test plan is provided in Table 1.

Table 1: Test Plan

<table>
<tr><th>Week</th><th>Day</th><th>Plan Content</th><th>Specification</th></tr>
<tr><td>1</td><td>1</td><td rowspan="5">Getting Familiar with DER TF</td><td rowspan="5">• Learning device control availabilities
• Adaptation of monitoring and control codes
• Preliminary tests for data acquisition and automated control</td></tr>
<tr><td>1</td><td>2</td></tr>
<tr><td>1</td><td>3</td></tr>
<tr><td>1</td><td>4</td></tr>
<tr><td>1</td><td>5</td></tr>
<tr><td>2</td><td>1</td><td>1.1. Undervoltage Mitigation Test</td><td>Distribution Network Oriented Aggregated Demand Response</td></tr>
<tr><td>2</td><td>2</td><td>Test 1.1 Analysis of Results</td><td>Distribution Network Oriented Aggregated Demand Response</td></tr>
<tr><td>2</td><td>3</td><td>1.2. Overvoltage Mitigation Test and 2.1 Grid-driven Demand Increment During Undervoltage Test</td><td>Distribution Network Oriented Aggregated Demand Response & Distribution Network Threatening Utility-Driven Demand Response</td></tr>
<tr><td>2</td><td>4</td><td>1.3. Phase Balancing Test</td><td>Distribution Network Oriented Aggregated Demand Response</td></tr>
<tr><td>2</td><td>5</td><td>1.4. Network Reconfiguration Aiding DR Test</td><td>Distribution Network Oriented Aggregated Demand Response</td></tr>
</table>

3	1	3.2. Combined DR Application (demand reduction for the utility and demand increment for the local grid)	Combination of Distribution Network-Centered Demand Response and Utility-Driven Demand Response
3	2	3.1. Combined DR Application (demand increment for the utility and demand reduction for the local grid)	Combination of Distribution Network-Centered Demand Response and Utility-Driven Demand Response
3	3	Repeatition of tests with issues	Combination of Distribution Network-Centered Demand Response and Utility-Driven Demand Response
3	4	Sensitivity matrix tests	General
3	5	Analysis of test results	General

4.2 Standards, Procedures, and Methodology

Test cases were described using IEC 62559 format. Test specifications and experiment specifications were prepared using the templates provided in "D-NA5.1 Holistic Test Specification" workshop handout of ERIGrid.
The aim for the first group of tests was to investigate the impact of local DR actions using residential devices.
Device based performances were evaluated based on the achieved change in a device's demand after a DR action, while impact on the network issue is observed calculating the improvement in voltage profile or line loading of a specific part of the network.
Operational voltage limits defined in IEC 60038 standard was considered for voltage related tests [13], while for line loading limits, values indicated by device manufacturers were considered.
The heating system peak load in FlexHouse-1 is limited to 3 kW by purpose during tests, close to typical peak of such systems in small buildings. It is dispatched totally during DR. On the other hand, lighting load of the same building is dispatched up to 50%, which reduces its load from 1.42 kW to 0.71 kW. This is assumed to be a reachable amount through dimming or grouped dispatch of lights in a building with several rooms.

4.3 Test Set-ups

The tests were done using automated control and monitoring software coded in MATLAB in communication with the central remote real-time data acquisition system of the laboratory. Controllable loads and heating system in FlexHouse-1 was controlled remotely and automatically, while other residential loads were controlled locally and manually. Network configuration is changed using the available graphical user interface of the laboratory by the host research infrastructure technical staff for security purposes during the test.

Undervoltage Mitigation Set-up

The setup for the undervoltage mitigation test is given in Figure 1.
Mobile Load-1 (CEE in Fig 1. in building 319), FlexHouse-1 and Flexhouse-3 were located far to the substation, while wind turbines (Gaia and Aircon in Fig. 1) and PV panels were located rather closer. The length of Cable A1 and A2 are 25 m each, while Cable F1 is 250 m, Cable E2 is 450 m and Cable F1 is 330 m.
Mobile Load-1 and Mobile Load-2 (CEE in the same figure in building 716) were loaded with 15 kW, while Flexhouse-1 (in building 715) heating system and lights were on. Moreover, dishwasher, clothes dryer and washing machine in FlexHouse 3 were operating at the first stage. At the second

step of the test, Flexhouse-1 demand was reduced to 1.42 kW (through stopping the heating system by setting a higher temperature set point). Change in the voltage of critical busses of the network was calculated, while observing the managed demand per house.

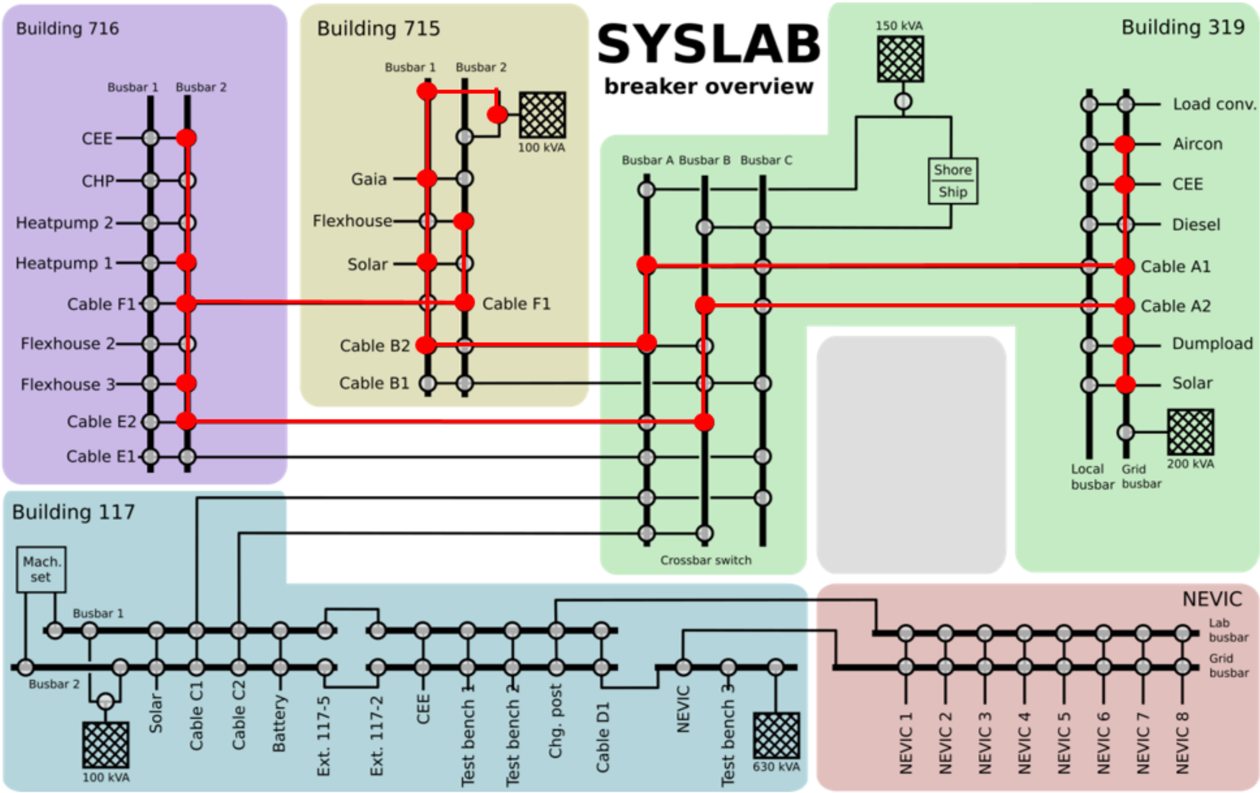

Figure 1: The setup for undervoltage mitigation test

Overvoltage Mitigation Set-up

The same setup of undervoltage mitigation test was used for overvoltage mitigation test. However, two space heaters and one water heater in FlexHouse-3 were also included in the DR process. FlexHouse-1 lighting system was lightly loaded (0.71 kW) initially, while power set points for both of the mobile loads were set to 0. In FlexHouse-3 the loads were off. At the second stage, FlexHouse-1 lighting and heating system was dispatched to increase demand and reached 4.42 kW, while all the manageable loads in FlexHouse-3 was turned on, reaching 8.16 kW. Same evaluation process of undervoltage mitigation test was followed.

Phase Balancing Set-up

A basic set-up is preferred to include the needed devices for this test (Figure 2). The main aim is to keep loading of each phase close to each other at the substation. Particularly and only for this test, a different type of mobile load is used. It is 45 kW three phase load, with independent load control option for each phases up to 15 kW. It is used for creating an imbalance in the network initially, while loads in FlexHouse-1 and FlexHouse-3 were managed to balance the phases. Changes in loading of each bus were recorded and differences between phases were analysed.

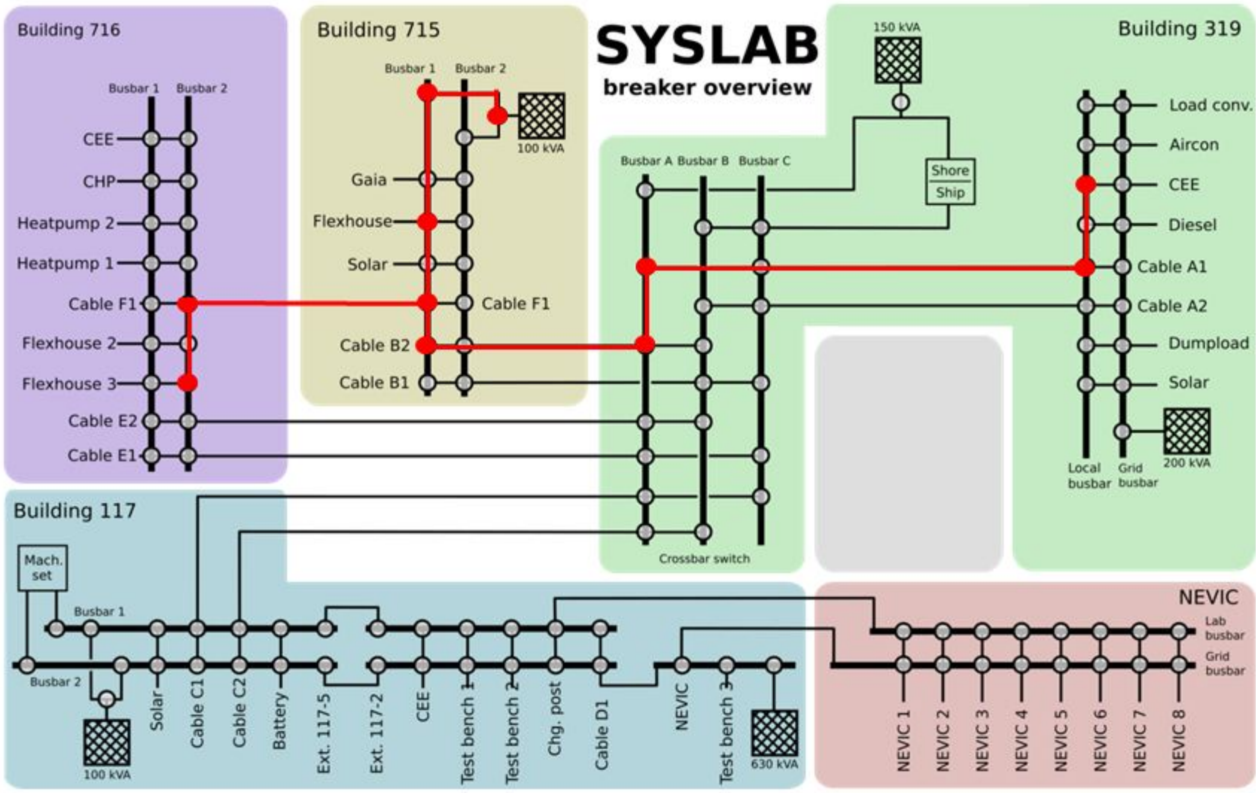

Figure 2: The setup for phase balancing test

Reconfiguration Set-up

A distinctive initial set-up was used for reconfiguration test (Figure 3). For online reconfiguration, firstly two feeders were connected to each other by Cable B2 between building 715 and crossbar switch of building 319, by closing the normally open breaker that connects Cable B2 to busbar 1 (Figure 4). Then, the breaker that connected busbar 1 to the substation was opened at the second stage, completing the online reconfiguration process (Figure 5). While both of the houses were highly loaded (4.42 kW for FlexHouse-1 and 6.13 kW for FlexHouse-3) together with mobile loads (15 kW each of the two), DR actions were applied to reduce demand of FlexHouse-3. Changes in bus voltages were observed. In Figure 3 and 5, the connection points colored with blue are the ones that change their status from open to closed or vice versa.

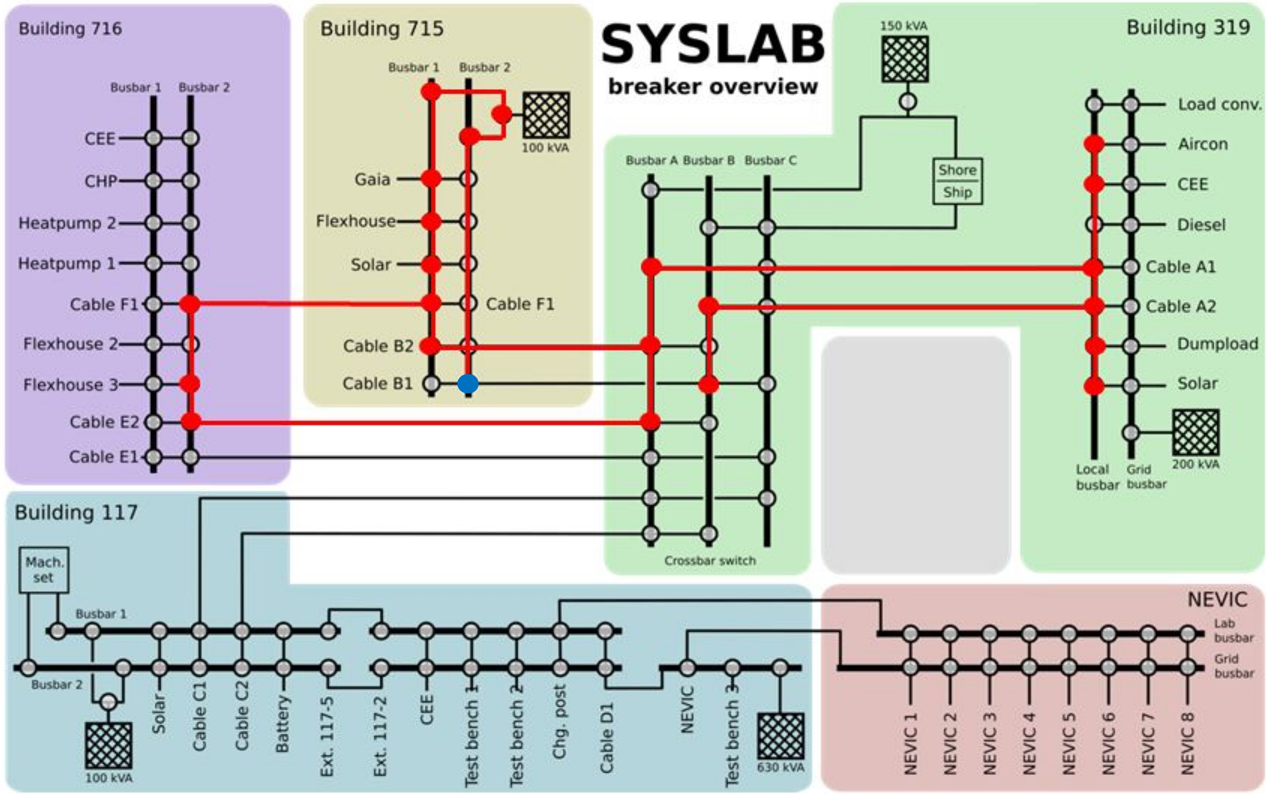

Figure 3: Initial set-up for online reconfiguration test

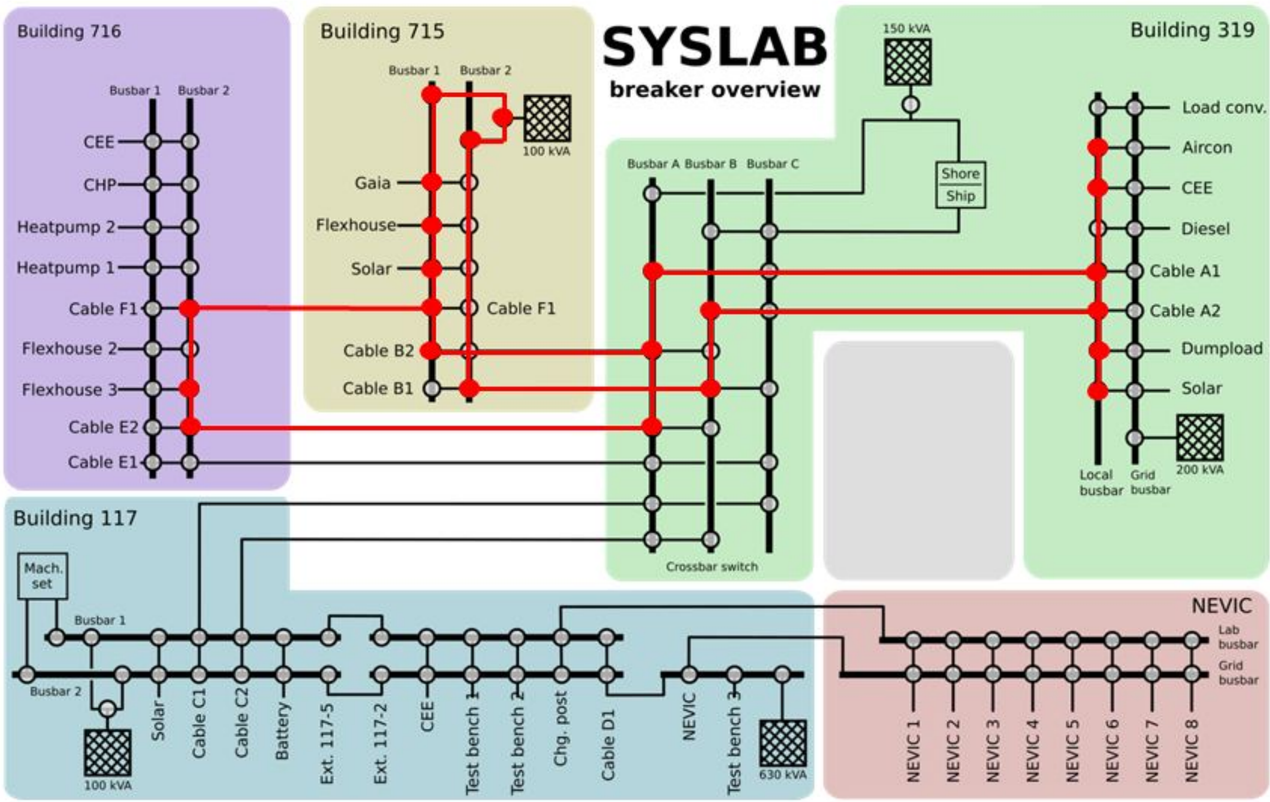

Figure 4: The first stage of online reconfiguration

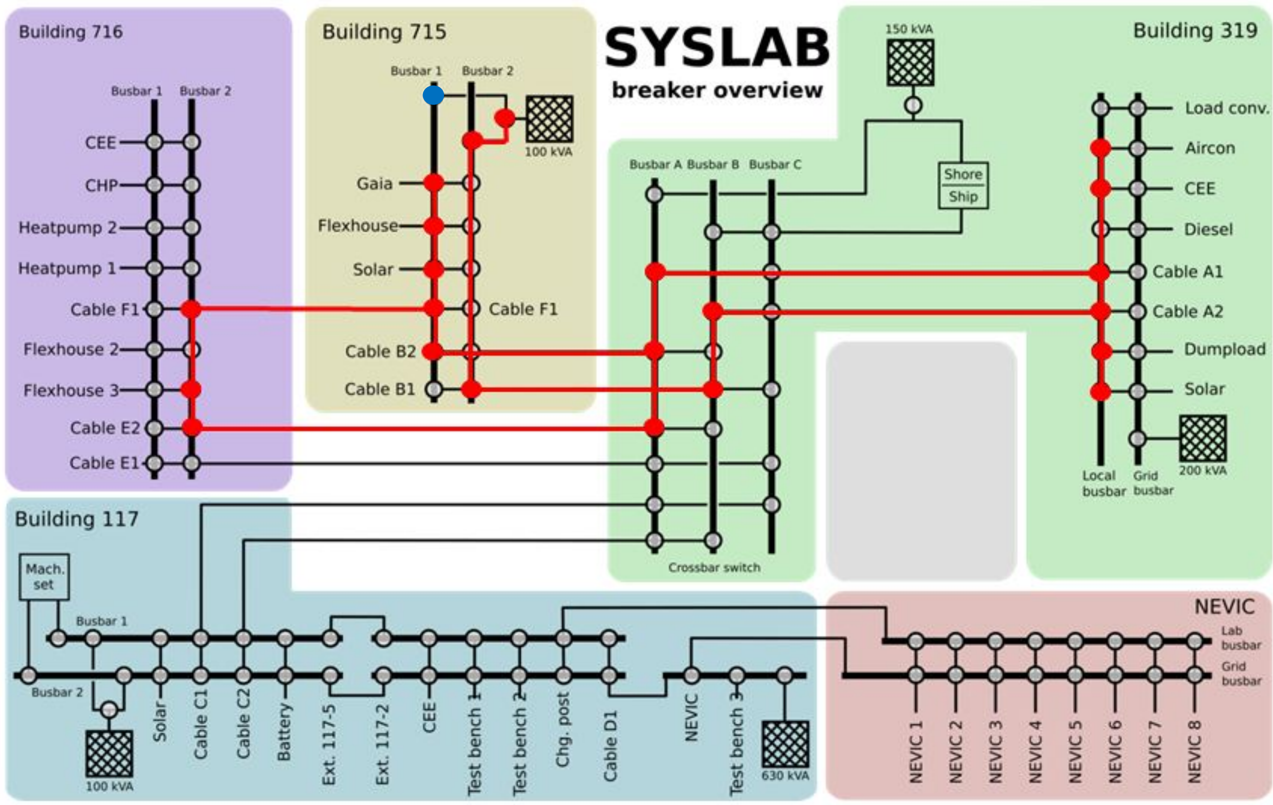

Figure 5: The second stage of online reconfiguration

Grid-driven Demand Increment During Local Undervoltage Set-up

The same configuration of undervoltage mitigation and overvoltage mitigation tests was used in this test. FlexHouse-1 was lightly loaded with only a part of the lighting system (0.71 kW), while FlexHouse-3 loads were off. Each of the mobile loads' power set point was set to demand 15 kW from the network. Due to a grid-driven demand increment request, FlexHouse-1 lights and heating system was managed to raise overall demand of the building, while the two space heaters, water heater, clothes dryer and washing machine in FlexHouse-3 was turned on. Changes in power of each house and voltage of each critical bus were analysed.

Combined DR Application (demand reduction for the utility and demand increment for the local grid) Set-up

Test system was formed using the substation in building 319, both of the mobile loads and both of the houses (Figure 6). Test sequence consists of 3 stages. The first stage is initialization, where mobile loads were set to demand 10 kW each, FlexHouse-1 heating system and lights are on, demanding 4.42 kW in total; while the water heater and one of the space heaters in FlexHouse-3 are on, consuming 3.44 kW. In the next stage, FlexHouse-1 and FlexHouse-3 reduce their demand to aid the local grid issue and changes in the bus voltages were recorded. After that, Mobile Load-1 (in building 319) increases its power output from 10 kW to 15 kW for responding to a grid-driven DR event that requires demand increment. The opposite changes in critical bus voltages were recorded and compared with of stage 1 and 2.

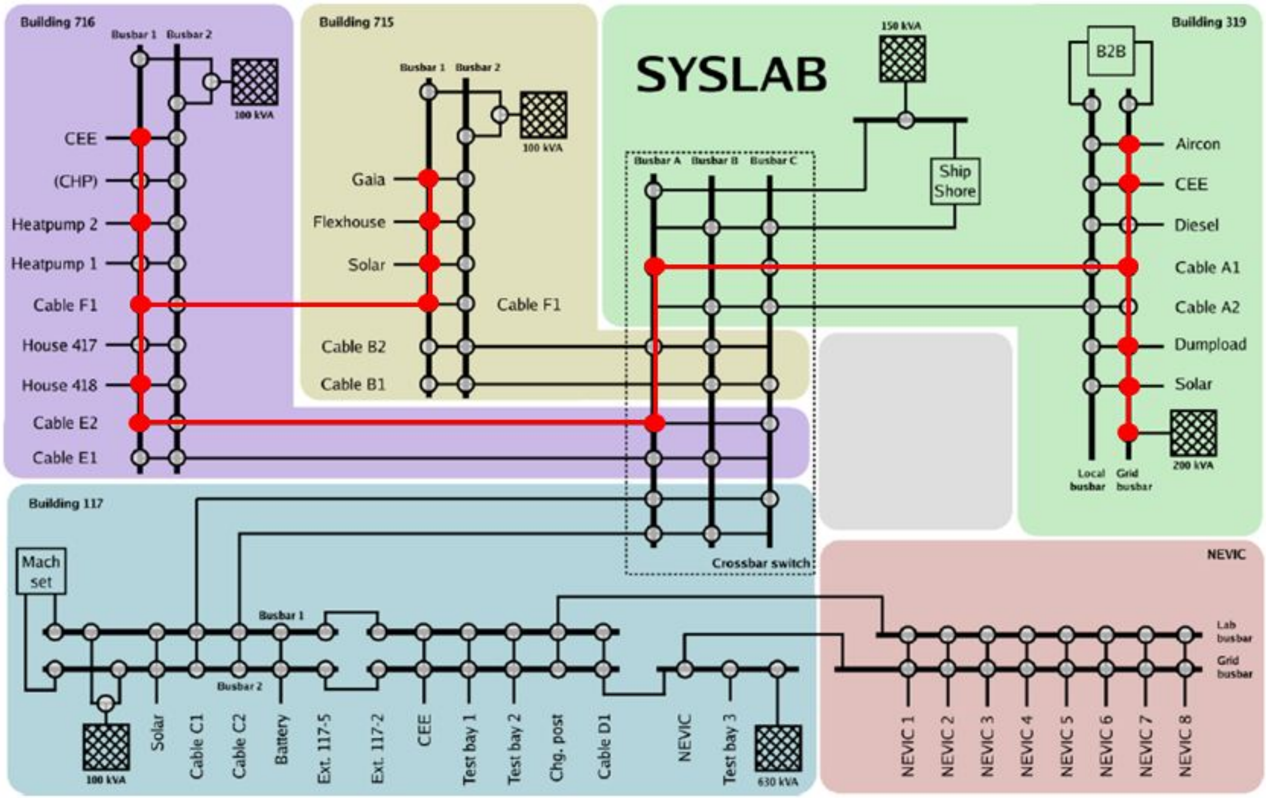

Figure 6: Combined DR application test set-up

Combined DR Application (demand increment for the utility and demand reduction for the local grid) Set-up

The same set-up for the previous combined DR application test was used. The differences in the test were initial demands of FlexHouse-1 and FlexHouse-3, while all the manageable loads were off, except 50% of lighting load in FlexHouse-1. Each of the mobile loads were set to demand 10 kW initially. The flexible loads in the houses were activated to increase demand in the second stage. In the last stage, power set point of Mobile Load-1 near substation was reduced by 5 kW. The bus voltage of each participator for each step was recorded and compared.

Voltage Sensitivity Matrix Test Set-up

Using the same test set-up of combined DR tests, voltage sensitivity matrix was derived. It represents the impact of changes in power exchange of each bus on its own voltage and voltages of all the other busses. It is derived according to the flow chart provided in Figure 7. Briefly, the system collects bus voltage data, makes a step change in the power exchange of one of the busses and collects bus voltages again. Calculating the difference between two collected values for each bus, one row of the matrix is filled out. The same process is repeated by changing the power exchange of another bus to fill out another row of the matrix and the process continues until all the matrix is derived.

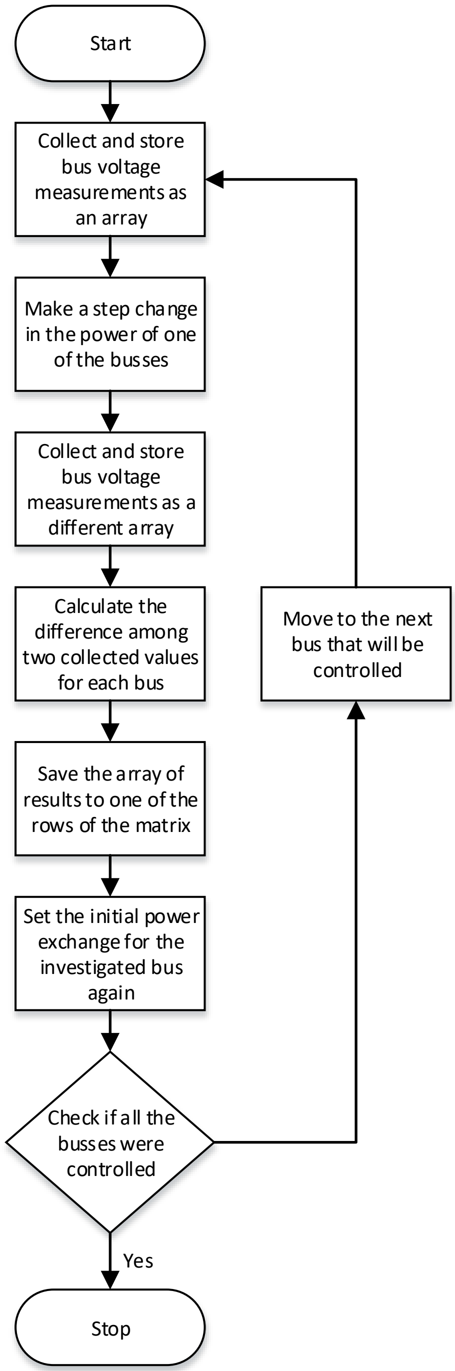

Figure 7: Voltage sensitivity matrix derivation approach

4.4 Data Management and Processing

Monitoring system that runs in the user team's computer has 5 second resolution, while the laboratory has a central data acquisition system with 1 second resolution. However, high resolution data stored by the central data acquisition system is available at the end of the day; because the system saves the collected data to daily record files at the end of each day. For this reason, the monitoring system of the user team was used during testing and stored data as a back-up, while mainly the data stored by the central data acquisition system was obtained the following day and used during evaluation of test results.

5 Results and Conclusions

5.1 Distribution Network Oriented Aggregated Demand Response Results

Undervoltage Mitigation

The power management performances of FlexHouse-1 and FlexHouse-3 are given in Table 2.

Table 2: Power management results for each house

Building Name	***Demand Before DR [kW]***	***Demand After DR [kW]***	***Managed Demand [kW]***
FlexHouse-1	3.99	1.43	2.55
FlexHouse-3	5.06	0.13	4.93
Total	9.05	1.56	7.48

The changes in the voltage drops for the three critical busses are provided in Table 3.

Table 3: Improvement in bus voltages

Bus Name	***Voltage Drop Before DR [%]***	***Voltage Drop After DR [%]***	***Contribution of FlexHouse-1 to Voltage Profile Improvement [%]***	***Contribution of FlexHouse-3 to Voltage Profile Improvement [%]***
FlexHouse-1	-4.72	-3.12	0.75	0.85
FlexHouse-3	-4.90	-3.40	0.45	1.05
Mobile Load-2	-4.90	-3.45	0.45	1.00

The results showed that, considerable improvements in voltage profiles can be achieved through localized DR actions. 2.55 kW of managed demand for FlexHouse-1 is able to improve bus voltages by 0.45 to 0.75%, while 5 kW of managed demand in FlexHouse-3 contributes to voltage profile improvement by 0.85 to 1.05%. Since the test infrastructure has lines with cross-sectional areas (ranging from 95 to 240 mm^2) bigger than typical LV distribution networks, positive DR impact on bus voltages in typical systems could be rather higher. Furthermore, there would be more customers and devices to contribute to DR events in typical networks compared to the test setup, providing a rather higher and sustainable management potential.

Overvoltage Mitigation

Following an evaluation procedure similar to undervoltage mitigation test power managed per house is given in Table 4.

Table 4: Power values for the test

Building Name	***Demand Before DR [kW]***	***Demand After DR [kW]***	***Managed Demand [kW]***
FlexHouse-1	0.81	4.40	3.59
FlexHouse-3	0.09	8.16	8.07
Total	0.90	12.56	11.66

Changes in the voltage drop of three critical busses are presented in Table 5.

Table 5: Bus voltage improvements for overvoltage test

Bus Name	***Voltage Drop Before DR [%]***	***Voltage Drop After DR [%]***	***Contribution of FlexHouse-1 to Voltage Profile Improvement [%]***	***Contribution of FlexHouse-3 to Voltage Profile Improvement [%]***
FlexHouse-1	-0.28	-1.83	-0.69	-0.86
FlexHouse-3	-0.42	-2.03	-0.60	-1.01
Mobile Load-2	-0.46	-1.96	-0.60	-0.90

The results highlighted the local impact of DR based on load increment. 3.59 kW managed demand from FlexHouse-1 has impact on bus voltages ranging from 0.60 to 0.69%, while 8.07 kW demand change in FlexHouse-3 has influence between 0.86 and 1.01%.

Phase Balancing

The order of DR actions to balance phases were given in Table 6.

Table 6: DR actions for phase balancing

Content	***Phase A Loading [kW]***	***Phase B Loading [kW]***	***Phase C Loading [kW]***	***Average Imbalance Between Phases [kW]***	***Maximum Imbalance Among Phases [kW]***
Initial Case	4.30	3.70	3.80	0.40	0.60
Water Heater in FlexHouse-3 is on	4.30	5.11	5.25	0.63	0.95
A group of lights in FlexHouse-1 were switched on	4.60	5.11	5.25	0.43	0.65

One of the air conditioners in FlexHouse-1 were switched on	5.00	5.11	5.25	0.17	0.25
Another group of lights in FlexHouse-1 were switched on	5.14	5.11	5.25	0.09	0.14

Phase loadings before and after DR actions were given in Figure 8. Total loading of all the phases were shown in Figure 9. Comparing the average imbalance and maximum imbalance values before and after DR actions, it can be observed that average imbalance is reduced by 77.5% (from 0.40 to 0.09 kW), while maximum imbalance is reduced by 76.7% (from 0.60 to 0.14 kW). The total increment in power was 3.9 kW. Based on the portfolio and current availability of devices in a network, demand reduction can also be preferred for balancing.

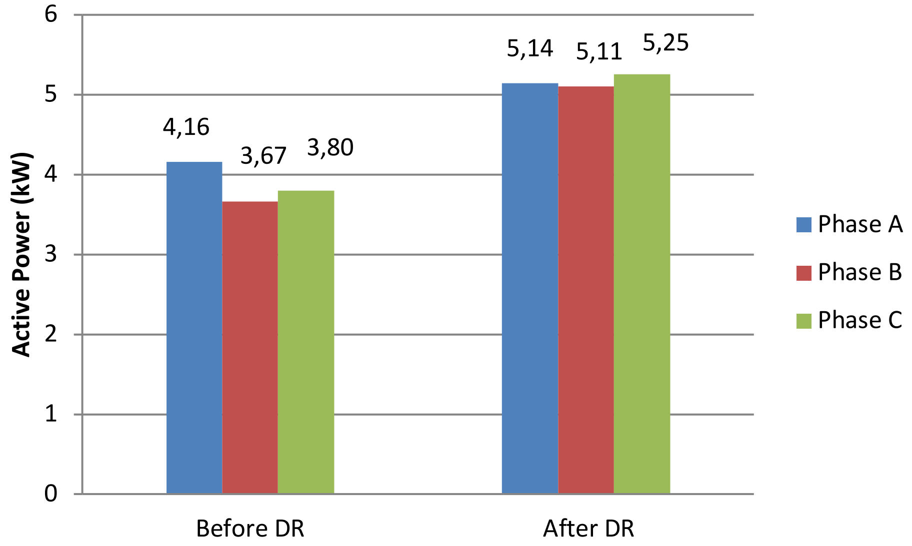

Figure 8: Loading of each phase before and after the deployment of DR actions

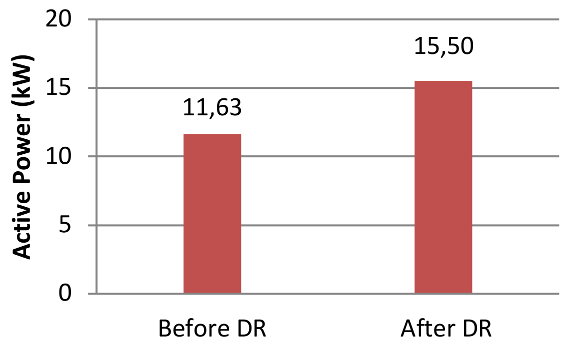

Figure 9: Total loading of all the phases

Reconfiguration

The changes in the voltage drop of three critical busses in the network are shown in Figure 10.

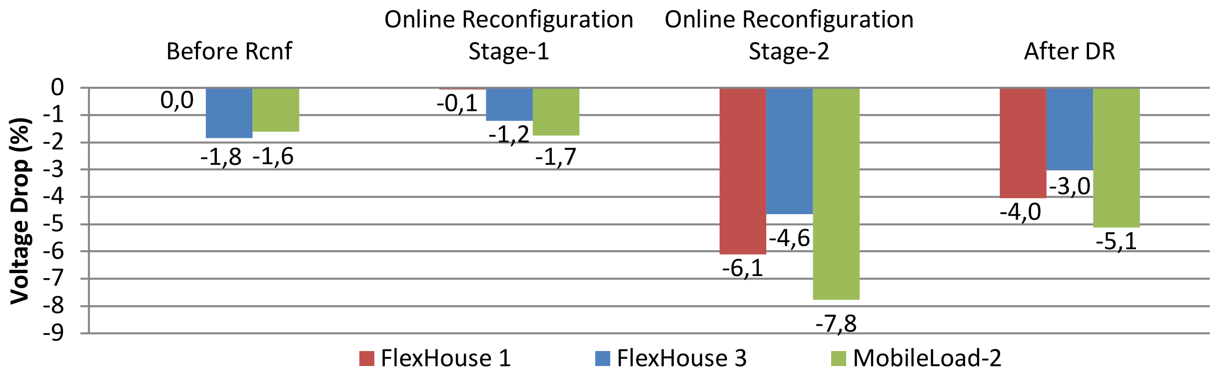

Figure 10: Voltage drops for three critical busses for each stage of online reconfiguration test

As can be seen from Figure 10, moving the loads of a feeder to another one affected bus voltages from 4.4 to 6.1%. Reduction of 6.1 kW in FlexHouse-3 considerably improved voltage profile by reducing voltage drops by 1.6 to 2.7%.

Grid-driven Demand Increment During Local Undervoltage

Following the same evaluation procedure preferred for undervoltage and overvoltage mitigation tests, power changes in buildings that participate to DR are given in Table 7.

Table 7: Changes in power of each participating building

Building Name	***Demand Before DR [kW]***	***Demand After DR [kW]***	***Managed Demand [kW]***
FlexHouse-1	0.74	3.99	3.25
FlexHouse-3	0.16	5.86	5.70
Total	0.90	9.85	8.95

Affection of bus voltages for the three critical busses are presented in Table 8.

Table 8: Changes in voltage drops

Bus Name	***Voltage Drop Before DR [%]***	***Voltage Drop After DR [%]***	***Contribution of FlexHouse-1 to Voltage Profile Improvement [%]***	***Contribution of FlexHouse-3 to Voltage Profile Improvement [%]***
FlexHouse-1	-3.45	-4.87	-0.63	-0.79
FlexHouse-3	-3.46	-4.77	-0.54	-0.77

Mobile Load-2	-3.52	4.78	-0.55	-0.71

The test shows the negative impact of a grid-driven DR action on a local network during a prospective undervoltage problem. The results showed that, increment of demand by 8.95 kW through participation of two houses in a local area can reduce bus voltages by 0.54 to 0.79%. Especially for wide deployment of grid-driven DR actions with many participators from the same region, local problems may become much worse. Therefore local network conditions should be considered during wide grid-driven DR deployments to prevent possible local network issues.

Combined DR Application (demand reduction for the utility and demand increment for the local grid)

Changes in power demand of three participators were provided in Figure 11.

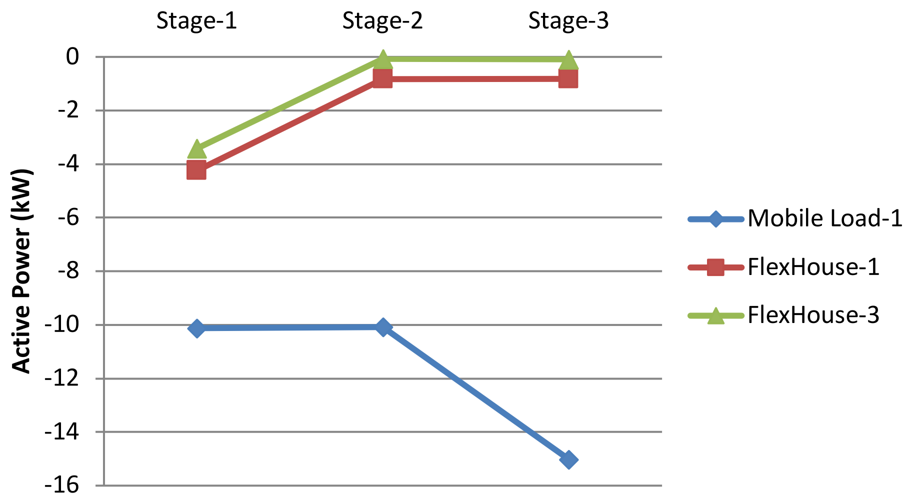

Figure 11: Changes in the demand of participators for each stage of the test

Changes in the voltage drop for each critical bus can be seen in Figure 12.

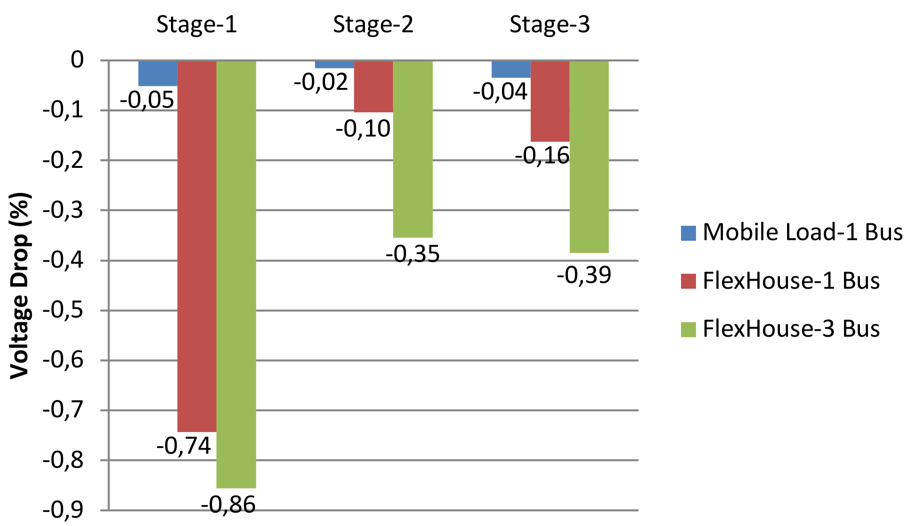

Figure 12: Changes in voltage drop of participator busses for each stage of the test

Comparison of stage-2 and stage-3 results gives insights about simultaneous deployment of two DR actions with opposite targets in the same network. 7.6 kW of demand reduction in total (from FlexHouse-1 and FlexHouse-3) improved critical bus voltages by 0.51 to 0.64%. On the other hand, 5 kW of demand increment by Mobile Load-1, located closer to the substation than the houses resulted in a slight opposite change in bus voltages by 0.04 to 0.06%. Stage-3 results can be summarized as “a distribution network region facing a prospective local undervoltage problem responded to a grid-driven DR event requiring demand increment by 5 kW with slight differences in the voltages of critical busses”. The negative impact of this DR action on the achieved local DR performance in stage-2 for FlexHouse-1 bus is 0.06 of 0.64% (9.37% of the achieved performance for that bus) and for FlexHouse-3 bus is 0.04 of 0.51% (7.84% of the achieved performance for that bus).

Combined DR Application (demand increment for the utility and demand reduction for the local grid) Set-up

Applying an evaluation process similar to the previous combined DR test, changes in power of each participator is shown in Figure 13.

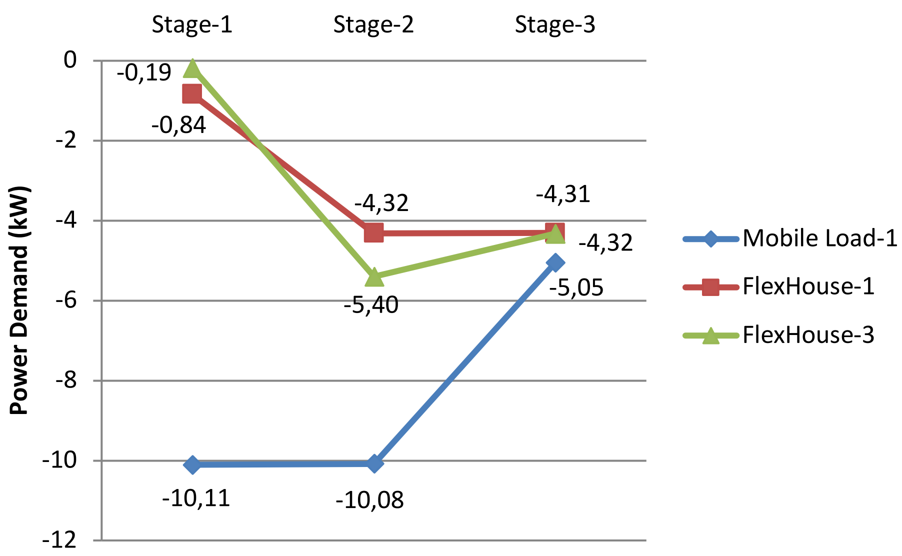

Figure 13: Changes in the demand of participators for each stage of the test

Changes in the voltage drop of each participator bus were depicted in Figure 14.

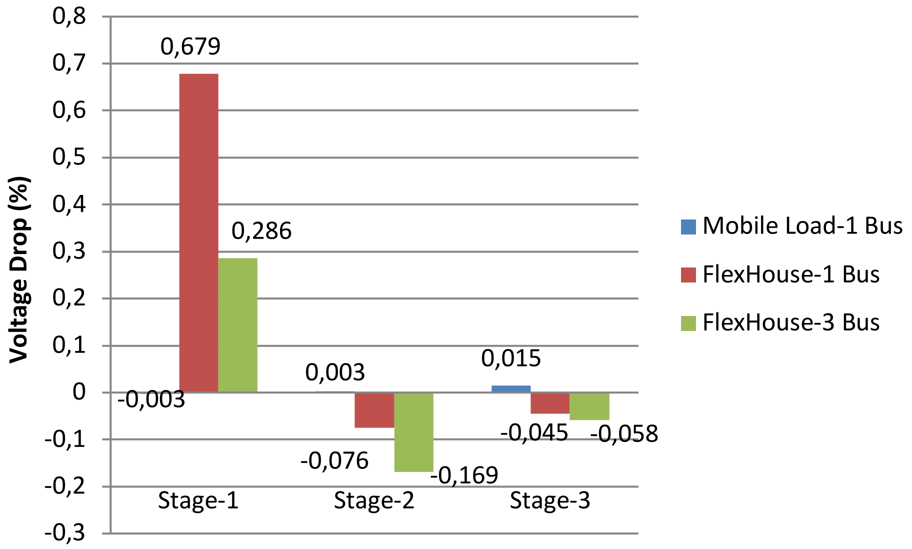

Figure 14: Changes in the voltage drops for each participator busses

According to the results, local DR actions performed by FlexHouse-1 and FlexHouse-3 resulted in 7.6 kW demand increment in total, improving voltage profile of their busses by around 0.74% and 0.44% respectively. The DR action with the opposite target performed by Mobile Load-1 around 5 kW, located close to the substation affected the bus voltages by around 0.03 and 0.11 respectively. The negative impact of the grid-driven DR action performed by Mobile Load-1 on the achieved local DR performance is from 0.03 of 0.74% (4.05% of the achieved performance) for FlexHouse-1 and 0.11 of 0.044% (25% of the achieved performance) for FlexHouse-3. The main reason for different results for FlexHouse-3 in this test compared to the previous test is due to change of its demand in the last stage by around 1.1 kW. This is sourced by change in the power profile of washing machine due to its washing cycle. It is a considerable impact that can additionally affect DR performance in load increment based DR events and included in the analysis.

Voltage Sensitivity Matrix Test

The test was repeated for a number of times to test the reliability of the matrix parameters that were derived. Average of 30 voltage measurement collected consecutively with 1 second resolution before and after a step change in power, was found to provide reliable results. The results of the three identical tests were shown Fig. 17, 18 and 19 for each row of the matrix.

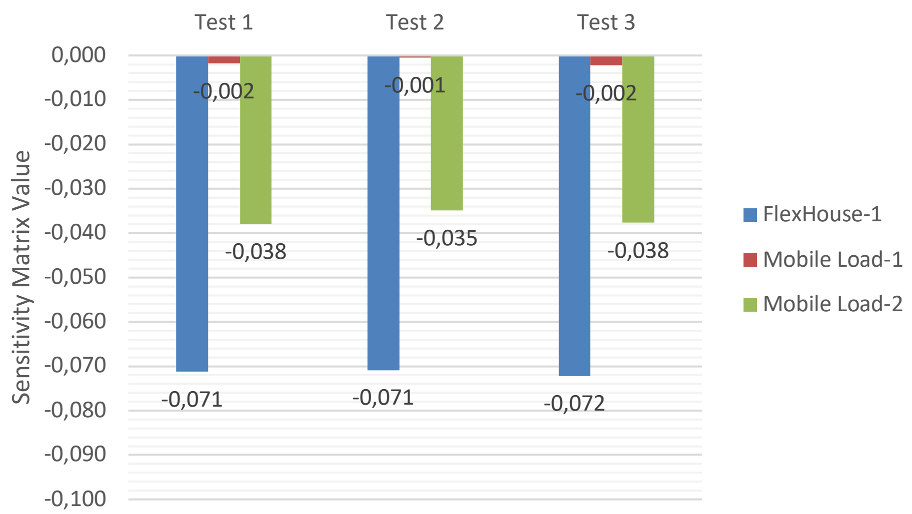

Figure 17: Impact of a step change in the power exchange of FlexHouse-1 bus on other busses

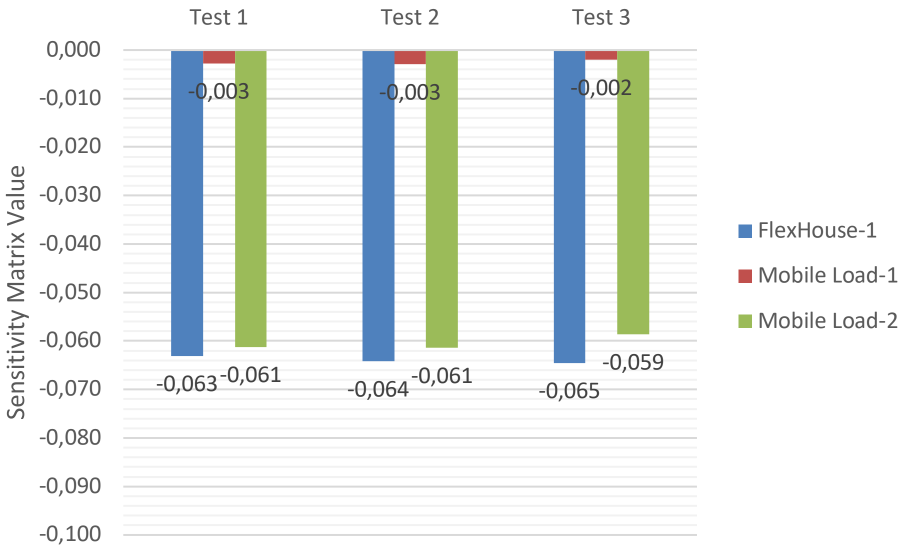

Figure 18: Impact of a step change in the power exchange of Mobile Load-2 bus on other busses

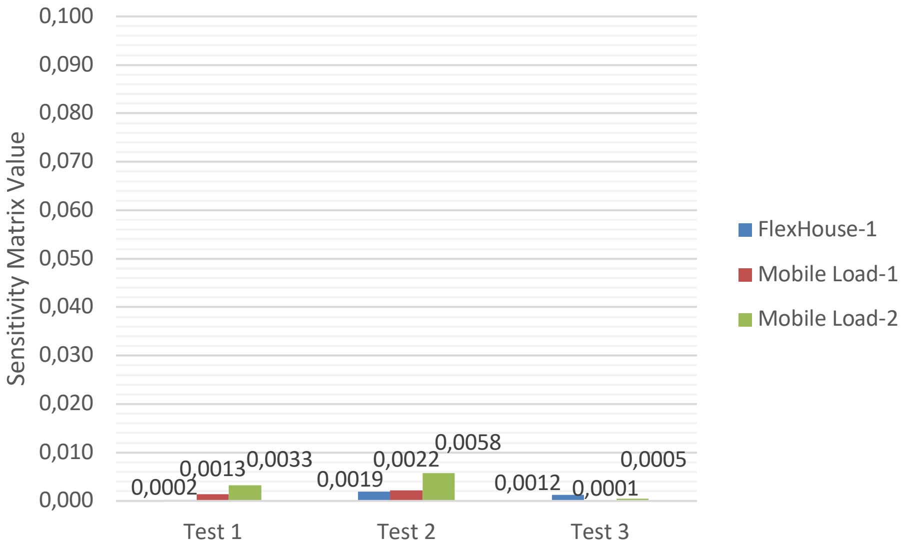

Figure 19: Impact of a step change in the power exchange of Mobile Load-1 bus on other busses

As can be seen from the results, the measurement equipment used in the test provided satisfactory results for differences above 10 mV (Figure 17 and 18). However, the monitoring system was found not sensitive enough for devices that are close to substation and have negligible impact on other busses (Figure 19). The parameters found for FlexHouse-1 and Mobile Load-1 highlighted their effectiveness for mitigating the issues on the local network. As long as the system configuration is not modified, these values can be used as a basis to decide on which customers to dispatch effectively in the case of a localized problem.

6 Open Issues and Suggestions for Improvements

DiNODR project has been one of the first field tests of distribution network aiding demand response using residential loads. The results are encouraging with considerable impact and potential of participators to cope with the challenges faced with in local grids.
One of the open issues is automated and remote management of home appliances using their existing control features. While heating/cooling systems and lights can be controlled through automation devices with IP gateways, remote home appliance control is still an emerging field with a num-

ber of pioneer models developed by different manufacturers. Some of the recent appliances in the market have cloud connection mostly for basic information representation rather than control and energy management. Furthermore, devices should have a common language or interface through which the users and aggregators can monitor, control and define preferences.

Another open issue is device response durations. Thermostatically controlled load cycles may vary due to changes in environment temperature and customer use (such as door and window openings), while manually controlled loads have different programs that they can follow resulting in different power values and response durations at the time of a local event. Machine learning methods can be useful to understand device operation patterns and provide aggregators more insight about sustainability of initially achieved management performances. Furthermore, more advanced aggregation approaches can be developed for effective management by just in time filling of devices that complete their response duration and become unavailable.

The sensitivity matrix derivation approach preferred in this project was sufficient to provide satisfactory results. However, further improvements can be made to reduce the number of samples to be collected and calculation times. It is also important to perform further tests in numerous distribution networks to get more insights about the ways to better group local participants according to their impact on others, and the ways to choose several participants for mitigating a local problem effectively.

7 Dissemination Planning

The project has a number of dissemination tools. Formal dissemination activities are going to be scientific publications (two journal papers and one conference paper) and the project website, while there are three semi-formal activity groups as a session in a workshop, social media pages (LinkedIn and ResearchGate), newsletters as well as reference on the websites of the Departments of Electrical Engineering of both Istanbul Technical University (ITU) and Western Macedonia University of Applied Sciences (TEIWM). In every 2 months following the field tests, a newsletter that explains dissemination activities will be published. It is planned to be distributed through a registered mailing list and also the user project website.

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