D-Suite

Work Package 5 - Site Selection Report

3/28/24

Future Networks

About Report

Report Title	:	TRIAL SITE SELECTION (Example sites and Procedures)
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Abbreviations and Definitions

Abbreviation	Definition
ST	Smart Transformer
LCT	Low Carbon Technology
LVAC	Low Voltage AC
LVDC	Low Voltage DC
NOP	Normal Open Point
SPD	SP Distribution
SPM	SP Manweb
ADMD	After Diversity Maximum Demand
BaU	Business as Usual
EV	Electric Vehicle
PED	Power Electronic Device
POC	Point of Connection
RMU	Ring Main Unit
STATCOM	Static Synchronous Compensator
SPM-U	Scottish Power Manweb Urban
SPM-SU	Scottish Power Manweb Sub-Urban
SPD-U	Scottish Power Distribution Urban
SPD-SU	Scottish Power Distribution Sub-Urban

Contents

1. Introduction

The purpose of this document is to outline the D-Suite Power Electronic Device (PED) hardware deployment requirements at potential trial locations. It also provides information about the trial site selection process and examples of potential trial sites for the D-Suite Project. It should be noted that this report does not include all the trial sites selected for the D-Suite schemes; only those analysed for Work Package 1 are included in this report. A complete list of trial sites can be found in a SPEN internal document, which will be updated regularly to reflect progress towards achieving the Project objective.

1.1. Project Overview

Solving issues, including voltage increase, phase imbalance, and transformer overload, the D-suite project seeks to expedite the integration of Low Carbon Technologies into the DNO network using Power Electronic Devices (PEDs). Electric vehicle (EV) chargers, heat pumps (HP), and photovoltaics (PV) are examples of Low Carbon Technologies (LCTs) under consideration for the D-Suite project.

High penetration of Photovoltaics (PV) can cause statutory violations, including Voltage Rise (VR) and Voltage Imbalance (VI) on LV feeders. Large PV penetration also causes protection issues, increased feeder losses, transformer and cable rating issues, sudden voltage rise and reverse power flow. These problems can be exacerbated if high PV penetration is unbalanced between the three LV phases. Voltage Imbalance (VI) has been a significant power quality problem in low voltage residential feeders, due to the random location and capacity of single-phase rooftop photovoltaics (PV), Plug in Electric Vehicles (PEV) and Heat Pumps (HP).

National standards specify that the nominal voltage at the source should be in a narrow tolerance range of 230V with a tolerance between +10% and -6%. According to IEC 61000 and EN 50160 standards, the allowable limit for VI is 2% in LV networks for 95% of the data measured over a 7-day period in 10-minute RMS values. Additionally, Engineering Recommendation P29 also limits the VI to 1.3% at the load point. The two issues of VR and VI can be addressed in different ways by the D-Suite PEDs, such as the D-STATCOM. The D-Suite project aims to remove these barriers by:

- Providing optimised design of several D-Suite PED, suitable for LV deployment, which can operate in a coordinated control regime or a stand-alone control solution.
- Addressing the detailed operational and public safety requirements, protection considerations and overall network interface requirement in the hardware designs.
- Providing a coordinated control algorithm to maximise the existing network utilisation.
- Providing a holistic and systematic approach to identify niche scenarios for practical guidance for future network planning and investing; and
- Trialling the 1st GB demonstration of a resilient D-Suite enabled LV network (SIF-Beta)

Compared with conventional solutions, SPEN will better be able to address both thermal and voltage issues that is increasingly experienced in LV networks. The Technology Readiness Levels (TRL) of this project is approximately 4-5 currently, and will benefit from dedicated innovation support to uplift the readiness of the following technologies:

1. LV Distributed STATCOM (D-STATCOM) - A D-STATCOM is a PED, which is primarily envisioned as a device for providing steady-state congestion mitigation, as phase imbalance is much more likely to be in distribution. By controlling the currents injections from each leg of the D-STATCOM, the powers flowing in each phase of the network can be adjusted. It can also inject balanced reactive power to adjust voltages. This technology has never been deployed in UK network.

2. Distributed Soft Open Point (D-SOP) – D-SOP is a PED constructed of back-to-back converters and is conventionally installed in-place of a normally open link box. As compared to a STATCOM, it has increased flexibility as it can allow active power to be transferred between feeders. As with the STATCOM, the neutral connection enables increased flexibility for the converter when injecting unbalanced powers into the active phase legs.

3. Distributed Smart Transformer (D-ST) - The D-ST is the most complex of the D-Suite devices. These devices are connected in a shunt-series configuration, with a series transformer enabling a partially rated PED to inject a voltage V which can be used to adjust the voltages and currents on the secondary side of a distribution transformer. The active and reactive power P, Q is required to inject the voltage from the series converter. Modification of existing technology to produce a more flexible and sustainable solutions distributed Smart Transformer (D-ST) –Building up on learnings from Network Innovation Competition project, LV Engine to fit a partially rated power electronics within slim design distribution transformer; and

4. Distributed Harmonic Filter (D-HF) - There are number of solutions on the market that need further development for LV applications to incorporate the D-HF into the above three technologies.

To test the capabilities of the D-Suite devices to their full extent, specific network type and characteristic requirements need to be met at the test locations. SP Energy Networks has two licence areas, SP Distribution (SPD) and SP Manweb (SPM), both with different network configurations and challenges. SPD has predominantly radial network configuration while SPM has interconnected network configuration. The next section outlines the key differences and characteristics of each license area to aid site selection process of each D-suite devices.

2. SP Energy Networks Distribution System

The SP Energy Networks licence areas, for distribution, are split into two distinct regions: SP Distribution (SPD), in Central and Southern Scotland, and SP Manweb (SPM), in the districts of Wales and Merseyside. Within this total licence area, over 30,000 substations distribute electricity through 40,000 km of overhead line and 65,000 km of underground cable.

The current distribution system is configured in a number of standard running arrangements and the network operates at 33 kV, 22 kV, 11 kV and 6.6 kV and 0.4 kV (LV), providing supply to the connection point of all remaining customers for industrial, commercial, and domestic purposes.

The two Distribution areas (SPM and SPD) share many similarities, however, there are some fundamental differences in their design philosophies. SPD, like most UK electrical networks, is configured as a radial network arrangement at the 11kV and 0.4kV level as shown in Figure 1. Interconnectors to the neighbouring primary substations or 11kV circuits from the same primary substation may be installed to provide operational flexibility for demand transfer when required. In all cases, the circuit must run with a split or 'normal open point' at an operationally approved point on the circuit.

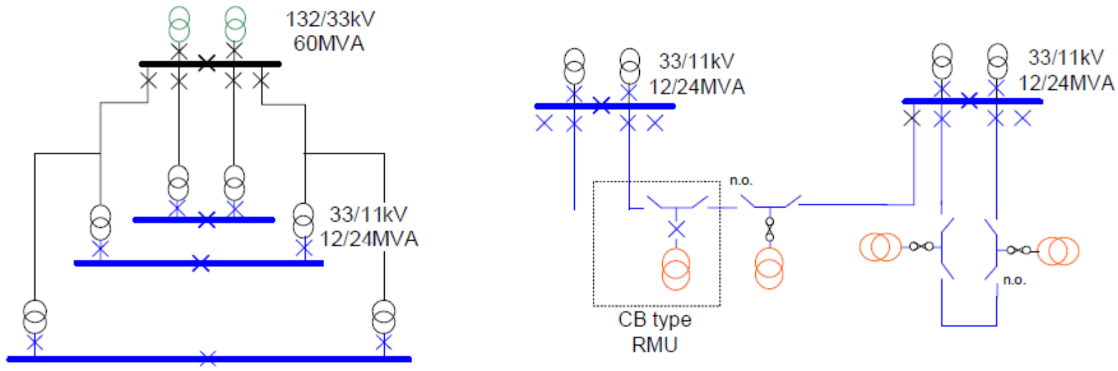

Figure 1: Example of conventional network arrangement at 11kV to 132kV. 11kV network topology must be considered for D-SOP and D-ST installations in interconnected networks.

The LV network, whilst having the capability to offer interconnection, is run radially with fuses or links removed at substations, LV surface mounted pillars or underground link boxes. The alternative network approach is to design a meshed or 'interconnected' configuration, where all feeders, at all voltage levels, are supplied from two or more ends, with these ends terminating at separate substations.

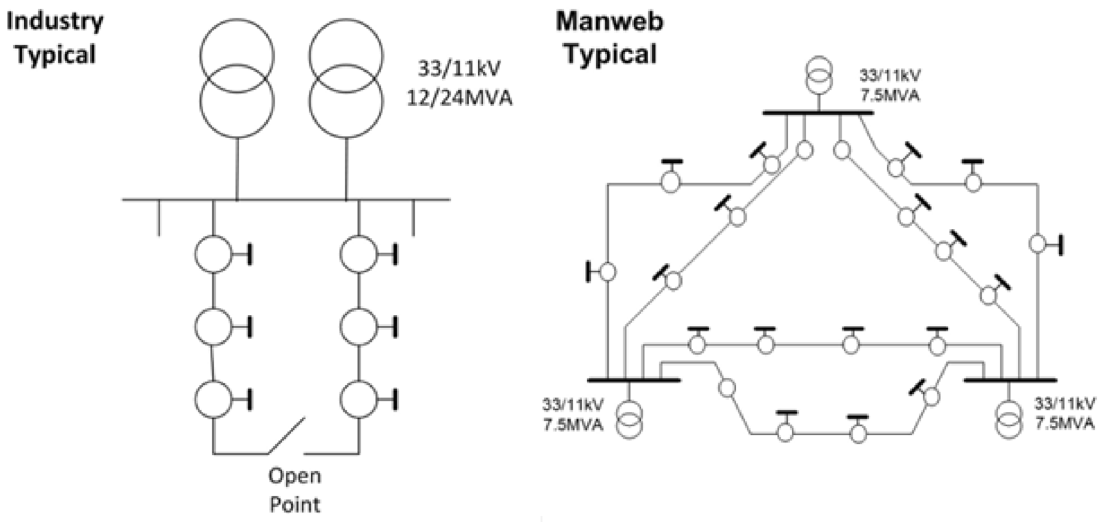

Figure 2: Example of a mesh / interconnected networks [1].

It is this network approach that is implemented within the SPM region, as shown on the figure above . Within SPM, two different approaches, to achieve interconnection/meshing, are implemented: 'X-type' and 'Y-type'. Networks interconnected across all distribution voltages are normally referred as 'X-type' configurations, whilst systems with less interconnection are called 'Y-type'. The essential difference is 'X-type' Ring Main Units (RMU) allow the use of unit protection, with the resulting network fully meshed. Conversely, with 'Y-type' RMUs, the occurrence of some faults can result in a loss of supply. For example, a fault on an 11kV circuit can mean loss of supply to several substations on that circuit.

The approximate split of the SPM network, in this arrangement, is 55% as 'X-type', 23% as 'Y-type' and the remaining 22% of traditional radial arrangement. The plant and protection, for X-type and Y-type networks, form part of the substation infrastructure.

2.1. Substation Infrastructure

Both types of network, radial arrangement of SPD and the interconnected network of SPM, supply electricity to a combination of domestic, commercial, and industrial customers. The assets contained within these substations, namely transformers HV switchgear, RMU, circuit breakers, fuses, and switches, are of high importance. Their failure can cause a loss of supply, reduced reliability, and serious safety implications.

Keeping these risks under consideration, the general requirements of standard unit substation design are as follows:

- Transformer mounted 11kV Ring Main Unit.
- 11kV/433V Transformer (500kVA or 1MVA rating).
- Transformer mounted 400V fuse cabinet, 1600A busbars, 5 way, 92mm centre fuses.

Other combinations of directly mounted attachments, to the transformer (e.g., cable boxes to facilitate cable connection of HV switchgear or LV fuse cabinet), may also be installed where appropriate. The above is often within an enclosure for environmental and physical protection usually in the form of a brick-built building or Glass Reinforced Plastic (GRP) enclosure.

Prefabricated GRP enclosures are the preferred means of installation, due to their low cost, durability and ease of installation. Using GRP enclosures is subject to conditions of the substation location, customer type and requirements of the local planning authority. Galvanised steel or masonry/brick enclosures are commonly used alternatives in instances when GRP enclosures are unsuitable. To ensure sufficient installation space is available, brick-built substations are more likely to be suitable for a partially rated D-ST. Figure 3 shows a conventional unit substation arrangement with typical dimensions outlined.

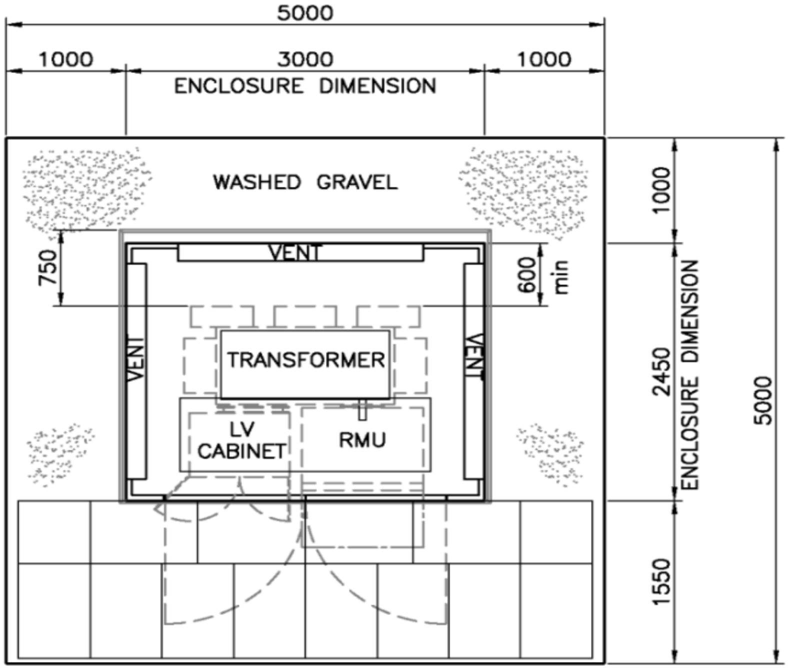

Figure 3: Conventional secondary substation layout [2] *(*All units are in mm)*

While most secondary substations, within the SPD licence area will conform to the design requirements mentioned prior, substations that exist on the SPM 'X-type' network require additional consideration. This type of substation contains additional protection equipment, taking more space within the substation enclosure.

A 'X' type secondary substation, shown in Figure 4, comprises of the following Equipment:

- Free standing X type 11kV Ring Main Unit (fully rated T off earth switch).
- 11kV/433V Transformer (500kVA rating).
- Wall mounted 400V fuse cabinet (Type 'A').
- Wall Mounted Solkor Protection Panel.
- Battery and Charger.

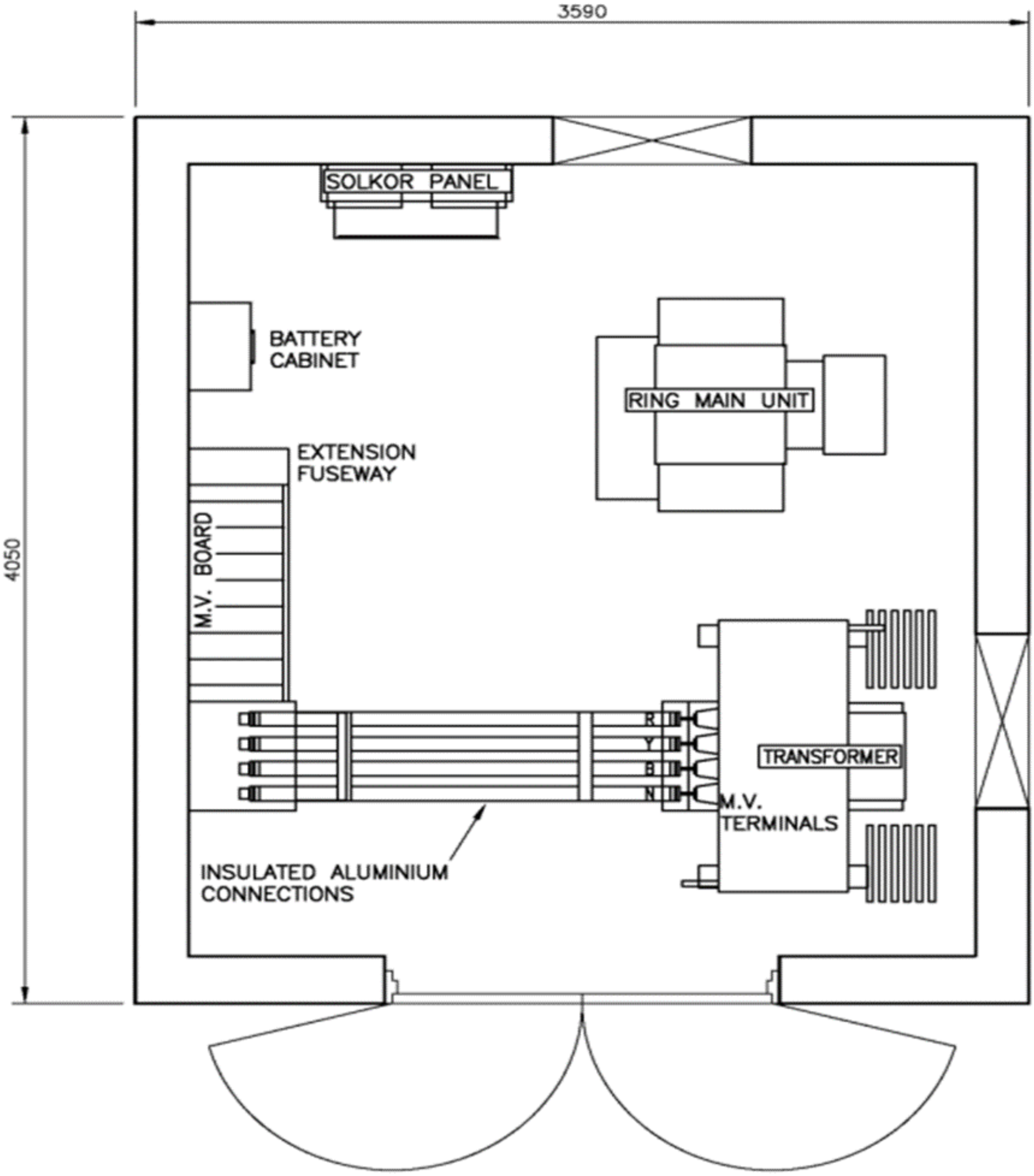

Figure 4: X-type secondary substation layout [2] *(*All units are in mm)*

The final type of secondary substation, applicable to this project, is that of the 'Industrial LV type'.

The general layout of the site, as shown in Figure 5, is similar to the unit substation, except it has a customer metering annex. Depending on the distance between the LV point of supply and industrial premises, the customer tariff metering equipment may be situated in the metering annex to the secondary substation or could be situated in the customers' premises.

An Industrial LV Customer substation comprises of the following equipment:

- Transformer mounted 11kV Ring Main Unit.
- 11kV/433V Transformer.
- Transformer mounted 400V fuse cabinet with metered ways.
- 400V Tariff Metering Equipment.

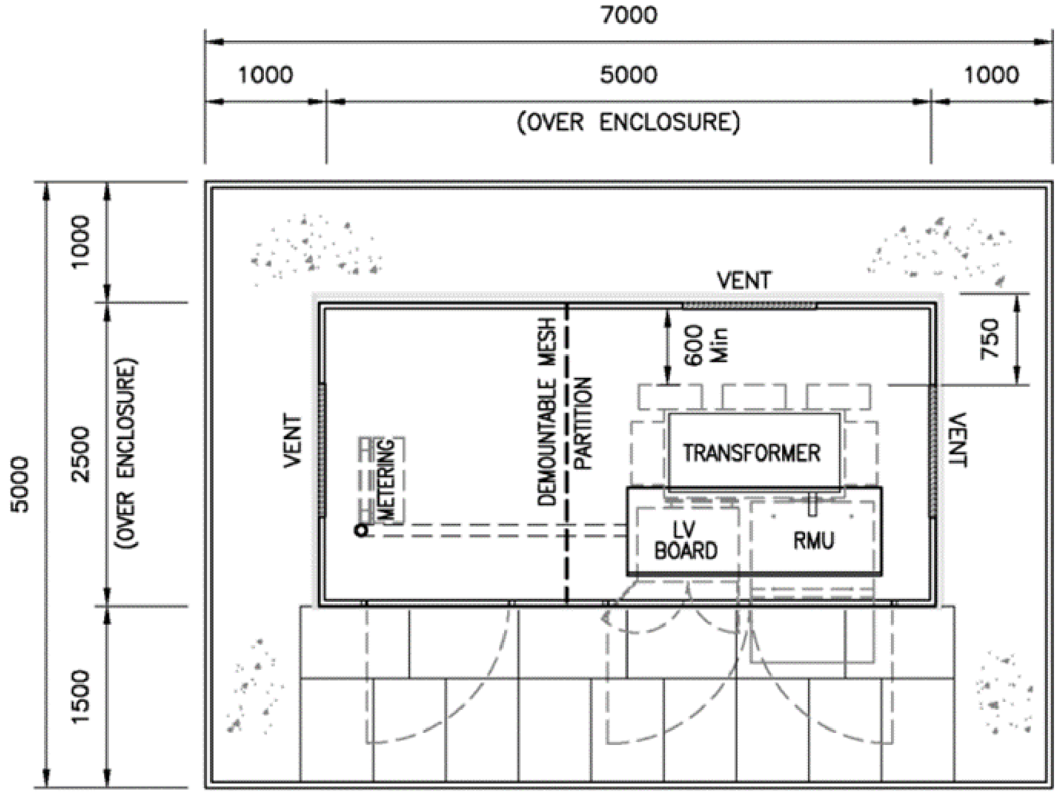

Figure 5: Industrial type substation layout [2] *(*All units are in mm).*

Regardless of substation type, access/egress to substations is required 24-hours a day for authorised personnel. This includes suitable 24-hour street-level vehicular access/egress to support the use of equipment for installation and maintenance.

With many substations, in the SPM and SPD licence areas, built in the 1950's, 1960's and 1970's, several are exhibiting a decline in both performance and condition as they approach the end of their service life. Providing the correct level of reinforcement alongside the introduction of new initiatives, such as D-Suite PED, which improves the network performance and operations. D-Suite PED are not limited to a D-ST at the substation. A 2-Terminal Soft open Point (2T D-SOP) and D-STATCOM can be installed at the street level in bespoke enclosures. Installation considerations, of these two device types, are explored in the Section 3.

3. D-Suite PED Placement Considerations

3.1. D-Suite PED Overview and Functions

This section describes the physical considerations at the street level, when installing 2T D-SOP, D-STATCOM and D-ST. The philosophy of D-Suite is to use power electronic modules as building blocks, to form each of the four D-Suite devices, so it is expected suppliers offer solutions with modularity. Alternatives to modularity, are partially rated devices, which provide significant reductions in space requirements over fully rated PED. The physically largest D-Suite street installation is the 2T SOP, due to its back-to-back nature, requiring double amount of Power Electronics as the D-STATCOM. All dimensions in this section have been supplied by manufacturers, through the PQQ process under Work Package 4.

3.2. Two Terminal Distribution Soft Open Point

D-Suite D-SOP aims to enhance LV network operations, by adding intelligent controls and automation functionalities to Normally Open Points (NOPs). The device will be able to shift demand between transformers by controlling the power flow through the NOP. The rated size of device is between 30-180MVA, depending on the nature of the network. Consequently, it will be able to shift up to 36% of a transformer's loading to the neighbouring substation. D-Suite will trial the 2T D-SOP, at different trial sites, to demonstrate all its capabilities including:

- Phase Voltage Regulation.
- Power Flow Control.
- Reactive Power Control.
- Current and Voltage Imbalance Mitigation.

The technical and operational information of the D-SOP is described in [3]. This report focuses on the high-level installation requirements of the device only.

There are two types of D-SOP devices, Two-Terminal SOP (Shown on Figure 6) and Three-Terminal SOP, only Two-Terminal devices will be used in the D-Suite trial. 2T-D-SOP dimensions are estimated to be 2.1 m (Width) x 1.7 m (Height) x 0.5 m (Depth). The dimensions are expected to be reduced significantly, almost 30% reduction in volume, compared to previous innovation trials, by optimising the PED ratings to maximise component utilisation. This is a crucial part of the project, as the 2-terminal version is installed as street furniture within an enclosure onto the 0.4kV network.

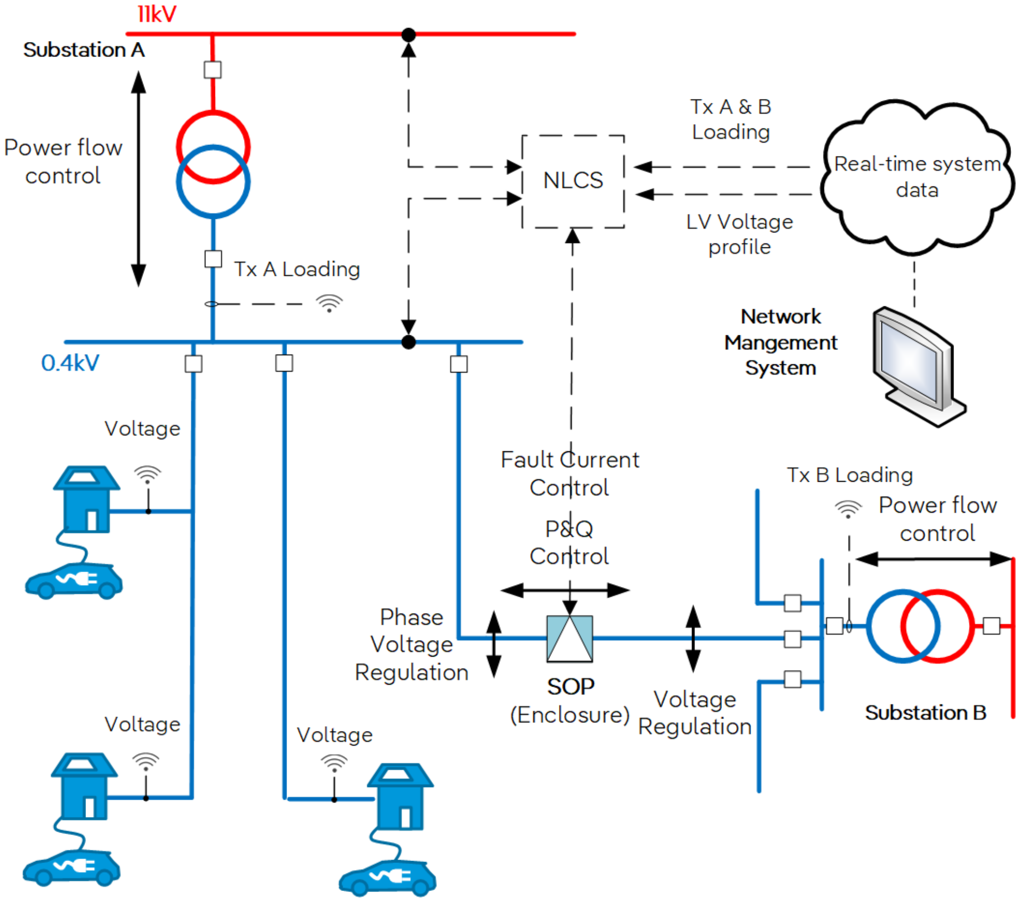

Figure 6: D-SOP Two-Terminal (2T) Concept Schematic.

3.2.1. Space Considerations

For installation of a street situated PED, enough area, surrounding the PED is required to excavate and install terminating cable and isolation equipment such as LV link boxes. Terminating cable needs space to satisfy its minimum bending radius usually ~ 850mm^2, with depth of cover at least 600mm. Please refer to Figure 7 for the cross-sectional diagram of a typical distribution LV mains cable trench.

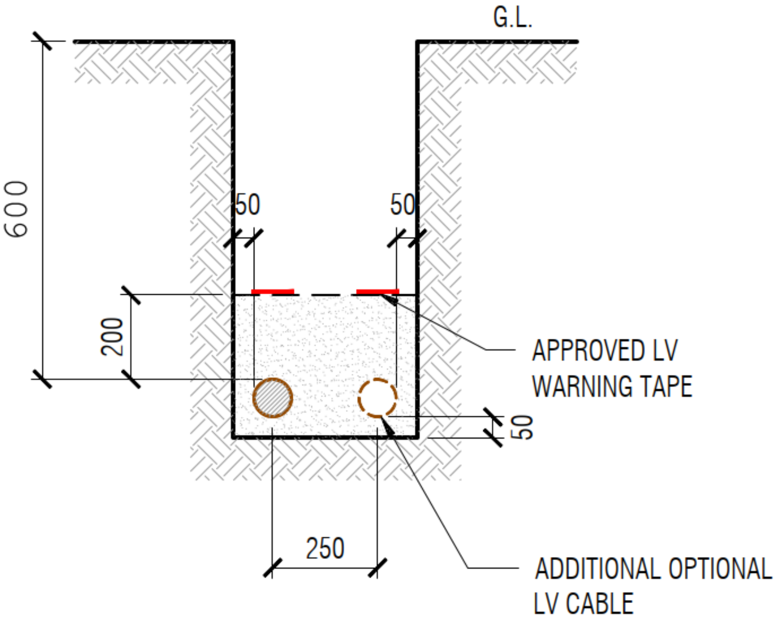

Figure 7: LV cable trench details for direct laid LV cable installation.

In terms of installation, the required space for installation of D-SOP, on either side, should be minimum 2.6m, as shown in Figure 8. This area required to deposit soil from the trench, for installation, with access and egress for the working party and safety barriers and signage.

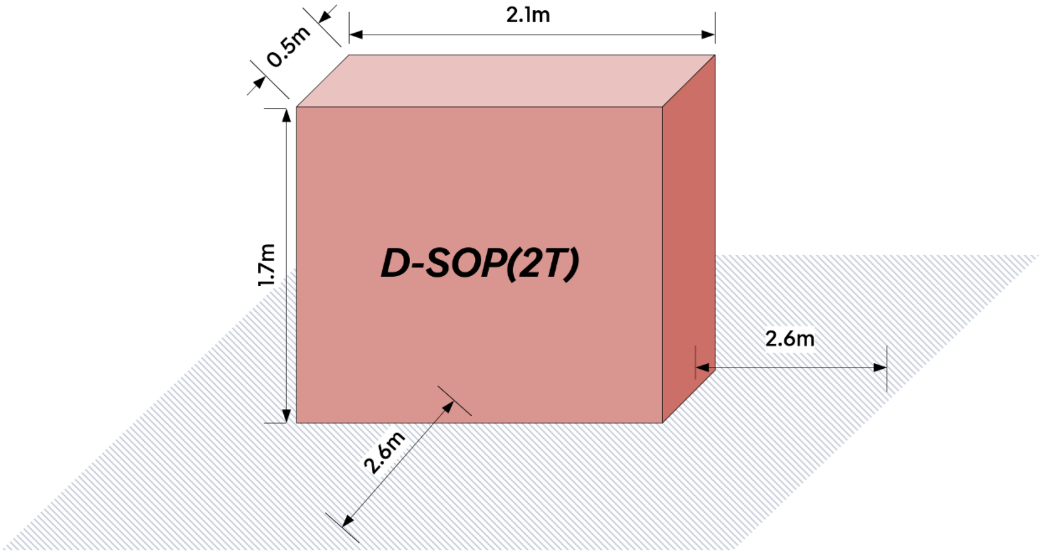

Figure 8: D-SOP device size and Installation space requirements.

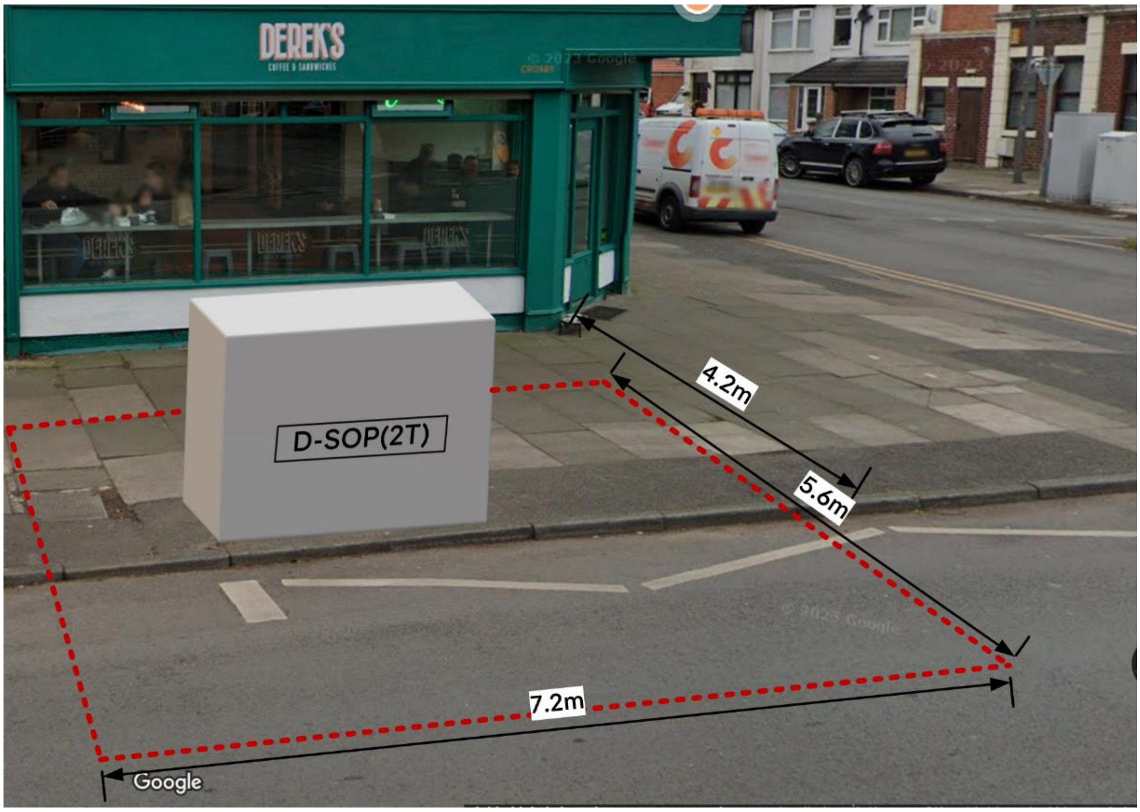

Figure 9: Example installation area required for the D-SOP device, including excavations for jointing onto mains LV cable. Mechanic protection from bollards between PED and the curb has been omitted.

3.3. Physical Protection Requirements

Equipment enclosure shall be designed in a robust manner to prevent vandalism. The minimum degree of protection of the external enclosure against mechanical impact shall meet the minimum mechanical strength requirements (IK08, 5J impact) according to IEC 62262 Application of the IK Code. Additionally, the unit shall be installed with bollards to prevent units against vehicle impact damage. Identical physical protection requirements apply to the D-STATCOM.

3.4. Distribution STATCOM

The D-STATCOM aims to enhance LV networks operation by adding reactive power control at the point of connection. The concept of the D-STATCOM is to offer independent voltage and phase current regulation and reactive power control, to improve the voltage profile and cable utilisation upstream of the installation location.

The Device consists of a DC voltage source, inverter circuit, coupling transformer and a PED switching control module. The forecasted rating of the device is 30 - 120kVA, equivalent to most LV feeder capacity. The STATCOM is designed to installed in street furniture or be pole mounted. The predicted optimal placement of each device is determined by the 0.4kV feeders individually.

Dimensions of the D-STATCOM device are 1.4m (Width) x 1.6m (Height) x 0.66m (Depth) respectively as shown in Figure 10. The required installation space for working party is minimum 1.5m in each direction, less than the 2T-D-SOP due to half the amount of terminating cable into the device. Other parameters, such as bending radius, depth of cover etc. will be similar as mentioned above for the D-SOP.

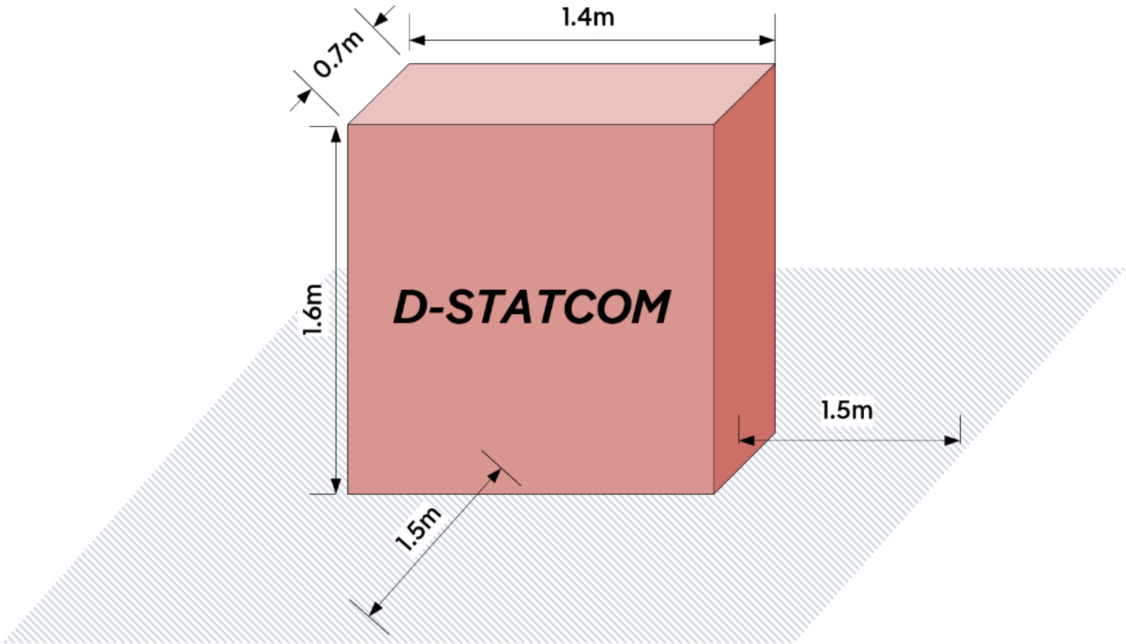

Figure 10: D-STATCOM device dimensions and installation space requirements.

3.4. Smart Transformer (D-ST)

D-Suite D-ST aims to enhance LV networks operation by adding intelligent controls and automation functionalities to Secondary Substations. A general concept of the D-ST is shown in Figure 11. The ST can control the power flow passing through and the voltage at its output terminals via the PED in response to set points received from a Network Level Control System (NLCS).

There are strict dimension requirements for the D-ST, as the space in secondary substations is limited. The device does not need to be fully rated, to achieve the technical benefits, as it is not series connected with the supplied loads. Consequently, the optimal rating of the device is 30MVA, allowing it fit into a bolt on box with minimal modifications. The device will also require retrofitting a tertiary transformer winding. Alternative solution would be to replace the current transformer with a new D-ST, identical in size, which is more viable in GRP enclosed secondary substations.

Dimensions of the D-ST device, including the transformer, are 2.2m (Width) x 1.58 m (Height) x 1.1 m (Depth) respectively and will be installed in secondary substations during the D-Suite site trials, which are selected under the trail selection process.

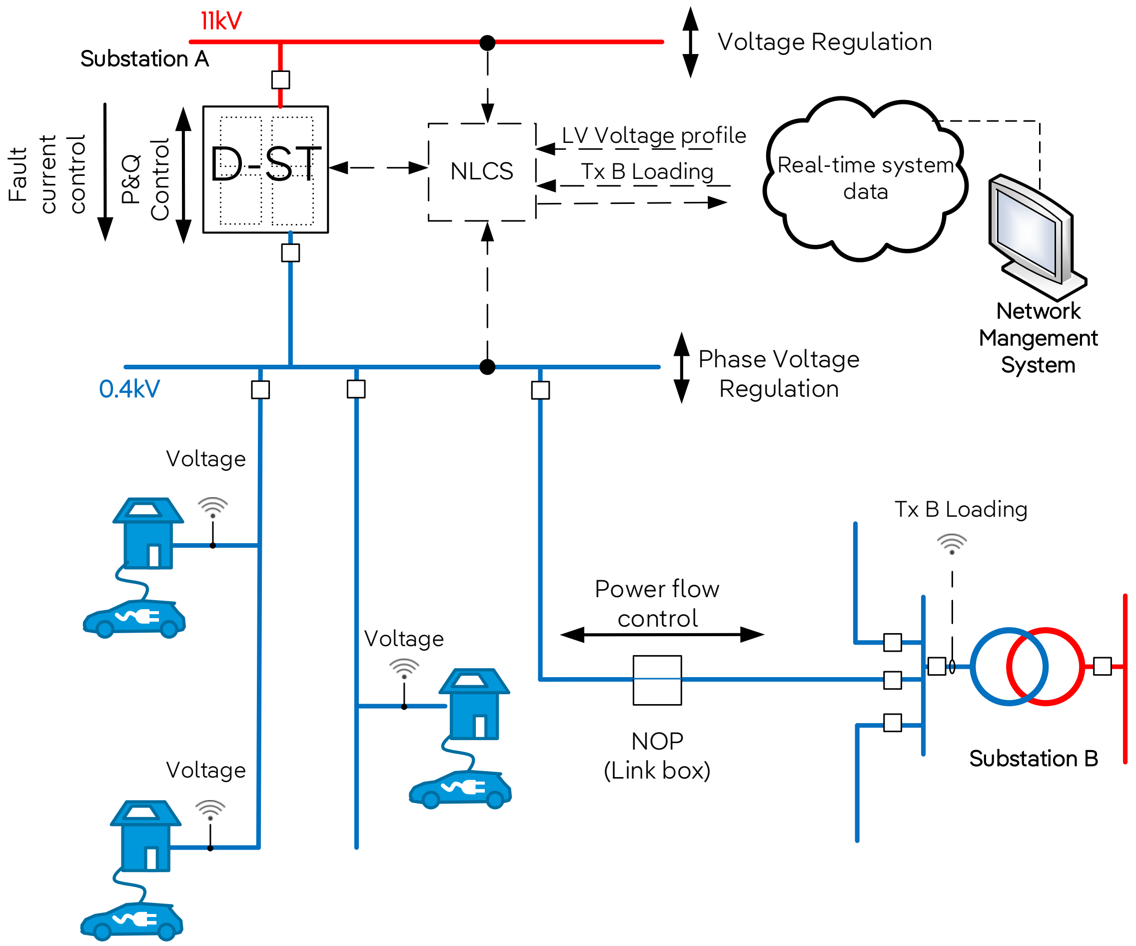

Figure 11: D-Suite control and operational D-ST concept.

4. Trial Site Selection Process

4.1. Overview

To assess all proposed sites for trial, it was necessary to develop several criteria which could measure applicability for use. It was also imperative that the devised approach sought to capture all available knowledge to the project and use this to define a list of criteria which will allow the proposed sites to be compared.

A key factor in determining suitable criteria, for assessing proposed sites, is communicating between the various districts within the SPEN distribution system. Through communication, a much greater understanding of potential sites can be gained. The approach in the Alpha Stage uses the SP Energy Networks Distribution Future Energy Scenarios (DFES) and Heat-Up and EV-Up tools to identify trial sites that are predicted to encounter thermal issue due to LCT deployment. DNO Licence district stakeholders were engaged to brief them on the project and these stakeholders provided feedback on what issues are already being encountered on LV networks, as of 2024. Further engagement will be necessary in the Beta stage to select the best trial sites.

With consideration of the above approach during the Alpha stage, the following process was developed:

Step 1 - Initial Engagement with Project Stakeholders: In the preliminary stages, the project engaged with network planning, district managers and/or engineers to use their local knowledge to determine which sites may be suitable for further assessment as potential sites for D-Suite PED sites.

Step 2 - Preliminary Guide for Trial Sites: Meetings were held with stakeholders identified in Step 1. The information captured will then be used in conjunction with the prototype LV-Design Tool used to analyse the trial sites (see Work Package 1 Deliverables).

Step 3 - Development of Selection Criteria: The project team developed assessment criteria which are applicable to the D-Suite Schemes.

Step 4 - Assessment: Using the criteria developed, list of substations underwent a detailed assessment including data collection during site visits. The project made use of available resources including NAVI, Heat-UP, EV – UP and Half Hourly network simulation (see LV design Tool), site and street imagery and engagement from district engineers.

Step 5 - Communication of decisions: The short-listed sites were discussed and communicated with the relevant parties in SPM area. More stakeholder engagement is planned to maximise engagement and participation across the business.

4.2. Criteria

The following section outlines the devised criteria used to assess all proposed sites for the four D-suite PED.

As outlined in Section 4, each scheme has its own specific needs and requirements to enable the desired behaviours to be exhibited. However, this does not make the criteria used in assessing these trial sites exclusive, as commonality exists between the various schemes.

A list of all relevant criteria is given in Table 1.

Table 1: Trial Site Assessment Criteria.

Criteria	Reasoning
Site with Imbalanced Loads	Site should have imbalanced loads across the phases to demonstrate D-Suite PED ability to balance LV phase voltages and currents i.e., imbalance mitigation.
Growing LCT Integration (PV, HP and EVs)	Using a site already showing clustering of LCT, together with further connections of LCTs predicted in DFES, Heat-Up and EV-Up, make the network a good candidate to demonstrate high utilisation of D-Suite PED.
Site with Daily Voltage Fluctuation	The chosen trials sites should demonstrate a large variation in network voltage due to a high uptake of LCTs (PV, EHP, EVs). This will allow the schemes to demonstrate the capability of a D-Suite PED to regulate phase voltage adequately.
Substation Structure and Maintenance Access	The site should have an access route to support any maintenance that will be required throughout the duration of the network trials. The D-Suite PED requires beneficial ambient conditions therefore weighting is given to those secondary substations that are of brick build construction and circuit routes with areas of open space for installation works.
Highly Loaded Transformer and capacity availability in neighbouring transformers	A highly loaded transformer will provide an opportunity to demonstrate the load sharing capability that SSTs can offer to alleviate congestion at peak loads.
Complementary Load Profile	The chosen trial sites will benefit if the neighbouring transformers have complementary load profiles or spare capacity available to allow the benefits of load sharing to be demonstrated adequately.
Available NOP	The chosen network sites will require Normally Open Points (NOP) within each feeder to allow capacity sharing between neighbouring transformers. Complexity of network arrangement and number of NOPs has a direct effect on required control equipment.
Available substation space alongside existing conventional transformer	There needs to be physical space available within the existing substations to allow a D-ST to be installed alongside the pre-existing transformer and to allow the switch over. Expansion of existing substation within General Permitted Development (GPD) is also considered in this criterion.

Criteria	Reasoning
Network Connection	Selected substations should be suitable to facilitate the connection of the PEDs. Information regarding switchgear at HV and LV level is provided, including cable information, where applicable.
Network Interconnection (SP MANWEB Only) *	SP MANWEB networks are connected either as X-type or Y-type configurations. Y-type configurations are suitable for use as the Smart Transformer.

Subsequently, the methodology used in the assessment has looked to consider all common aspects of sites and limit the significance of these by attributing them with a lesser impact. Specific features of each individual sites are then addressed on a case-by-case basis.

Practical aspects of each substation and circuit route were a major factor in influencing the decision of whether to progress with further investigation, consequently, this held a significant influence on the decision to progress.

5. D-Suite Site Examples

Based on the analysis of network connectivity model, four distinct sites have been chosen. However, other sites may be selected in future trial based on a Beta stage district engagement. Every network region has been judged suitable for use in real-world trials, and when applicable, the rationale is provided. The following trial locations may be appropriate for the D-Suite project, although they might alter if these networks are reinforced prior the trial.

5.1. D-Suite Trial Site Example 1

The first trial example is in Merseyside district of Scottish Power Manweb license sub urban (SPM-SU) area. The substation is situated away from residential property and built at the corner of park, positioned within a fenced area.

Figure 12: View of secondary X-type substation SP Manweb Sub Urban (SPM-SU) Network.

Figure 12 above shows that the substation is located on the corner of a public park. It has vegetation on both sides. This substation itself is brick built (3.6m x 4.3m) and has a typical X-Type arrangement that is suitable for the D-Suite PED and associated equipment. The primary and secondary voltage ratings are 11kV and 0.4kV (HV and LV respectively). Cabling of both voltage levels run directly outside the substation so it would be possible to utilise this for connection purposes. The substation transformer rating is 500kVA and the protection device used is the Lucy Electric VRN6a circuit breaker installed in 2014.

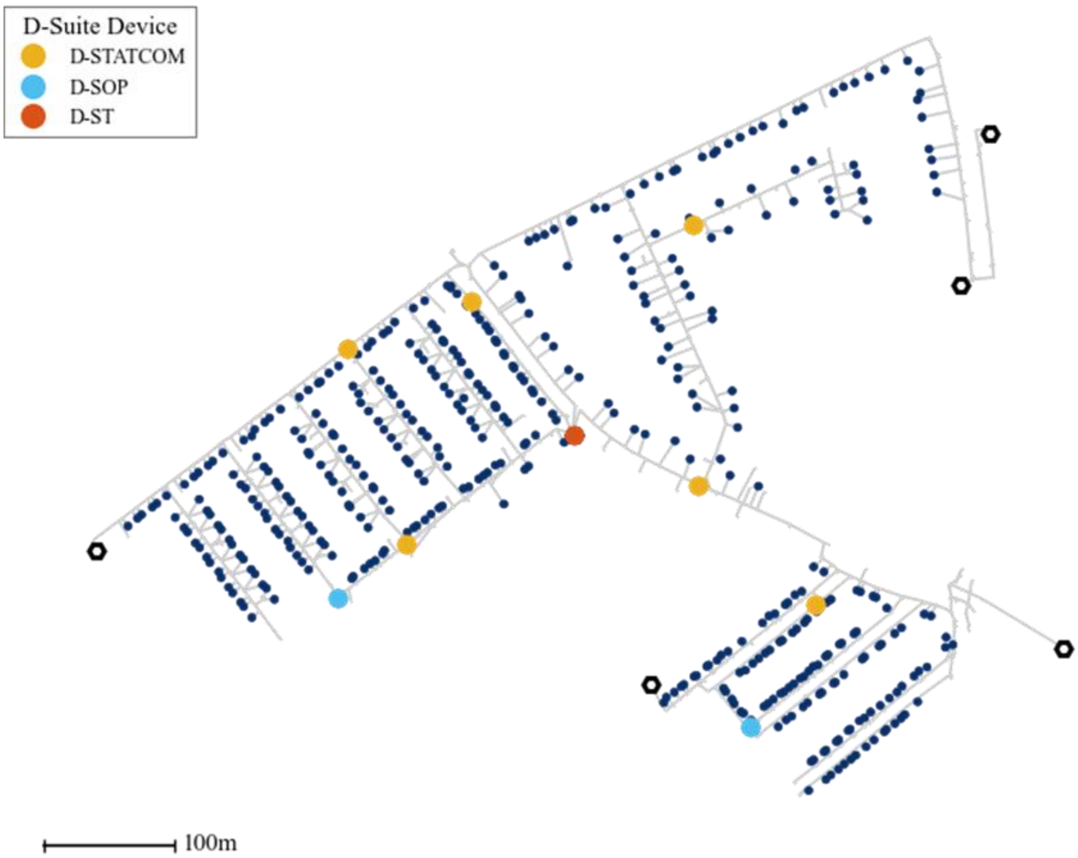

Figure 13: LV network for SPM-SU with potential locations of D-Suite devices.

The distance between the secondary substation SPM-SU and the closest primary substation is 532.8m. The 11kV incomer is a 0.1 inches 3 core copper cable, rated at 3.64 MVA. At LV level, the outgoing cable from the substation is 0.2 inches copper with a continuous rating of 224kVA.

The 11KV network is fed from the upstream primary via three feeders (not shown). The SPM-SU network, with transformer capacity 500kVA, has 4 feeders, serving residential houses interconnected with other neighbouring secondary substations.

Figure 13 indicates possible locations for the different D-suite PEDs. There are multiple possible locations for the D-SOP and D-STATCOM devices within the network however for the final trial only some of these locations will be selected.

LV connection can be made with other secondary substations through the link boxes, indicated with numbers in yellow circles on Figure 14, which allows the distribution of load between the substations. There is a link box, near the substation, which serves as a Normally Open Point (NOP), shown on the Single Line Diagram (SLD) below, this makes the site suitable for the trial.

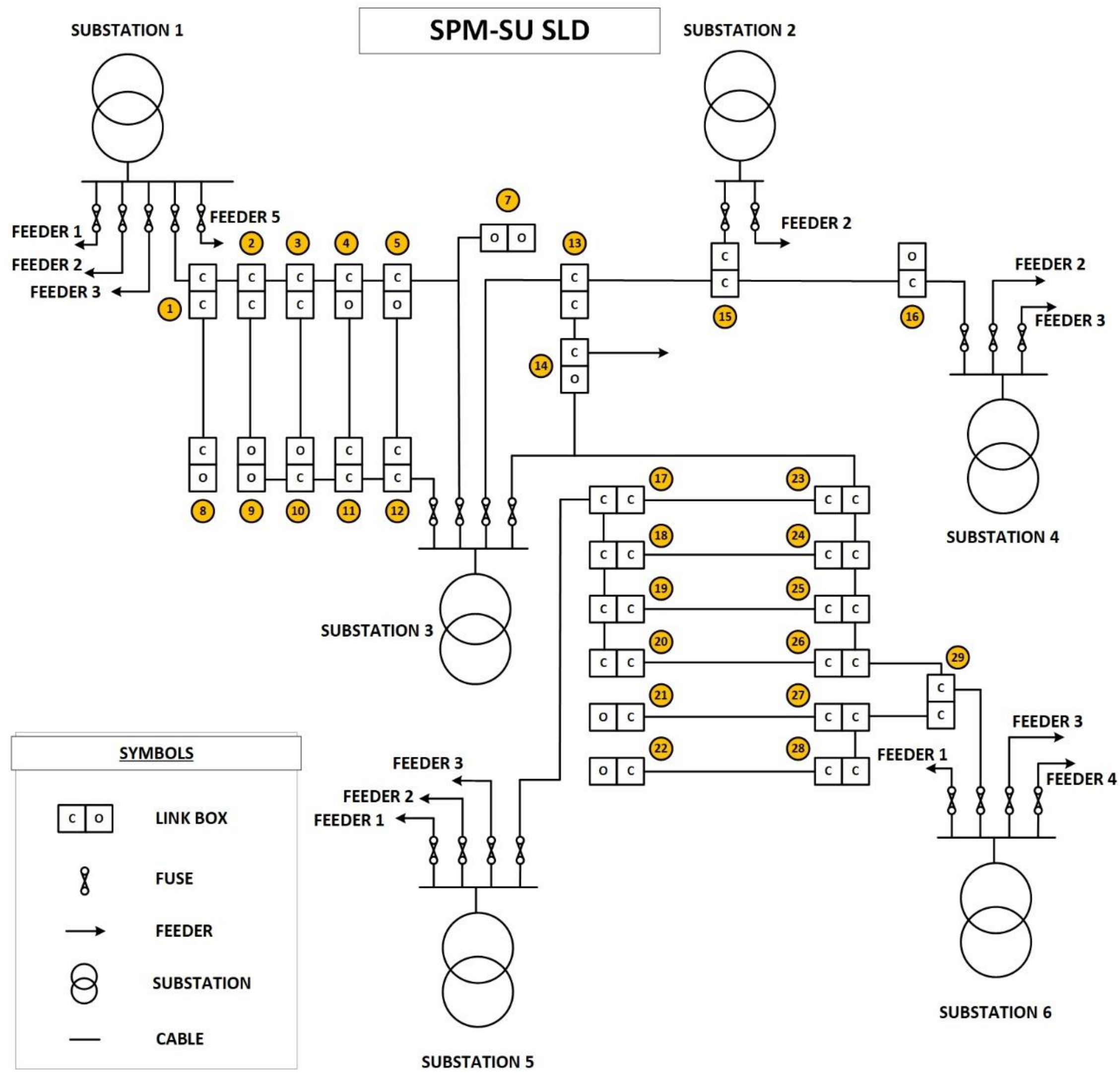

Figure 14: SPM-SU single line diagram showing the connected LV network.

There are 4 circuits fed from this substation. Feeder-1 feeding 135 properties, Feeder-2 linked with 65 properties, Feeder-3 with 157 properties and Feeder 4 is serving 76 properties. In 2023, the maximum load supplied by the transformer was 244kVA which is almost 49% of the total transformer capacity. As per 2023 maximum demand data, the neighbouring transformers have almost half of the capacity available, which will allow testing the load sharing capability of the D-Suite devices.

Different loads on each feeder lead to load imbalance, which is unsuitable for the substation network because it can cause transformer overheating and damage. This is caused by the imbalanced demands connected to the phases. The formula for calculating current imbalance for a feeder circuit is as follows:

$$UB\% = \frac{|I_{MAX} - I_{AV}|}{I_{AV}} \quad \text{EQ. (1)}$$

where, UB% is the current imbalance in percentage, I_{max} maximum current of the feeder, and I_{av} is the average current.

$$I_{AV} = \frac{|I_A| + |I_B| + |I_C|}{3} \quad \text{EQ. (2)}$$

I_a, I_b, I_c are the phases current.

I_{max} = Current in phase with Maximum deviation from I_{av}

5.1.1. Worked Example

Example 1: Let take Table 2 current readings as example to calculate substation imbalance value

I_a = 240A, I_b = 320A, I_c = 300A where I_{max} = I_b = 320A

First calculate I_{av} by putting valves in EQ (2)

$$I_{av} = \frac{|I_a| + |I_b| + |I_c|}{3} = \frac{|240A| + |320A| + |300A|}{3} = \frac{860A}{3} = 286.6 \text{ A}$$

Now put I_{av} and I_{max} values in equation 1

$$\text{UB\%} = \frac{|I_{max} - I_{av}|}{I_{av}} * 100 = \frac{320A - 286.6A}{286.6A} * 100 = \frac{33.4A}{286.6A} * 100 = 0.1165 * 100$$

UB% = 11.65

Similarly, it can be calculated for other substations. These phase imbalances are due to the diversity of household loads and single service connections. The installations of Low Carbon Technologies (LCT) are expected to worsen with further LCT penetration. The LCT growth depends on the uptake of Photovoltaics (PV), Heat Pumps (HP) and Electric Vehicles (EVs) charging points in this area.

D-Suite devices can reduce phase imbalances on the network. To test the capabilities of the devices, substations with high phase imbalances were chosen for trial site selection.

Table 2 shows the worst-case loading and phase imbalance for the SPM-SU substation, please refer to Appendix A.1 for data on neighbouring substations.

Table 2: SPM-SU5 Annual Peak Load

S. No	Recorded Date	Phases (Amps)			Loading %	Phase Imbalance %
		Red (Amps)	Yellow (Amps)	Blue (Amps)		
1	28/03/23	440	660	320	65	39.04
2	02/09/20	440	540	320	58	24.61
3	19/05/17	280	380	260	48	23.91

Table 3 below indicates there is an expected increase in total demand over 140% for the substation. The increase in demand is due to the increase in LCT as the After Diversity Maximum Demand (ADMD) figures are expected to stay the same over the years. In 2024 there was only 70.7kW of LCT in the network while this figure is expected to reach 1522.2kW by 2040. Please refer to Appendix B.1 for further data on expected demand increase in the area.

Table 3: Substation showing demand increase, Increase in LCT for SPM-SU2

Year	ADMD(KW)	ADMD + EVUp + HeatUp (KW)	Demand increase	Increase in LCT
2024	563.5	634.2	N/A	N/A
2028	563.5	814.7	28%	255%
2036	563.5	1474.3	132%	1188%
2040	563.5	1522.2	140%	1256%

Additionally, Figure 15 displays the increase in demand for respected LV network regions. The height of the hexagon is proportional to the predicted demand in 2040. The flat (green) columns indicate a small number of transformer violations while the darker colours refer to higher number of violations assuming no network reinforcements by the predicted time.

Figure 15: Infographic indication of LCT deployment on LV network by 2040. [Image has been blurred due to privacy reasons]

5.2. D-Suite Trial Site Example 2

The second trial example is in Merseyside district of Scottish Power Manweb Urban (SPM-U) license area.

Figure 17: View of secondary substation SP Manweb Urban (SPM-U) Network.

Figure 17 shows SPM-U substation, located in a restricted private parking on the opposite side, near a warehouse. The substation is brick built, and it is suitable for the D-Suite project. The voltage levels are 11kV and 0.4kV (HV and LV respectively). Cabling of both voltage levels run directly outside the substation so it would be possible to utilise this for connection purposes. The transformer rating is 500kVA and the protection is by Lucy Electric VRN6a circuit breaker installed in 2014.

The 11KV network is fed from two upstream primaries. The secondary substation has two outgoing feeders. One side is connected to a link box at the junction, and other side is supplying a feeder interconnected with another SPM-U substation (Figure 18). The length from the primary upstream is 200m. The 11kV installed is 185mm 3-core rated at 4.38MVA. At LV level, the nearest cable to the substation is 0.25 Inch aluminium rated at 196kVA. There is also a link box not far away which serves as a normal open point, shown on Figures 18. LV connection can be made with other secondary substations through the link box, making the site suitable to test and illustrate the load sharing capability of the D-SOP device. This substation is looped to other substations which feeds their respective connected circuits. There are different feeders which are interconnected with the substation (Figure 18 & Figure 19).

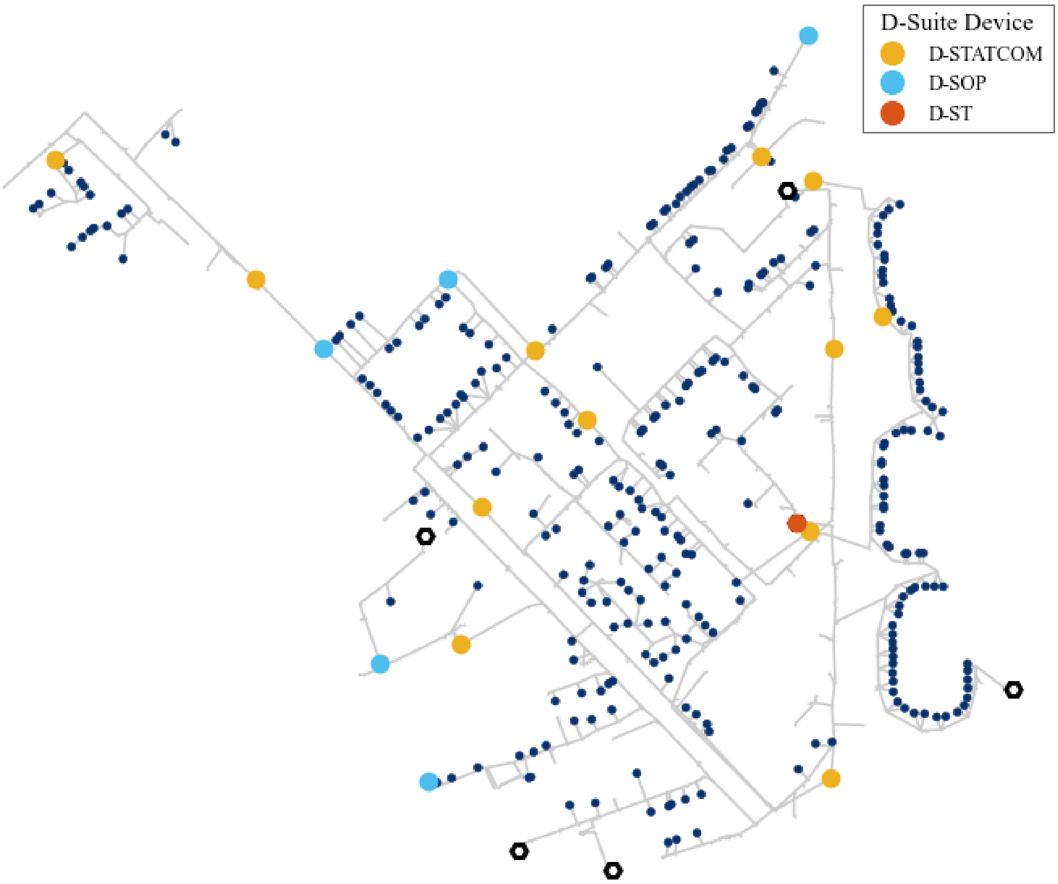

Figure 168: SP Manweb Urban (SPM-U) Network, geospatial view of the selected substation with possible locations of D-Suite devices.

Figure 168 indicates possible locations for the different D-suite PEDs. There are multiple possible locations for the D-SOP and D-STATCOM devices within the network however for the final trial only some of these locations will be selected.

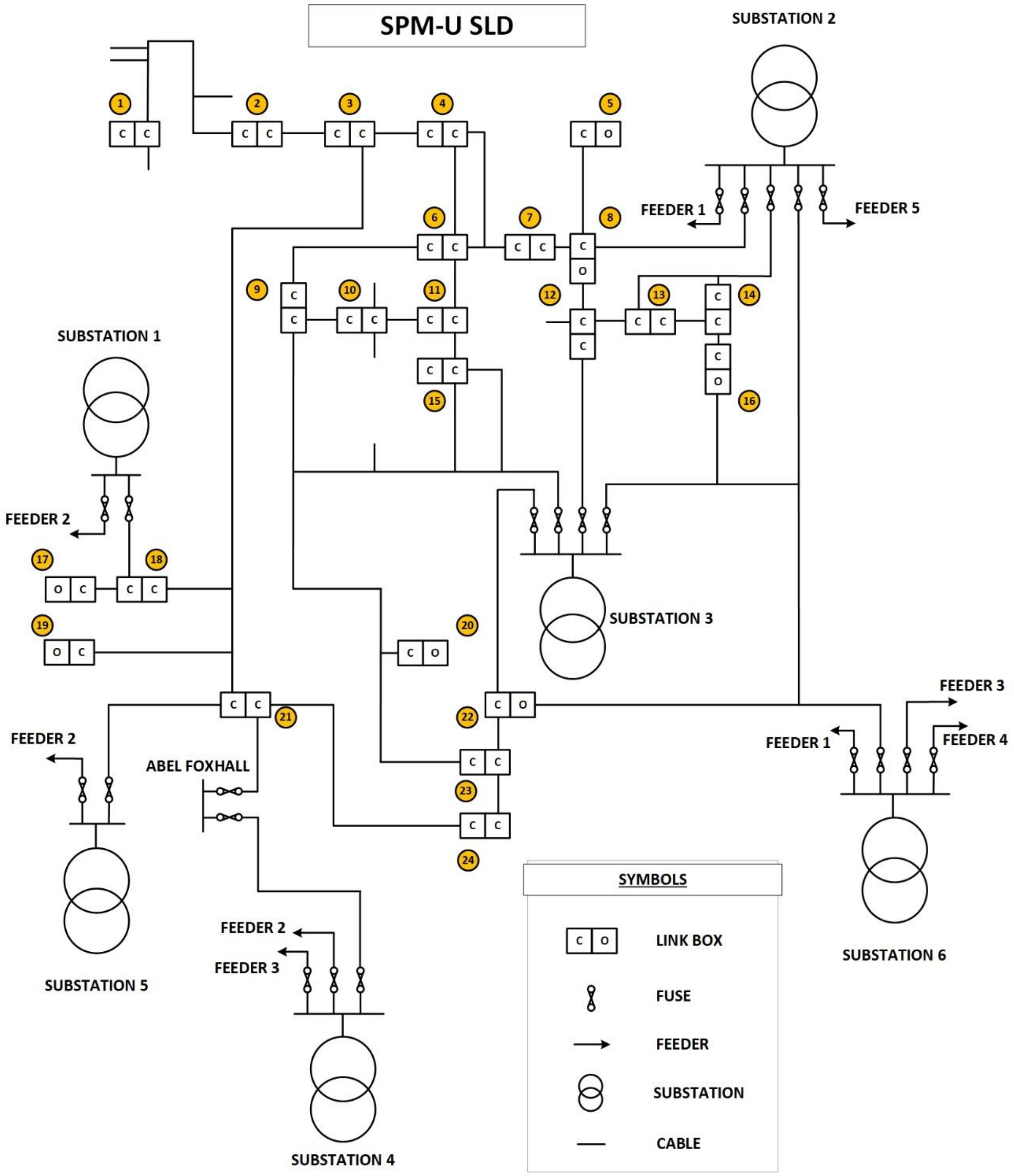

Figure 19: SPM-U single line diagram showing the connected LV network

In 2021, the maximum load supplied by transformer was 155kVA which is almost 31% of the total transformer capacity. In 2022, the maximum load supplied by transformer was 160kVA which is almost 32% of the total transformer capacity (Table 4). This implies that only a third of the transformer capacity is utilised. The available capacity from the secondary transformer meets the criteria for demonstrating the load sharing capability that substation can offer. As per 2022 maximum demand data, similarly, the neighbouring transformers have similar capacity available.

Table 4 below shows loading capacity and phase imbalance for the substation under review. Please refer to Appendix A.2 for data on neighbouring substations.

Table 4: SPM-U3 Annual Peak Load

S. No	Recorded Date	Phases (Amps)			Loading %	Phase Imbalance %
		Red (Amps)	Yellow (Amps)	Blue (Amps)		
1	12/09/22	200	200	300	32	28.57

Table 5: Worst case transformer loading including estimated ADMD and LCT increase for SPM-U6

Year	ADMD(KW)	ADMD + EVUp + HeatUp (KW)	Demand increase	Increase in LCT
2024	327.5	329	N/A	N/A
2028	327.5	369.3	13%	2687%
2036	327.5	594	81%	17667%
2040	327.5	626	91%	19800%

As seen from Table 5 there is an expected demand increase of 91% by 2040. The increase in demand is due to the increase in LCT as the ADMD figures are expected to stay the same over the years. In 2024 there was only 1.5kW of LCT in the network while this figure is expected to reach 298.5kW by 2040. Please refer to Appendix B.2 for further data on expected demand increase in the area.

Figure 17, displays the increase in demand for respected LV network regions. The height of the hexagon is proportional to the predicted demand in 2040. The flat (green) columns indicate a small number of transformer violations while the darker colours refer to higher number of violations assuming no network reinforcements by the predicted time.

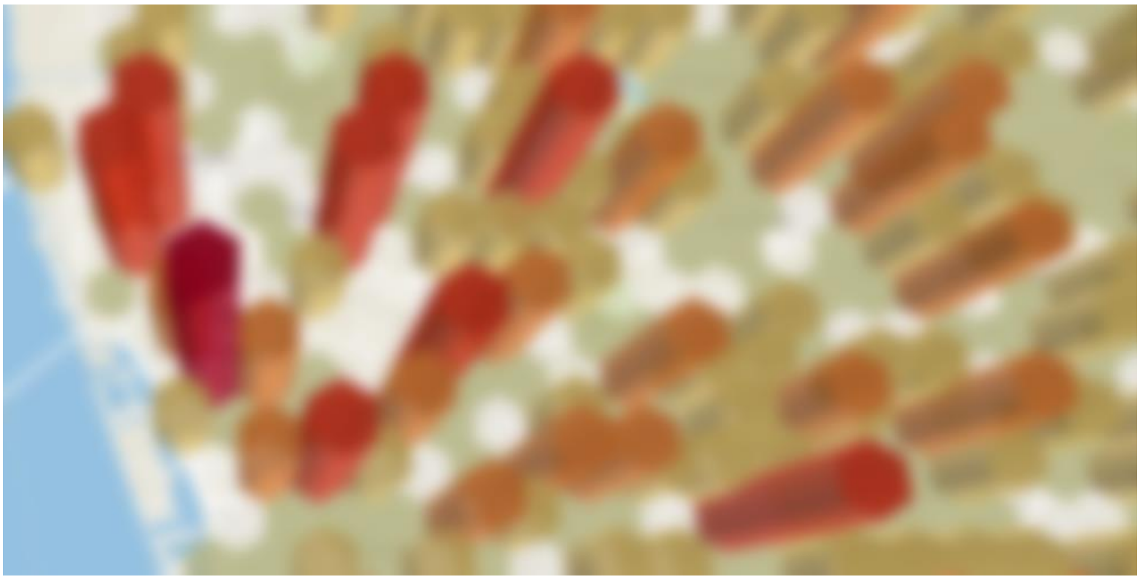

Figure 17: Infographic indication of LCT deployment on LV network by 2040. [Image has been blurred due to privacy reasons]

5.3. D-Suite Trial Site Example 3

The third trial example located in Scottish Power distribution license sub-urban (SPD-SU) area.

Figure 18: Outside View of secondary substation SPD Suburban Network.

Figure 18 above shows SPD-SU substation. The secondary substation has a ground mounted (GM) transformer, and it is located in a multi-use building. Extending the substation is not possible to facilitate a larger transformer, consequently only a partially rated smart-transformer is viable at this location, such as the D-ST, to accommodate increased network demand.

The primary and secondary voltage levels are 11kV and 0.4kV (HV and LV respectively), with about 405 customers connected to it. Cabling of both voltage levels runs directly outside the substation so it would be possible to utilise this for connection purposes. The substation transformer rating is 750kVA and the protection is Merlin Gerin CE6 630A ring master.

There are different feeders which are interconnected to the substation. Please refer to the network layout and proposed PED locations Figure 19. The feeder from the substation supplies over 54 customers. The maximum load supplied by the transformer as recorded in 2023 is 61% which is equivalent to 458KVA. As per 2023 maximum demand data, the neighbouring transformers have almost half capacity available. This fulfils the complementary load profile criteria which demonstrate the load sharing benefits in peak times.

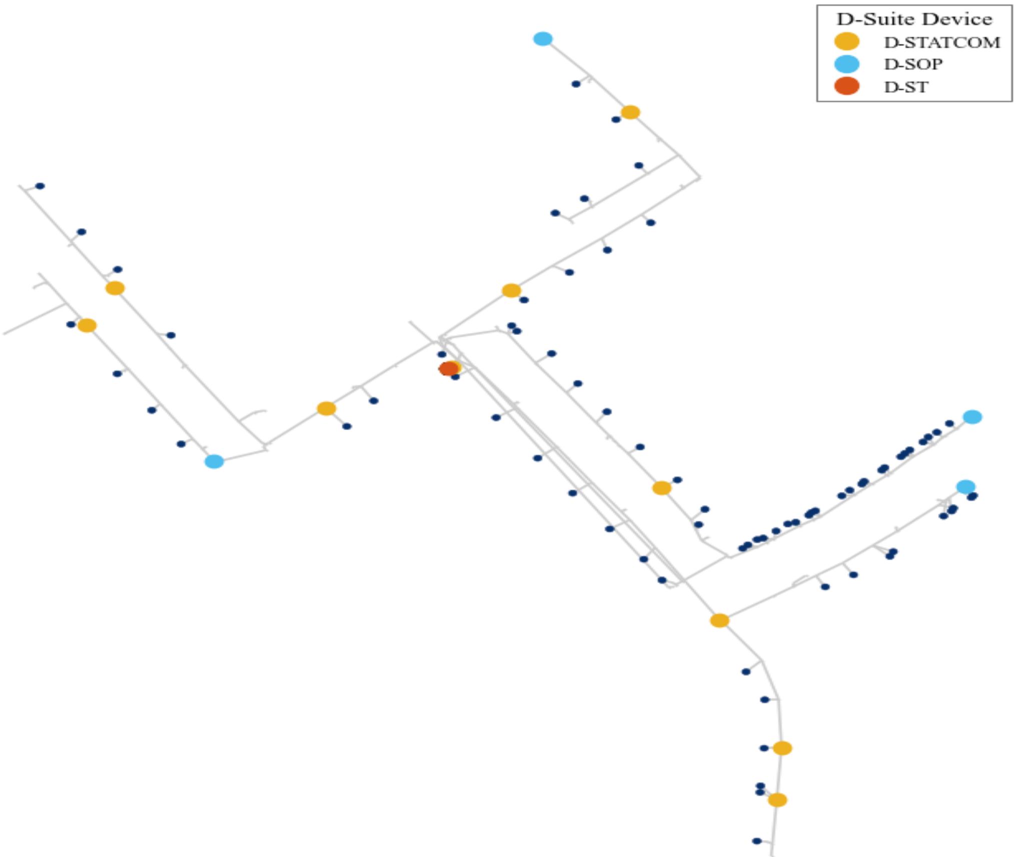

Figure 19: Network view of secondary substation on NAVI (SPD-SU).

Figure 19 indicates possible locations for the different D-suite PEDs. There are multiple possible locations for the D-SOP and D-STATCOM devices within the network however for the final trial only some of these locations will be selected.

For this substation, there are congestions on the outgoing feeders. Both D-SOPs and D-STATCOM can be used to mitigate these issues. However, for this network configuration, D-SOP is likely to be preferred to D-STATCOM due to its larger power flow control and load sharing capability between the feeders.

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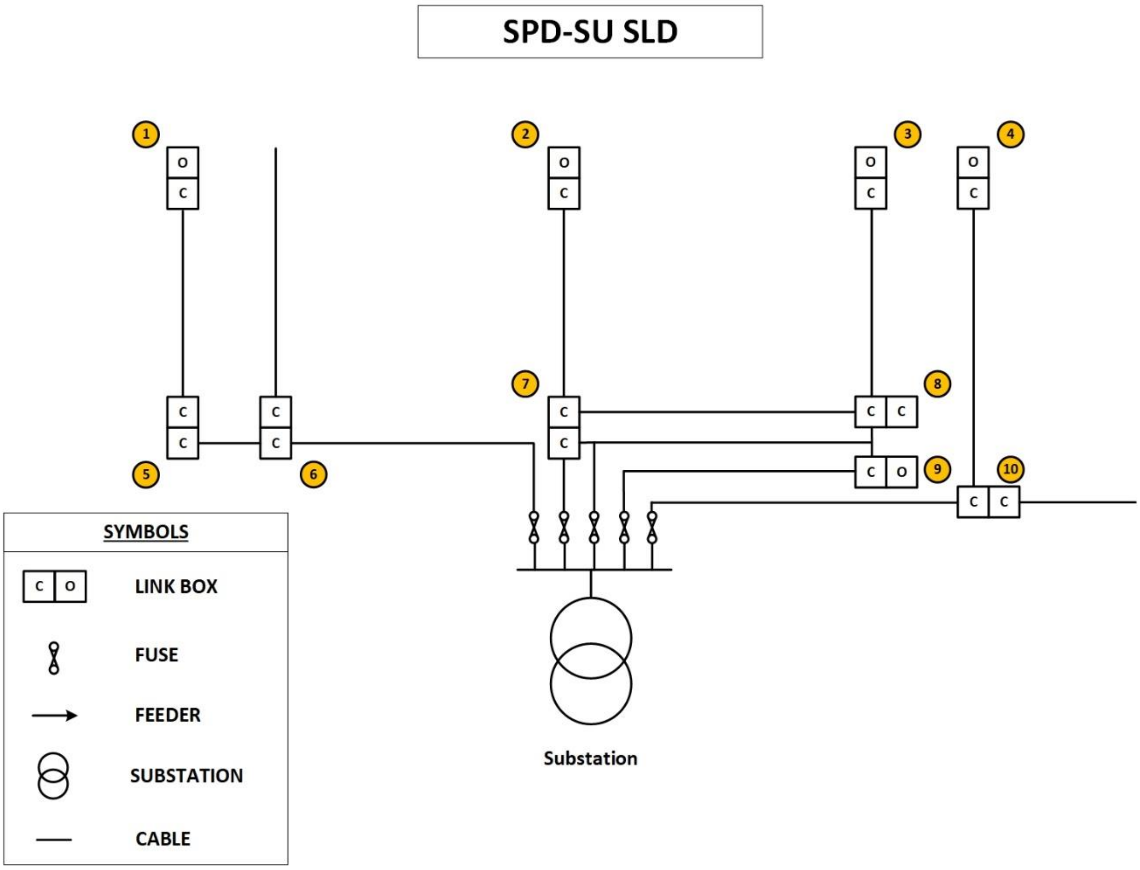

Figure 20: SPD-SU single line diagram showing the connected LV network

The length from the primary upstream is 701.6mm. The 11kV installed is 0.2ins (3) copper cable with a continuous rating of 4.87MVA. At LV level, the nearest cable to the substation is 185mm (4) Aluminium with a continuous rating of 208kVA. There is also a link box not far away which serves as a normal open point, making the site suitable to test and illustrate the load sharing capability of the D-SOP device.

Table 6 below shows loading capacity and phase imbalance for the substation under review.

Table 6: SPD-SU1 Annual Peak Load.

S. No	Recorded Date	Phases (Amps)			Loading %	Phase Imbalance %
		Red (Amp)	Yellow (Amp)	Blue (Amp)		
1	11/04/23	800	500	700	61	20
2	05/04/21	600	100	300	31	80
3	19/04/18	700	200	600	46	40

Table 7: Substation showing demand increase, Increase in LCT for SPD-SU1.

Year	ADMD(KW)	ADMD + EVUp + HeatUp (KW)	Demand increase	Increase in LCT
2024	439.5	443.4	N/A	N/A
2028	439.5	448.8	2%	138%
2036	439.5	475.1	8%	813%
2040	439.5	557.8	27%	2933%

As seen from Table 7 there is an expected demand increase of 27% by 2040. The increase in demand is due to the increase in LCT as the ADMD figures are expected to stay the same over the years. In 2024 there was only 3.9kW of LCT in the network while this figure is expected to reach 118.3kW by 2040.

The increase of demand in the area will cause an increase in transformer loading. Figure 21 below shows the expected increase in transformer demand.

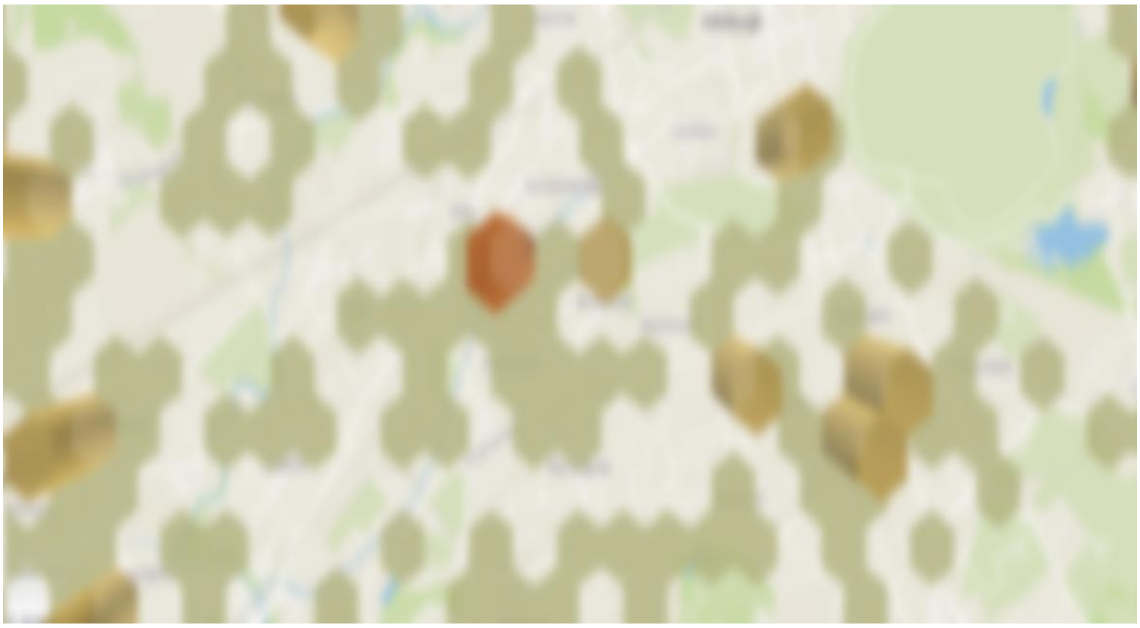

Figure 21: Infographic indication of LCT deployment without reinforcement on LV network by 2040. [Image has been blurred due to privacy reasons]

Figure 21 displays the increase in demand for respected LV network regions over time in this SPD-SU1 area. The height of the hexagon is proportional to the predicted demand in 2040. The flat (green) columns indicate a small number of transformer violations while the darker colours refer to higher number of violations assuming no network reinforcements by the predicted time.

5.4. D-Suite Trial Site Example 4

The fourth trial example is in district of Scottish Power distribution license urban (SPD -U) area. The substation is situated away from residential property and built at the corner of park, positioned in between a fenced area.

The Figure 22 shows a substation in an urban area. The secondary substation has a ground mounted (GM) transformer, and it is located in a multi-use building. Extending the substation is not possible to facilitate a larger transformer, consequently only a partially rated smart-transformer is viable at this location, such as the D-ST, to accommodate increased network demand.

Primary and secondary voltages ratings are 11kV and 0.4kV (HV and LV respectively), with around 1260 customers connected to it. Cabling of both voltage levels run directly outside the substation, so it would be possible to joint onto the LV mains cable directly from the substation. The substation transformer rating is 1000kVA and the protection is ABB 976640. The 11KV network is fed from two upstream primary substations and has six outgoing feeders providing power to the attached properties.

Figure 22: Outside View of secondary substation SPD Urban Network

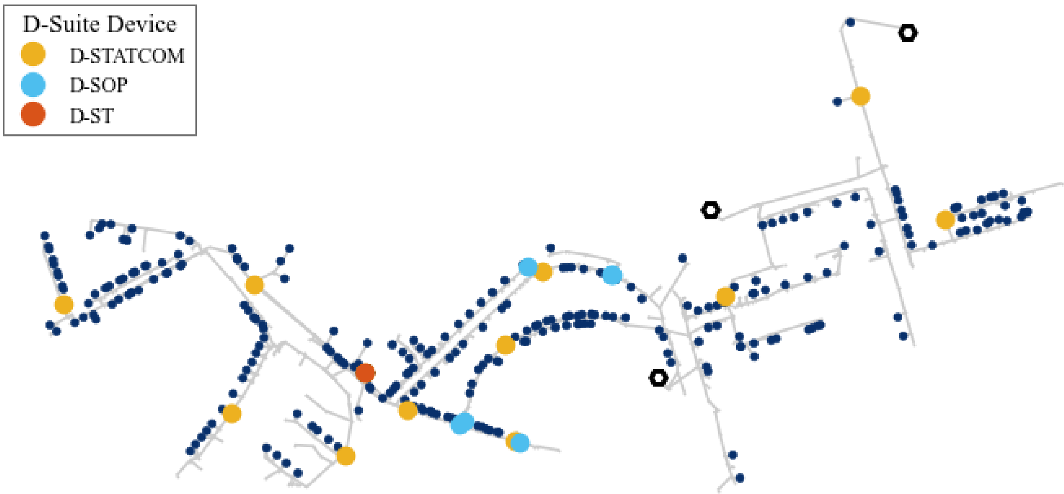

Figure 23: Network view of secondary substation on NAVI for SPD-U.

Figure 23 indicates possible locations for the different D-suite PEDs. There are multiple possible locations for the D-SOP and D-STATCOM devices within the network however for the final trial only one of these locations will be selected.

For this substation, there is network congestion at the substation and feeders. Therefore, there are several viable D-suite locations (Figure 23). Additionally

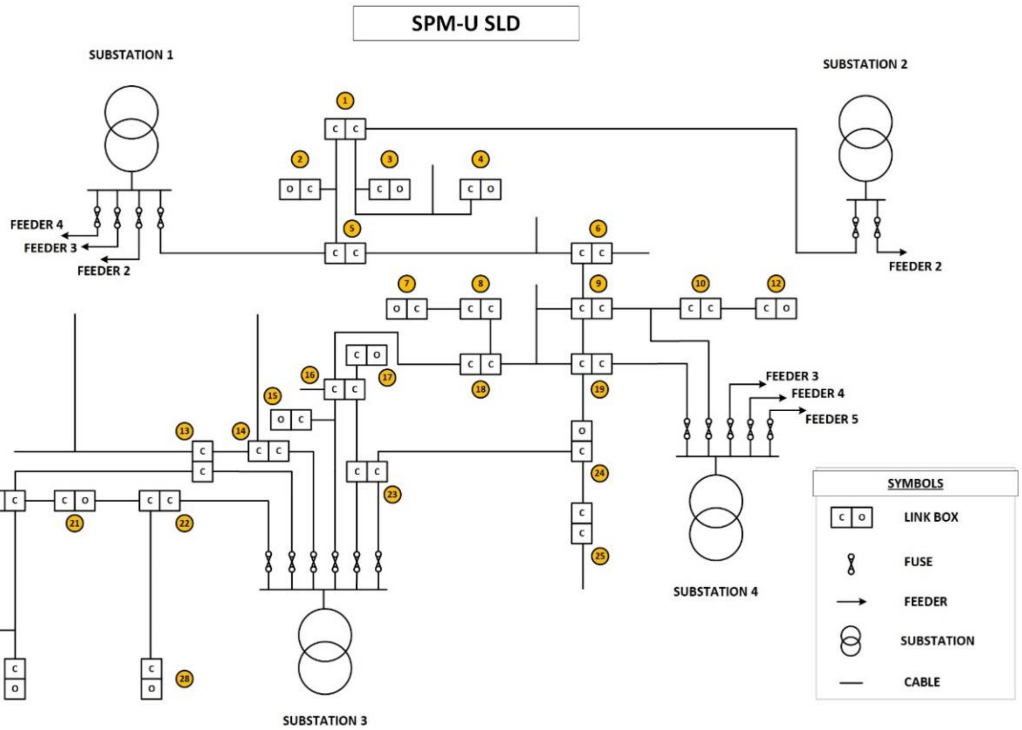

Figure 24: SPD-U single line diagram showing the connected LV network.

The length from the primary upstream is 701.6mm. The 11kV installed is 0.2ins (3) copper cable with a continuous rating of 4.87MVA. At LV level, the nearest cable to the substation is 185mm (4) Aluminium with a continuous rating of 208kVA. There is also a link box not far away which serves as a normal open point (Figure 24). LV connection can be made with other secondary substations through the link box, making the site suitable to test and illustrate the load sharing capability of the D-SOP device. The maximum load supplied by the transformer as recorded in 2022 is 90% which is equivalent to 900KVA. As per 2022 maximum demand data, the neighbouring transformers have almost 60% capacity available, making the site suitable to test and illustrate the load sharing capability of the PEDs

Table 8 below shows loading capacity and phase imbalance for the substation under review. Please refer to Appendix A.3 for data on neighbouring substations.

Table 8: SPD-U2 Annual Peak Load

S. No	Recorded Date	Phases (Amps)			Loading %	Phase Imbalance %
		Red (Amp)	Yellow (Amp)	Blue (Amp)		
1	01/03/23	500	500	200	34	25
2	08/04/19	800	500	800	60	14.28
3	21/04/17	800	600	500	55	26.31

Table 9: Substation showing demand increase, Increase in LCT for SPD-U1

Year	ADMD(KW)	ADMD + EVUp + HeatUp (KW)	Demand increase	Increase in LCT
2024	1436.4	1485	NA	NA
2028	1436.4	1555.9	5%	146%
2036	1436.4	1855.6	25%	763%
2040	1436.4	2047.8	38%	1158%

As Table 9 shows there is an expected total demand increase of 38% by 2040. The increase is due to the increase of LCT in the region. In 2024 there was only 49kW of LCT in the network while this figure is expected to reach 611.4kW by 2040. Please refer to Appendix B.3 for further data on expected demand increase in the area.

Figure 25: Infographic indication of LCT deployment without reinforcement on LV network by 2040. [Image has been blurred due to privacy reasons]

Figure 25 shows the expected transformer loading in the area where the height of the hexagon is proportional to the predicted demand in 2040. The flat (green) columns indicate a small number of transformer violations while the darker colours refer to higher number of violations assuming no network reinforcements by the predicted time.

6. Conclusion

To address the complex challenges posed by the integration of Low Carbon Technologies in existing electrical grids, the D-Suite site selection process not only identifies potential issues such as voltage rise and voltage imbalance, but also proposes candidate locations for each different type of D-Suite device. The deployment of innovative technologies such as the D-STATCOM, D-ST, D-HF and D-SOP PEDs ensure that the grid can accommodate a higher penetration of photovoltaics, heat pumps, and electric vehicle chargers without compromising on performance and allows deferment of traditional reinforcement.

The site selection process, described in this report, has taken into account key parameters such as device size, network configuration, and local demand. The pivotal considerations depend upon the expected increase in Low Carbon Technologies (LCT) adoption, the resulting network congestion, voltage imbalances, and the available capacity of nearby substations. Building on these technical specifications, the study identified four suitable sites within the SP Energy Networks for the installation of D-Suite PEDs. These sites were selected for their coverage of a substantial part of the SPEN network. Two of these substations are located within the SP Distribution (SPD) license area, while the other two fall under the SP Manweb (SPM) license area. This selection encompasses both suburban and urban network types, allowing for a comprehensive assessment of the D-Suite devices across diverse network environment.

7. References

[1] SPEN, "ESDD-01-013 - Interconnected Network Transitioning Policy," 2021.

[2] SPEN, "SUB-02-006 - Secondary Substation Installation and Commissioning Specification," 2014.

[3] SPEN, "D-Suite PED Functional Technical Specification," 2024.

Appendix A – Phase Imbalance Data

A.1. Trial Site Example 1

Table 10: SPM-SU1 Annuall Annual Peak Load

S. No	Recorded Date	Phases (Amps)			Loading %	Phase Imbalance %
		Red (Amps)	Yellow (Amps)	Blue (Amps)		
1	16/06/23	240	320	300	40	11.65
2	23/07/20	320	360	380	49	7.54

Table 11: SPM-SU2 Annual Peak Load

S. No	Recorded Date	Phases (Amps)			Loading %	Phase Imbalance %
		Red (Amps)	Yellow (Amps)	Blue (Amps)		
1	24/07/23	440	420	440	61	1.54
2	16/03/22	440	440	560	66	16.67

Table 12: SPM-SU3 Annual Peak Load

S. No	Recorded Date	Phases (Amps)			Loading %	Phase Imbalance %
		Red (Amps)	Yellow (Amps)	Blue (Amps)		
1	30/05/23	360	380	360	51	3.63
2	15/03/22	400	460	440	60	6.15
3	23/07/20	380	420	400	55	5

Table 13: SPM-SU4 Annual Peak Load

S. No	Recorded Date	Phases (Amps)			Loading %	Phase Imbalance %
		Red (Amps)	Yellow (Amps)	Blue (Amps)		
1	15/03/22	380	360	420	53	8.62
2	02/09/20	360	260	380	46	14
3	20/05/19	380	500	380	58	19.04

Table 14: SPM-SU6 Annual Peak Load

S. No	Recorded Date	Phases (Amps)			Loading %	Phase Imbalance %
		Red (Amps)	Yellow (Amps)	Blue (Amps)		
1	16/06/23	480	460	460	64	2.86
2	16/03/22	500	540	440	68	9.46
3	23/07/20	500	520	480	69	4

A.2. Trial Site Example 2

Table 15: SPM-U1 Annual Peak Load

S. No	Recorded Date	Phases (Amps)			Loading %	Phase Imbalance %
		Red (Amps)	Yellow (Amps)	Blue (Amps)		
1	02/02/21	140	300	240	31	32.35
2	28/09/18	0	340	140	22	112.5

Table 16: SPM-U2 Annual Peak Load

S. No	Recorded Date	Phases (Amps)			Loading %	Phase Imbalance %
		Red (Amps)	Yellow (Amps)	Blue (Amps)		
1	14/09/22	450	400	350	55	12.5
2	28/09/18	300	250	250	37	12.5
2	22/08/19	250	500	250	46	50

Table 17: SPM- U4 Annual Peak Load

S. No	Recorded Date	Phases (Amps)			Loading %	Phase Imbalance %
		Red (Amps)	Yellow (Amps)	Blue (Amps)		
1	08/12/22	360	300	360	47	5.882
2	12/09/21	400	300	380	50	11.11
3	11/10/19	400	380	400	54	1.69

Table 18: SPM-U4 Annual Peak Load

S. No	Recorded Date	Phases (Amps)			Loading %	Phase Imbalance %
		Red (Amps)	Yellow (Amps)	Blue (Amps)		
1	01/12/22	200	480	340	47	41.17
2	02/02/21	200	460	340	46	38
3	03/12/18	200	240	320	35	26.31

Table 19: SPM-U6 Annual Peak Load

S. No	Recorded Date	Phases (Amps)			Loading %	Phase Imbalance %
		Red (Amps)	Yellow (Amps)	Blue (Amps)		
1	01/02/22	220	300	200	33	25
2	22/01/21	220	280	220	34	16.66
3	08/11/18	240	380	300	42	23.91

A.3. Trial Site Example 4

Table 20: SPD-U1 Annual Peak Load

S. No	Recorded Date	Phases (Amps)			Loading %	Phase Imbalance %
		Red (Amp)	Yellow (Amp)	Blue (Amp)		
1	07/04/22	1200	1400	1300	90	7.69
2	14/12/21	1350	1400	1300	93	3.70
3	24/04/18	1300	1200	1100	83	8.33

Table 21: SPD-U3 Annual Peak Load

S. No	Recorded Date	Phases (Amps)			Loading %	Phase Imbalance %
		Red (Amp)	Yellow (Amp)	Blue (Amp)		
1	27/04/21	320	280	300	41	6.67

Table 22: SPD-U4 Annual Peak Load

S. No	Recorded Date	Phases (Amps)			Loading %	Phase Imbalance %
		Red (Amp)	Yellow (Amp)	Blue (Amp)		
1	06/06/22	700	600	500	41	16.67
2	07/05/20	500	400	450	31	11.11
3	06/05/19	700	600	500	41	16.67

Appendix B - Expected LCT Increase

B.1. Trial Site Example 1

Table 23: Substation showing demand increase, Increase in LCT for SPM-SU1

Year	ADMD(KW)	ADMD + EVUp + HeatUp (KW)	Demand increase	Increase in LCT
2024	494.7	526.1	N/A	N/A
2028	494.7	602.2	14%	242%
2036	494.7	867.2	65%	1086%
2040	494.7	926.0	76%	1274%

Table 24: Substation showing demand increase, Increase in LCT for SPM-SU3

Year	ADMD(KW)	ADMD + EVUp + HeatUp (KW)	Demand increase	Increase in LCT
2024	1077.7	1104.5	N/A	N/A
2028	1077.7	1171.7	6%	251%
2036	1077.7	1432.9	30%	1225%
2040	1077.7	1522.2	38%	1559%

Table 25: Substation showing demand increase, Increase in LCT for SPM-SU4

Year	ADMD(KW)	ADMD + EVUp + HeatUp (KW)	Demand increase	Increase in LCT
2024	412.3	471.2	N/A	N/A
2028	412.3	623.2	32%	258%
2036	412.3	1110.6	136%	1086%
2040	412.3	1167.6	148%	1182%

Table 26: Substation showing demand increase, Increase in LCT for SPM-SU5

Year	ADMD(KW)	ADMD + EVUp + HeatUp (KW)	Demand increase	Increase in LCT
2024	340.4	590.4	N/A	N/A
2028	340.4	519.5	-12%	-28%
2036	340.4	898.6	52%	123%
2040	340.4	956.2	62%	146%

Table 27: Substation showing demand increase, Increase in LCT for SPM-SU6

Year	ADMD(KW)	ADMD + EVUp + HeatUp (KW)	Demand increase	Increase in LCT
2024	502.3	571.3	NA	NA
2028	502.3	758.8	33%	272%
2036	502.3	1333	133%	1104%
2040	502.3	1402.6	146%	1205%

B.2. Trial Site Example

Table 28: Substation showing demand increase, Increase in LCT for SPM-U1

Year	ADMD(KW)	ADMD + EVUp + HeatUp (KW)	Demand increase	Increase in LCT
2024	561.9	563.3	N/A	N/A
2028	561.9	596.5	6%	2371%
2036	561.9	805.5	43%	17300%
2040	561.9	825.1	46%	18700%

Table 29: Substation showing demand increase, Increase in LCT for SPM-U2

Year	ADMD(KW)	ADMD + EVUp + HeatUp (KW)	Demand increase	Increase in LCT
2024	500.9	502.3	N/A	N/A
2028	500.9	526.9	5%	1757%
2036	500.9	699	39%	14050%
2040	500.9	715.5	42%	15229%

Table 30: Substation showing demand increase, Increase in LCT for SPM-U3

Year	ADMD(KW)	ADMD + EVUp + HeatUp (KW)	Demand increase	Increase in LCT
2024	832.9	834.3	NA	N/A
2028	832.9	899.6	8%	4664%
2036	832.9	1224.4	47%	27864%
2040	832.9	1253.9	50%	29971%

Table 31: Substation showing demand increase, Increase in LCT for SPM-U4

Year	ADMD(KW)	ADMD + EVUp + HeatUp (KW)	Demand increase	Increase in LCT
2024	559.9	561.3	N/A	N/A

Year	ADMD(KW)	ADMD + EVUp + HeatUp (KW)	Demand increase	Increase in LCT
2028	559.9	585.9	4%	1757%
2036	559.9	758	35%	14050%
2040	559.9	774.5	38%	15229%

Table 32: Substation showing demand increase, Increase in LCT for SPM-U5

Year	ADMD(KW)	ADMD + EVUp + HeatUp (KW)	Demand increase	Increase in LCT
2024	528.9	530.3	N/A	N/A
2028	528.9	555.5	5%	1800%
2036	528.9	744.3	40%	15286%
2040	528.9	760.9	43%	16471%

B.3. Trial Site Example 4

Table 33: Substation showing demand increase, Increase in LCT for SPD-U2

Year	ADMD(KW)	ADMD + EVUp + HeatUp (KW)	Demand increase	Increase in LCT
2024	1108.5	1154.8	NA	NA
2028	1108.5	1207.9	5%	115%
2036	1108.5	1523.3	32%	796%
2040	1108.5	1727.5	50%	1237%

Table 34: Substation showing demand increase, Increase in LCT for SPD-U3

Year	ADMD(KW)	ADMD + EVUp + HeatUp (KW)	Demand increase	Increase in LCT
2024	766.3	789.5	NA	NA
2028	766.3	820.5	4%	134%
2036	766.3	985.2	25%	844%
2040	766.3	1110.4	41%	1383%

Table 35: Substation showing demand increase, Increase in LCT for SPD-U4

Year	ADMD(KW)	ADMD + EVUp + HeatUp (KW)	Demand increase	Increase in LCT
2024	1008.1	1035.1	NA	NA
2028	1008.1	1070.8	3%	132%
2036	1008.1	1269.2	23%	867%
2040	1008.1	1426.4	38%	1449%