LV ENGINE

Demonstration of functions and performance

Deliverable #6

About Report	
Report Title	: LV Engine Deliverable #6 - Demonstration of Functions and Performance
Report Status	: Final

Report Summary & Disclaimer

This report provides the learnings captured from monitoring the performance of LV Engine solutions trialled in three sites in SP Energy Networks. This report forms Deliverable 6 of LV Engine project in line with LV Engine project direction.

This report has been prepared as part of the LV Engine project, a globally innovative project to demonstrate the functionalities of a Smart Transformer, funded by Ofgem through the Network Innovation Competition mechanism. All learnings, outcomes, models, findings information, methodologies or processes described in this report have been presented on the information available to the project team at the time of publishing. It is at the discernment and risk of the reader to rely upon any learnings outcomes, findings, information, methodologies or processes described in this report.

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1 Introduction

LV Engine, an innovation project funded through Network Innovation Competition (NIC) mechanism and led by SP Energy Networks (SPEN), aims to deploy power electronic technology to significantly enhance the functions delivered by a secondary substation. LV Engine is targeting the provision of a smart hybrid LV AC and LV DC supply offering a more efficient and improved quality of supply.

There are several devices designed, manufactured, and factory tested as part of LV Engine development. The overall performance of the LV Engine solution was then demonstrated in a controlled laboratory environment, replicating real network conditions. After the successful outcomes of the lab-based tests, the LV Engine solution was installed at three sites, namely Cresent Road, WH Smith DIY, and Falkirk for the purpose of performance demonstration in real-world operation. At this point, only the site at Falkirk has been equipped with the DC power supply for EV charging.

Section 2 provides an overview of the project re-capping the original project objectives and schemes and then describing main items of plant in an LV Engine substation.

Section 3 and Section 4 describe the results of performance monitoring from LV Engine sites and the trial tests conducted.

Section 5 is the performance analysis of the trials which describes the results of the field testing. These trials include:

- Voltage regulation;
- Capacity sharing / load balancing;
- Phase imbalance and power factor correction;
- LV customer phase identification;
- An assessment of system losses;
- An assessment of system performance whilst EV charging load is connected.

Section 6 describes the operational safety requirements and Section 7 the maintenance requirements at LV Engine substations.

After successful demonstration of the LV Engine system in the laboratory environment, this report demonstrates that LV Engine is stable, safe, can perform the functions required of it, in real life network deployment.

2 Terminology

Term	Description
EV	Electric Vehicle
HV	High Voltage – In the context of this report, this refers to the 11kV system.
LV AC o LVAC	Low Voltage Alternating Current – In the context of this report, this generally means a nominal voltage of 400V rms phase to phase, or 230V rms phase to neutral.
LV DC or LVDC	Low Voltage Direct Current - In the context of this report, this generally means 950V DC pole to pole, or ±475V pole to mid-point / neutral.
NIC	Network Innovation Competition
SPEN	SP Energy Networks
SST	Solid State Transformer – A generic term for a device that has an AC input either at HV or LV, and an LV AC and a LV DC output. The device includes power electronics and may include a transformer.
UPFC	Unified Power Flow Controller – The SST designed and built by ERMCO during the project and installed within LV Engine substations.

3 LV Engine System

3.1 Background

SP Energy Networks, in collaboration with UKPN, submitted the proposal for LV Engine under the Network Innovation Competition (NIC) mechanism in 2017. WSP, University of Strathclyde, and University of Kiel have also provided technical support for the proposal preparation. Ofgem approved the proposal and issued the Project Direction on the 16th of January 2018.The project commenced in January 2018 and is currently due to conclude in December 2024.

The LV Engine innovation project has trialled smart transformers within secondary substations as the central point of an active and intelligent 11kV and LV distribution network. The smart transformers trialled during the project have bought together sophisticated power electronic hardware with intelligent network monitoring and control to maximise the performance and efficiency of the distribution network.

4 LV Engine concept and functions

4.1 LV Engine Overview

LV Engine aims to demonstrate the following core functionalities that can be delivered by deploying power electronic technologies at secondary substations:

- Voltage regulation at LV Networks for each phase independently
- Capacity sharing with other substations
- Cancelation of LV imbalance load
- Reactive power compensation and power factor correction at secondary substations
- Provision of LVDC to supply rapid and ultra-rapid EV chargers.

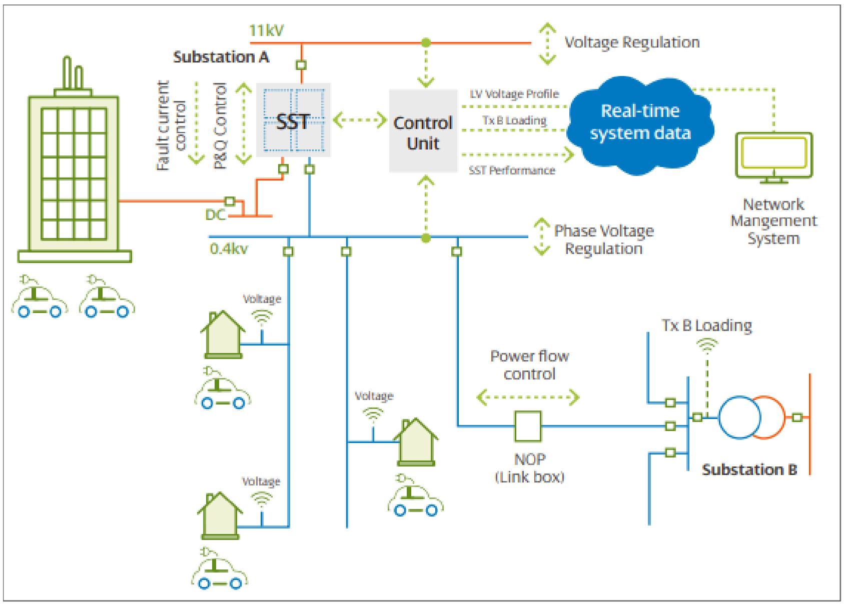

Figure 1 LV Engine project concept

4.2 LV Engine Schemes

At the beginning of the project, five schemes were proposed for LV Engine, Figure 2:

- Scheme 1 allows an LV Engine substation to be coupled to one conventional substation to allow capacity sharing on the LV AC network between the two;
- Scheme 2 allows an LV Engine substation to be connected to two conventional substations to allow capacity sharing between the three;
- Scheme 3 allows to LV Engine substations and one conventional substation to be interconnected to allow enhanced capacity sharing;
- Scheme 4 demonstrates an LV Engine substation providing an LV DC supply;
- Scheme 5 demonstrated and LV engine substation providing an LV DC supply and LV AC supply to a network.

This report describes the trial at Crescent Road and Smith DIY where Schemes 1 to 3 were trialled and also the trial at Falkirk which was a hybrid implementation of Scheme 4 and Scheme 5. The Falkirk trials, in addition to DC supply, provides an LV AC supply and connected to an LV AC distribution network, but it was only used to supply substation auxiliary loads at the time of writing this report. Nonetheless, work is ongoing at this substation to connect the AC customer's load in Jan 2025. It should be noted that the AC and DC simultaneous supply was demonstrated already as part of LV Engine Deliverable 4, Network Integration Testing.

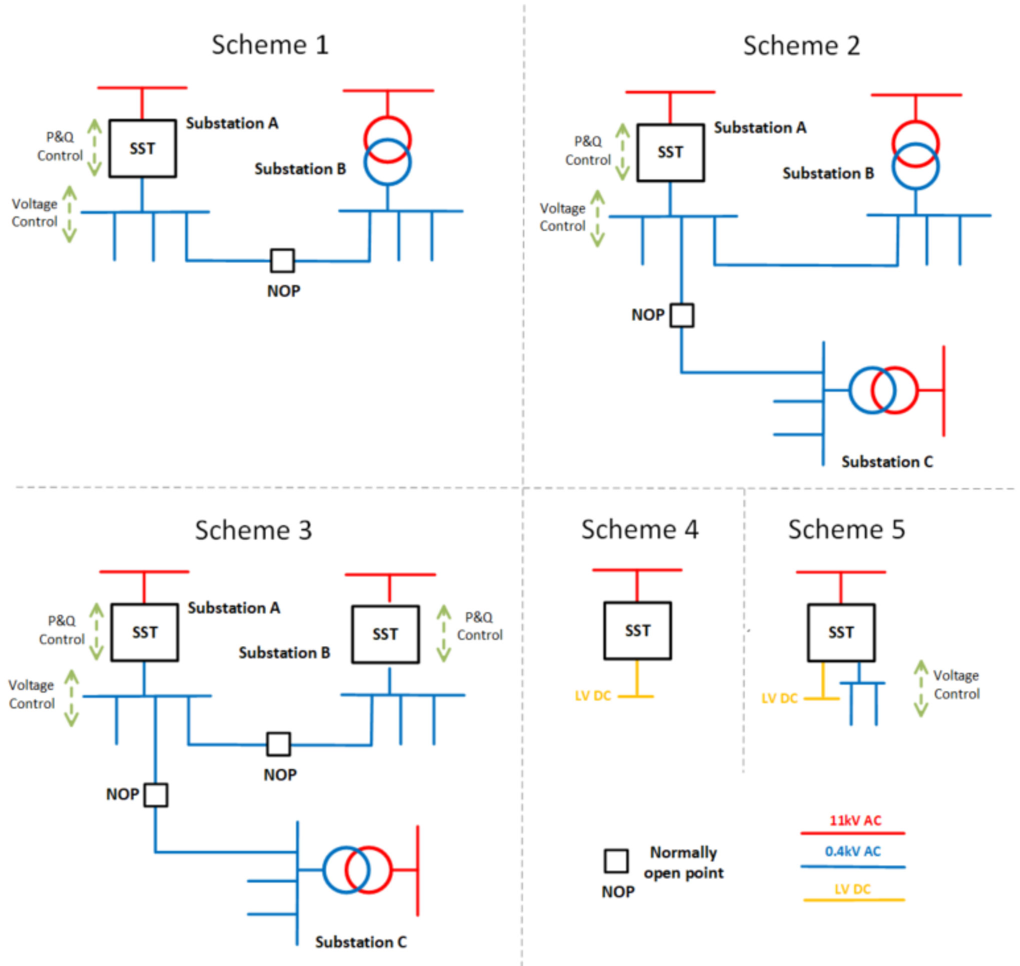

Figure 2 – Proposed schemes for LV Engine

4.3 SST Topologies

The focus of the LV Engine project is to demonstrate the performance of the core functionalities required by the network, there are different possible topologies which have been considered as part of LV Engine to deliver these functionalities. The two topologies considered are summarised below:

- Topology 1, using a conventional low frequency (LF) 50Hz transformer – This topology uses power electronics devices at the secondary side of conventional LF transformers (11kV/0.4kV). The power electronics devices can be added to the existing distribution transformers to deliver the core functionalities of LV Engine.

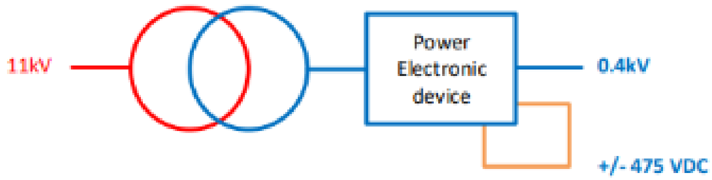

Figure 3 SST Topology 1

- Topology 2, using High Frequency (HF) transformers – Using HF transformers and power electronics may allow a modular and compact design while delivering the LV Engine Core Functionalities. This topology requires significant effort for design and manufacturing compared to the approach of retrofitting an LF transformer with power electronics.

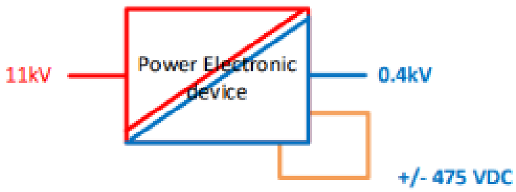

Figure 4 SST Topology 2

LV Engine progressed both topologies in parallel. However, after completion of the critical design stage and benchtop testing, it became more apparent that a Topology 2 product is most likely to remain a low-level technology readiness prototype with little confidence in trialling it in the network within LV Engine project lifetime. In order to avoid expending unnecessary effort developing a product that will remain at a factory prototype level and also ensure value for money for the activities in LV Engine, only Topology 1 was progressed into design, manufacturing and trial. This decision did not affect the business case initially constructed on the core functionalities targeted by LV Engine.

4.4 LV Engine substation components based on Topology 1

The power electronic device in Topology 1 is called a Unified Power Flow Controller (UPFC), Figure 6.The UPFC comprises a 250 kVA AC/DC converter connected through a DC-link to an 80 kVA DC/AC converter, Figure 6. The AC side of the DC/AC converter is coupled to each of the three phases on the secondary side of the transformers through three coupling transformers. This allows the LV Engine system to manipulate the current through the phases to adjust the parameters such as voltage, power factor, and reactive power. A key feature of this design is it allows high fault currents to be maintained on the LV AC network so that conventional protection schemes using fuses can be maintained. The DC link is also connected to a 150 kW DC/DC converter which provides ±475 V_{DC} for the purpose of electric vehicles charging.

The UPFCs were designed and manufactured in collaboration with ERMCO which was appointed through a competitive tendering process.

Figure 5 – The Unified Power Flow Controller (UPFC) – the power electronic device used in Topology 1

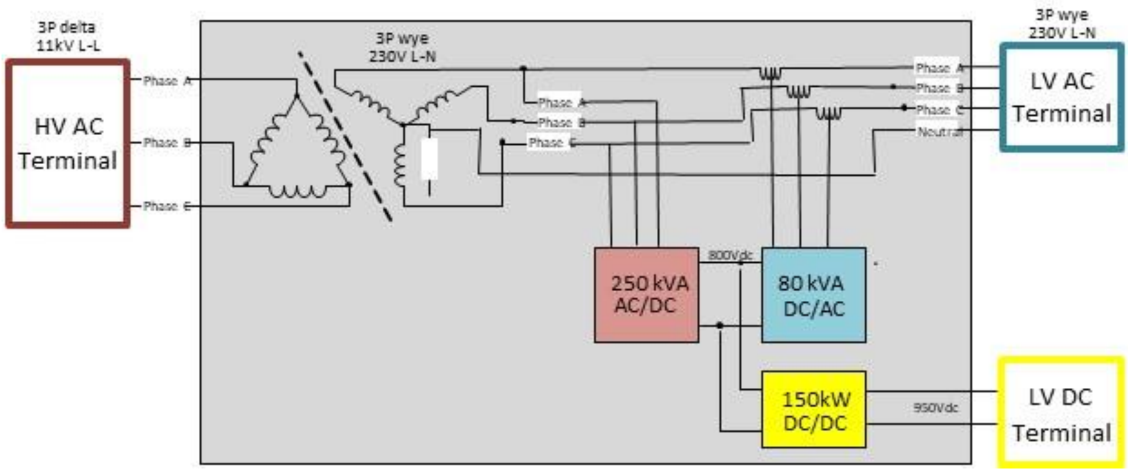

Figure 6 - SST Topology 1

In addition to the UPFC the main components of a Topology 1 LV Engine substation are:

- **Ring Main Unit (RMU)** – This is a typical 11kV RMU which is additionally fitted with a Shunt Trip Coil (STC), to enable the disconnection of the HV supply in case fault occurs in the substation or within UPFC.
- **An distribution 11kV/0.4kV transformer** – This is a conventional oil filled transformer with an off-load tap changer. In the case of the Falkirk site, settlement class CTs were fitted in the LV cable box to facilitate CoP5 settlement metering. This was necessary as there are no industry codes to support LV DC settlement metering.
- **LV AC switchboard** – At the Wrexham LV Engine substations controllable LV circuit breakers (Kelvatek WEEZAPs) replace conventional withdrawable fuses, Figure 7

Figure 7 – LV AC switchboard fitted with LV circuit breakers

- **LV DC switchboard -** This is manufactured by Schneider Electric, Figure 8. The switchboard accepts the DC output from the UPFC. The main function of the switchboard is to distribute power to DC customers. Additionally, the switchboard houses protection and isolation equipment. The LVDC distribution board is fitted with disconnectors, Moulded Case Circuit Breakers (MCCB) and under-voltage release relays. Furthermore, an earth leakage protection relay is installed in the distribution board measuring current through the earth-neutral link. The Bender RCMB301 earth leakage protection relay has been selected to deliver this function. The suitability of this relay has been confirmed previously following tests independently carried out at Power Network Demonstration Centre.

Figure 8 – LV DC switchboard

- **Local Control System (LCS)** - This is an alarm display and telecoms panel, designed specifically for LV Engine, Figure 9. The panel provides status indications of the substation plant. A router, communicating the monitored data, is also fitted within the panel.

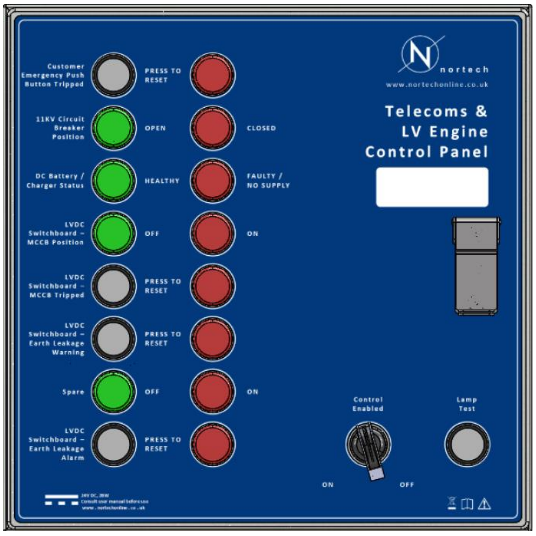

Figure 9 – Local Control system

The 150 kW EV charger at Falkirk is a Tritium PKM150 DC model (Figure 10) which is owned and operated by a customer. The charger can have a mix and match of EV charger connectors (CHAdeMO/CCS1/CCS2), with dual outputs of CCS or CCS and CHAdeMO. The charger at Falkirk has CCS (200 A) and CHAdeMO (125 A) outputs. The charger provides 150 kW on a single charge connector, providing this rate of charge is accepted by the car, or 2x75 kW on the two output connectors simultaneously.

Figure 10 – Tritium EV 150 kW DC Charger

5 Scheme 1 to 3 Trial

In this trial two LV Engine enabled substations on the existing LV AC (0.4kV) network in the town centre, Figure 11. The LV Engine enabled substations are labelled SST (Solid State Transformer) which is a generic term used to represent a substation accommodating a UPFC (Unified Power Flow Controller).

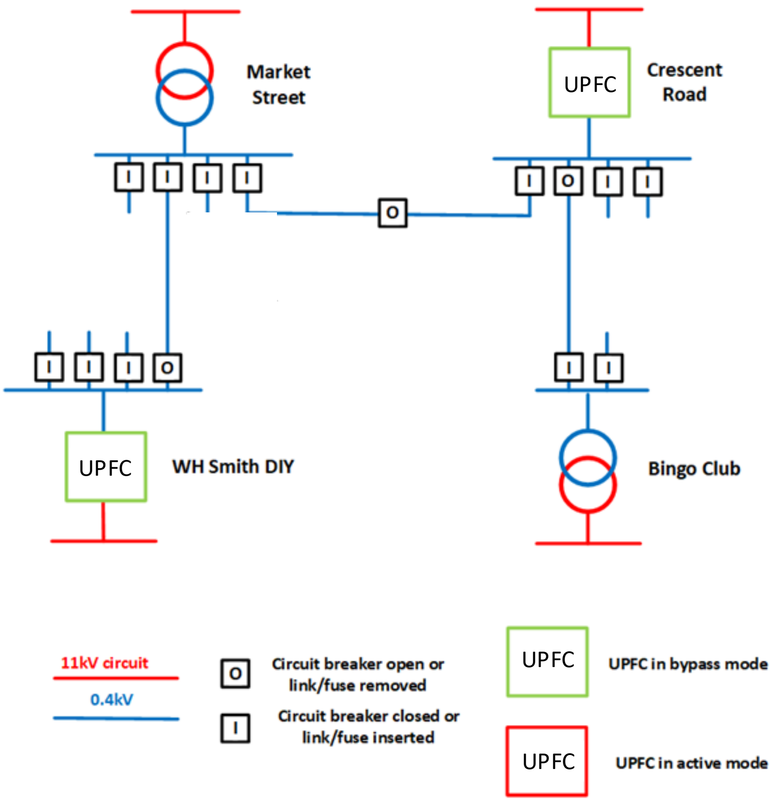

Figure 11 – Network connectivity for trialling

The make-up of an LV Engine substation in this trial is shown in Figure 12. The substation's primary components are:

- an 11kV Ring Main Unit (two disconnectors and one circuit breaker);
- a delta-star 11kV/0.4kV conventional distribution transformer;
- a UPFC (Unified Power Flow Controller);
- and an LV switchboard.

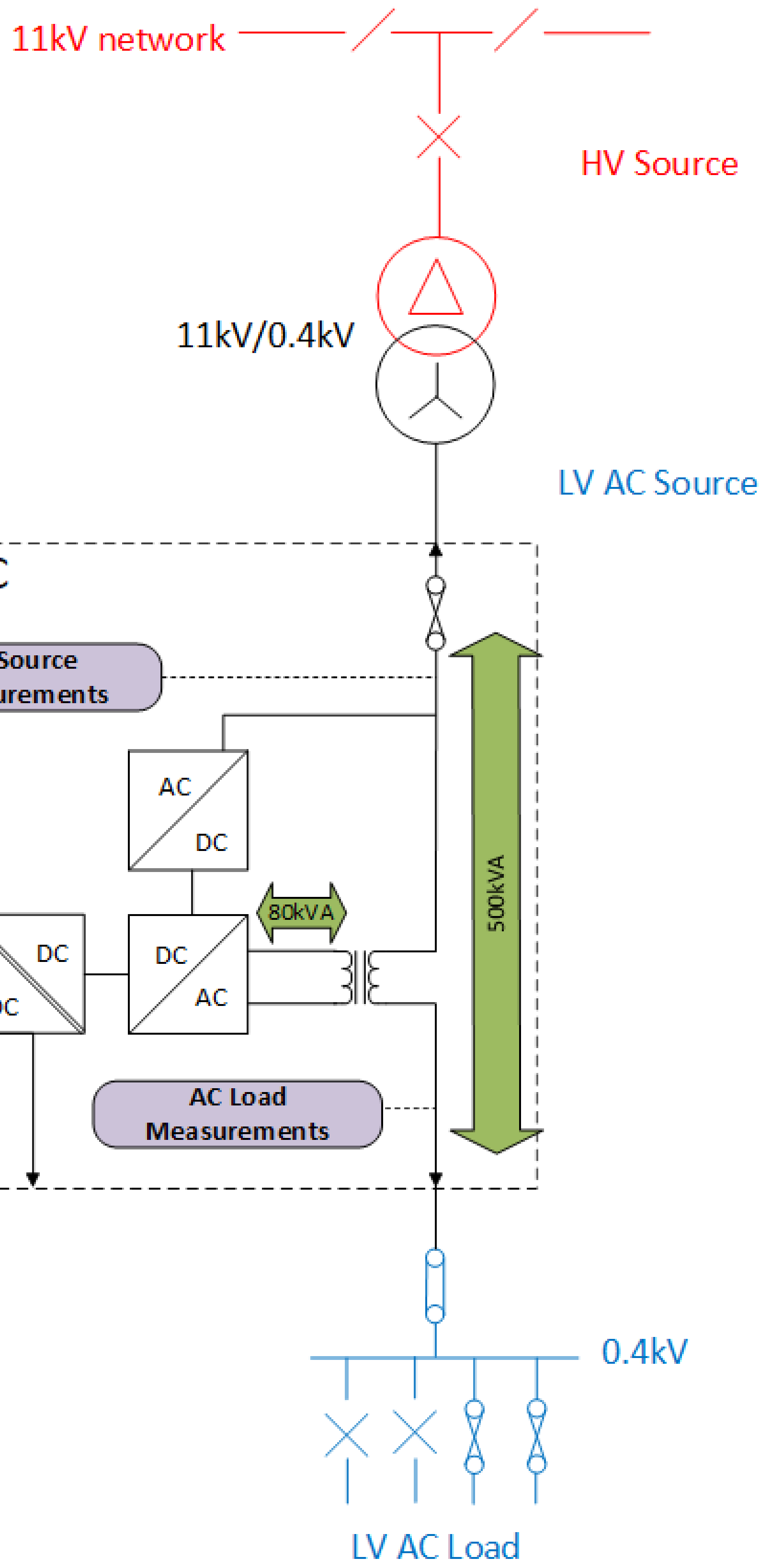

Figure 12 – SST substation at Wrexham

The LV switchboard may have conventional fuses on its outgoing ways or LV circuit breakers.

The UPFC has three terminals:

- An LV AC Source;
- An LV AC Load;
- An LV DC Load.

For the trials at Crescent Road and Smith DIY, LV DC Load terminal is not connected to anything. The UPFC has two AC service modes: Active and Bypass. In the AC Service Active mode the power electronics provide various service including Load voltage control, or phase imbalance cancellation and power factor correction on the LV AC Source side.

In the AC Service Bypass mode, the power electronics does not provide any services and only pass through the voltage supply from the distribution transformer.

Measurements of voltage, current, apparent power, active power and reactive power are taken at the AC Source and AC Load sides of the UPFC to an accuracy of ±0.5% or better.

Scheme 1 to Scheme 3 trials explore the ability of LV Engine to:

- control power sharing between conventional and LV Engine enabled substations;
- regulate voltage per phase on the LV network;
- provide conservation voltage reduction (CVR);
- identify LV customer phase connectivity in conjunction with customer smart meters;
- control current imbalance and power factor on the source side of the UPFC.

Test	Substations affected	Date / Time
Capacity sharing between Crescent Road and Bingo Club	Crescent Road Bingo Club	12 August 2024 11:45 - 11:58
Capacity sharing between Crescent Road and Bingo Club	Crescent Road Bingo Club	11 October 2024 09:02 - 09:31
Capacity sharing between Crescent Road, Bingo Club, and Market Street	Crescent Road Bingo Club Market Street	11 October 2024 10:54 - 11:14
Capacity sharing between Smith DIY and Market Street	Smith DIY Market Street	11 October 2024 11:49 – 12:03
Capacity sharing between Crescent Road, Market Street and Smith DIY	Crescent Road Market Street Smith DIY	11 October 12:03 – 12:46
Crescent Road voltage control tests	Crescent Road only	11 July – 7 Aug
Crescent Road customer phase identification	Crescent Road Only	22 July – 24 July
Crescent Road imbalance / power factor correction test	Crescent Road only	30 May 13:20 – 13:27
WH Smith DIY voltage control tests	WH Smith DIY only	25 June 11:50 – 11:57
Conservation Voltage Reduction	Crescent Road only	11 October 06:45-08:30

Table 1 – Tests conducted at Smith DIY and Crescent Road

6 Performance Analysis – Scheme 1 to 3

6.1 Capacity Sharing Tests

When two substations are serving the complementary load, the installation of a UPFC at one of the substations can support optimising capacity sharing between them. The voltage control function of the UPFC allows for adjustment of the output voltage at the substation where it is installed. By increasing or decreasing the voltage set points, the UPFC can effectively influence the proportion of load that each substation supplies when they operate in an interconnected arrangement. A higher voltage at the UPFC equipped substation would result in increased power flow (both active and reactive power) from that substation to the shared load, while lowering the voltage would shift more of the load to the other substation. This dynamic control capability enables efficient load sharing, improves overall system stability, and can be used to prevent overloading of one substation while ensuring balanced power distribution between the two.

The capacity sharing tests at Crescent Road and Smith DIY substations were performed on 12 August and 11 October. The purpose of the tests was to demonstrate that the voltage control capability on the UPFC can be effectively used in the field to adjust the capacity sharing among the substations. Four separate tests were performed under different network configurations on this day and the details and results from each test are explained in the following sections.

6.1.1 Capacity sharing between Crescent Road and Bingo Club on 12 August

The first capacity sharing test at Crescent Road substation was performed on 12 August. The purpose of the test was to demonstrate that the voltage control capability on the UPFC installed at Crescent Road can be effectively used to adjust the load sharing with the Bingo Club substation. The steps that the test consists of are shown in Table 2 and Figure 14. The LV AC load voltage and the load active and reactive power recorded at Crescent Road during the test are shown in Figure 13.

The test begins with putting the UPFC in bypass mode so that the UPFC in not performing any of its functions. Then the circuit breaker connecting the Bingo Club and Crescent Road is closed so that the two substation is now interconnected via LV network. Then UPFC is configured to operate in voltage control mode at various voltage set points. Figure 14 shows that when the voltage set point is raised to 242V at 11:54, this results in a 50kW rise in active power supplied by Crescent Road. This would correspond to a 50kW decrease in active power supplied by Bingo Club substation. Later when the voltage set points is lowered to 241V at 11:55, the active power share from Crescent Road reduces by approximately 20kW.

The results from this test show that the voltage control functionality of the UPFC can be effectively used for capacity sharing among substations. Further capacity sharing tests were performed at Crescent Road and Smith DIY substations on 11 October and details on the results are provided in the following sections.

Table 2 – Steps followed for performing the capacity sharing test at Crescent Road substation

Step	Description	Expected Response	Time
1	Crescent Road SST in voltage control mode (active)		Before 11:45
2	Crescent Road SST put into bypass mode (passive)	Natural change in load at Crescent Road	11:45
3	Circuit breaker feeding Bingo Club at Crescent Road is closed	Re-balancing of loads between Crescent Road and Bingo Club	11:53
4	Crescent Road SST voltage set point changed to 242V	Load increase at Crescent Road picking more load from Bingo Club	11:54
5	Crescent Road SST voltage set point changed to 241V	Load reduction at Crescent Road as a result of load shift to Bingo Club	11:55

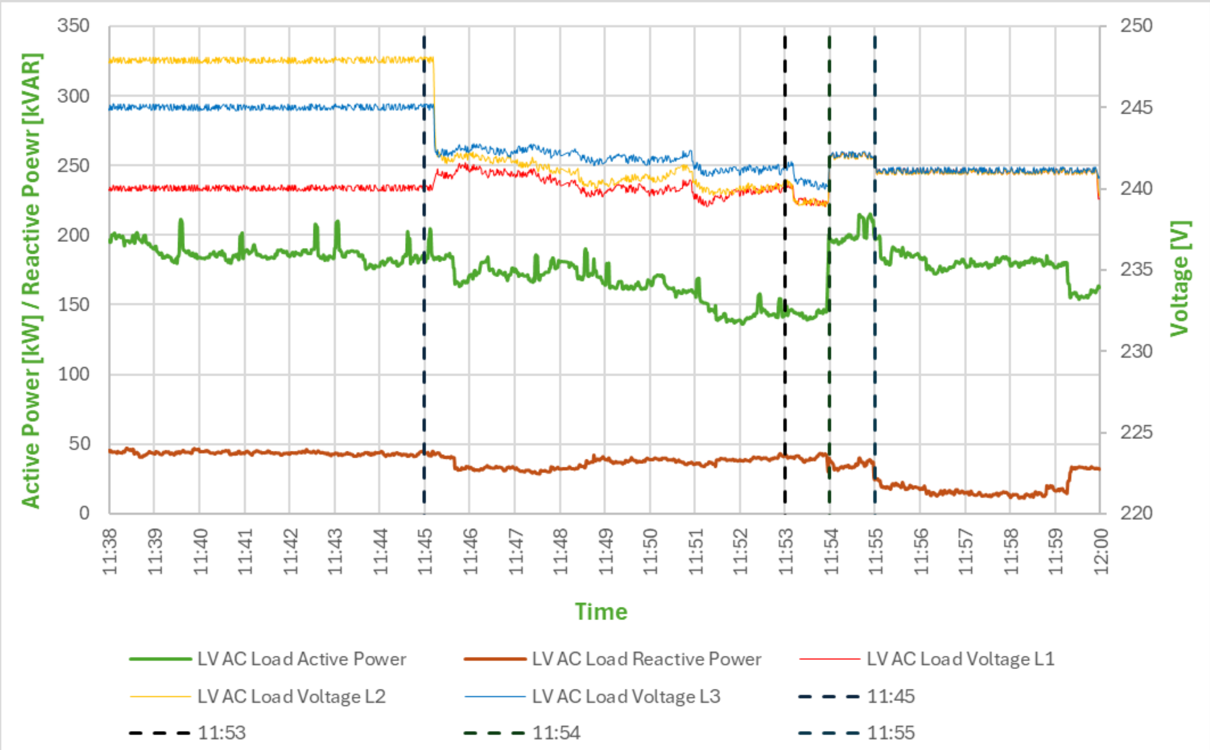

Figure 13 – Measurements taken at Crescent Road during capacity sharing test with Bingo Club on 12 August

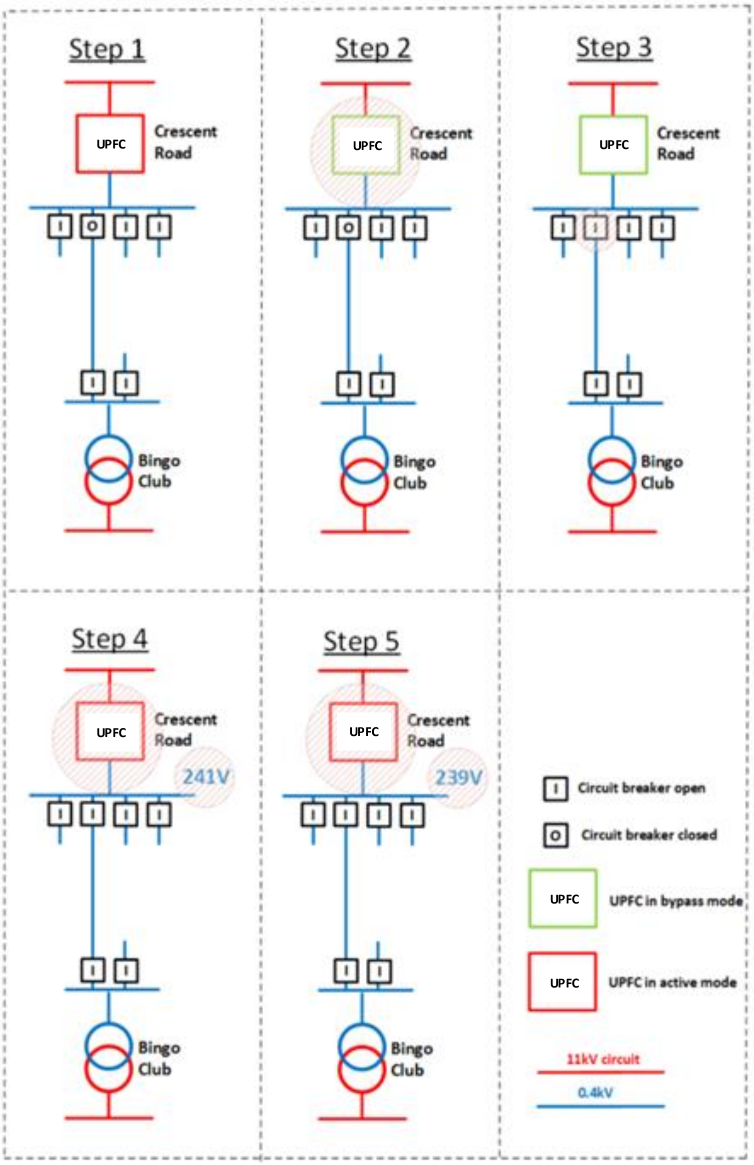

Figure 14 – Steps followed for performing the capacity sharing test at Crescent Road substation

6.1.2 Capacity sharing between Crescent Road and Bingo Club on 11 October

The second capacity sharing test between Crescent Road and Bingo Club substations was carried out between 09:02 and 09:31 on 11 October. The circuit breaker for the interconnection between Crescent Road and Bingo Club was closed at 09:02 as shown in Figure 15, and the UPFC at Crescent Road was put into voltage control mode at 09:06 with a voltage setpoint of 243 V. Subsequently, the UPFC was provided with different voltage setpoints throughout the test and the resulting changes in active and reactive power were assessed.

The active power, reactive power and the LV AC Load Voltage during the test are shown in Figure 16, and the change in active/reactive power as result of change in voltage set point is shown in Table 3. It is clear from the Figure 16 and Table 3 that a rise in voltage at Crescent Road results in an increase in active power supplied, and a drop in voltage results in a decrease in active power.

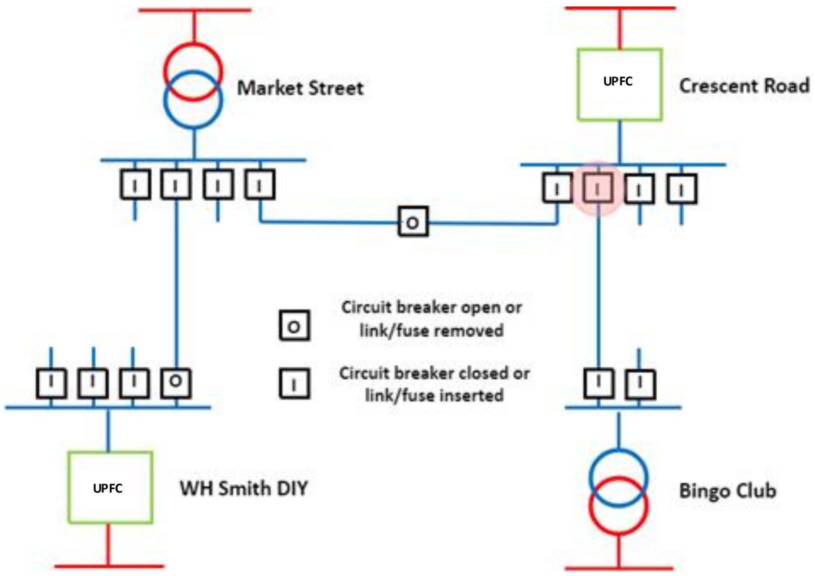

Figure 15 – Network configuration during the capacity sharing test between Crescent Road and Bingo Club

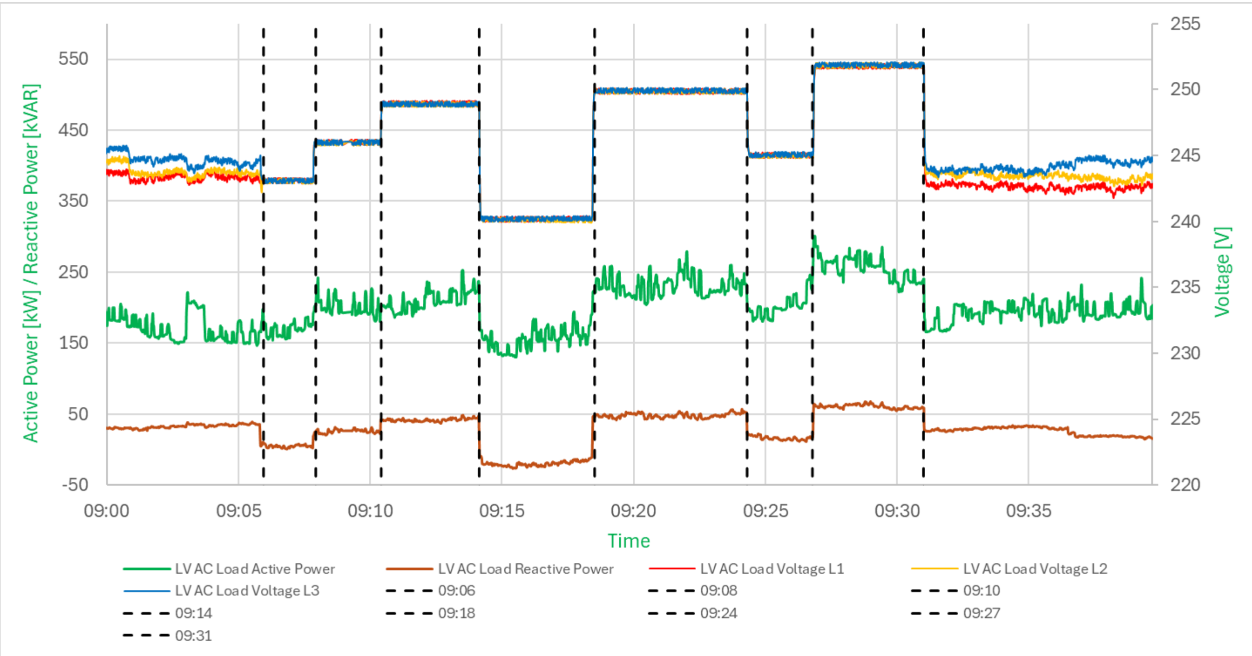

Figure 16 – Output Active power and voltage at Cresent Road during the capacity sharing test between Crescent Road and Bingo Club

Table 3 – Change in active power w.r.t change in voltage setpoints during the capacity sharing test between Crescent Road and Bingo Club

Time	Voltage Setpoint [V]	Change in Voltage Setpoint [V]	Change in Active Power [kW]	Change in Reactive Power [kVAR]
09:06	243	0	5	-32
09:08	246	3	31	20
09:10	249	3	0	15
09:14	240	-9	-77	-65
09:18	250	10	70	63
09:24	245	-5	-41	-33
09:27	252	7	54	46
09:31	243	-9	-65	-31

6.1.3 Capacity Sharing between Crescent Road, Bingo Club, and Market Street

The capacity sharing test between Crescent Road, Bingo Club, and Market Street substations was carried out between 10:54 and 11:14 on 11 October. The circuit breakers for Crescent Road – Bingo Club interconnection, and Crescent Road – Market Street were closed at 10:54 and 10:55 respectively as shown in Figure 17. The UPFC at Crescent Road was put in voltage control mode at 11 and subsequently, the UPFC was provided with different voltage setpoints throughout the test and the resulting change in active power was assessed.

The active power and the LV AC Load Voltage during the test are shown in Figure 18, and the change in active power as result of change in voltage set point is shown in Table 4. It is clear from the Figure 18 and Table 4 that a rise in voltage at Crescent Road results in an increase in active power supplied, and a drop results in a decrease in active power.

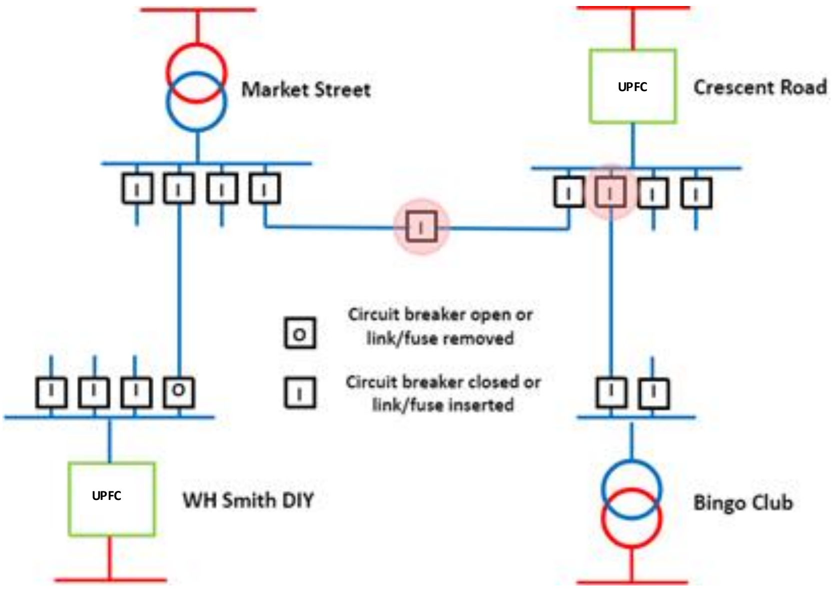

Figure 17 – Network configuration during the capacity sharing test among Crescent Road, Bingo Club and Market Street

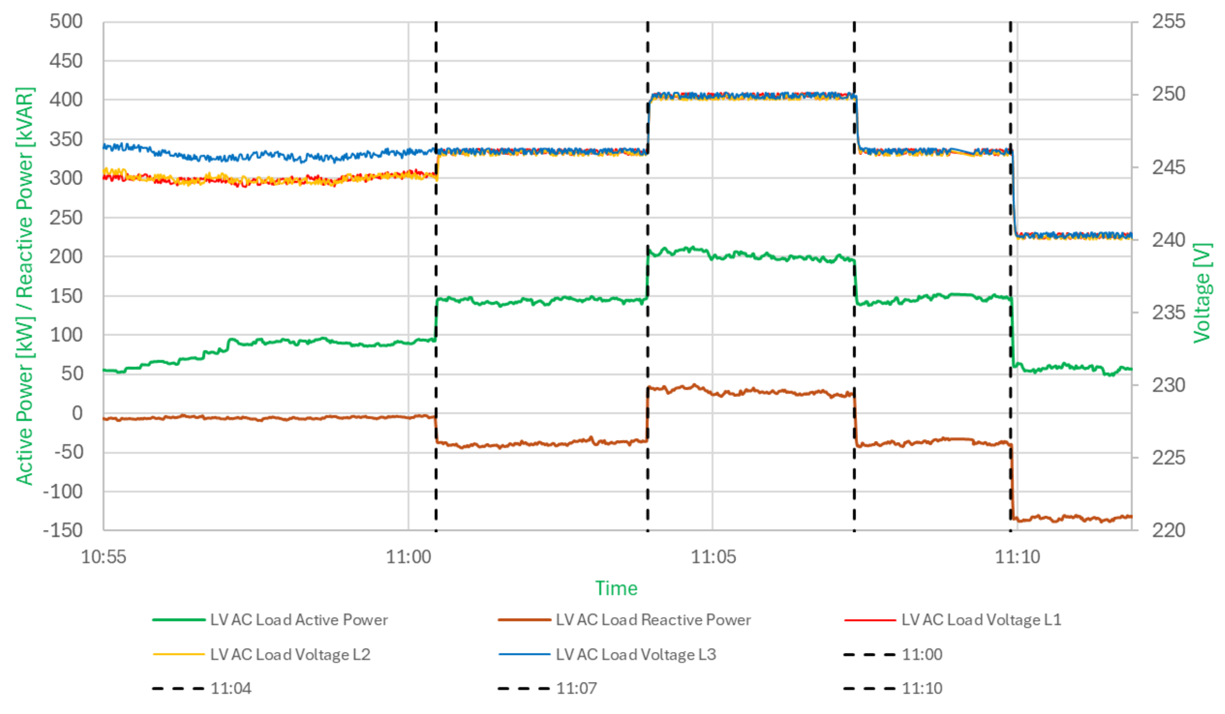

Figure 18 – Output Active power and voltage at Cresent Road during the capacity sharing test among Crescent Road, Bingo Club and Market Street

Time	Voltage Setpoint [V]	Change in Voltage Setpoint [V]	Change in Active Power [kW]	Change in Reactive Power [kVAR]
11:00	246	2	53	-37
11:04	250	4	61	67
11:07	246	-4	-55	-64
11:10	250	-6	-90	-97

Table 4 – Change in active power w.r.t change in voltage setpoints during the capacity sharing test among Crescent Road, Bingo Club and Market Street

6.1.4 Capacity Sharing between Smith DIY and Market Street

The capacity sharing test between Bingo Club and Market Street substations was carried out between 11:49 and 12:03 on 11 October. The circuit breakers on the interconnection between Smith DIY Market Street was closed at 11:30 as shown in Figure 19 and the UPFC was put in voltage control mode with the setpoint of 250V. During the test, the UPFC was provided with different voltage setpoints and the resulting change in active and reactive power was assessed.

The active power, reactive power and the LV AC Load Voltage during the test are shown in Figure 20, and the change in active and reactive power as result of change in voltage set point is shown in Table 5. It is clear from the Figure 20 and Table 5 that a rise in voltage at Crescent Road results in an increase in both active and reactive power, and a drop results in a decrease.

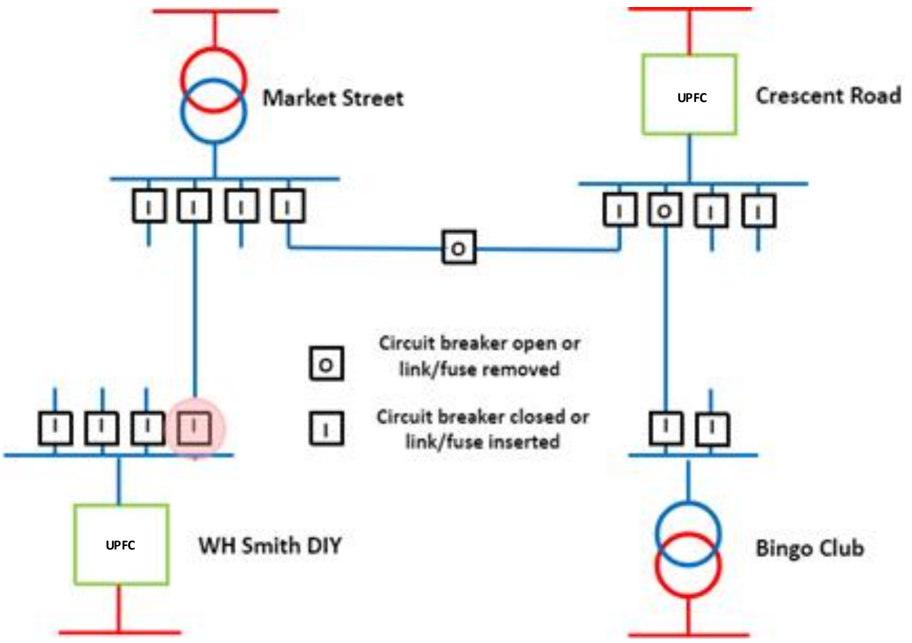

Figure 19 – Network configuration during the capacity sharing test between Smith DIY and Market Street

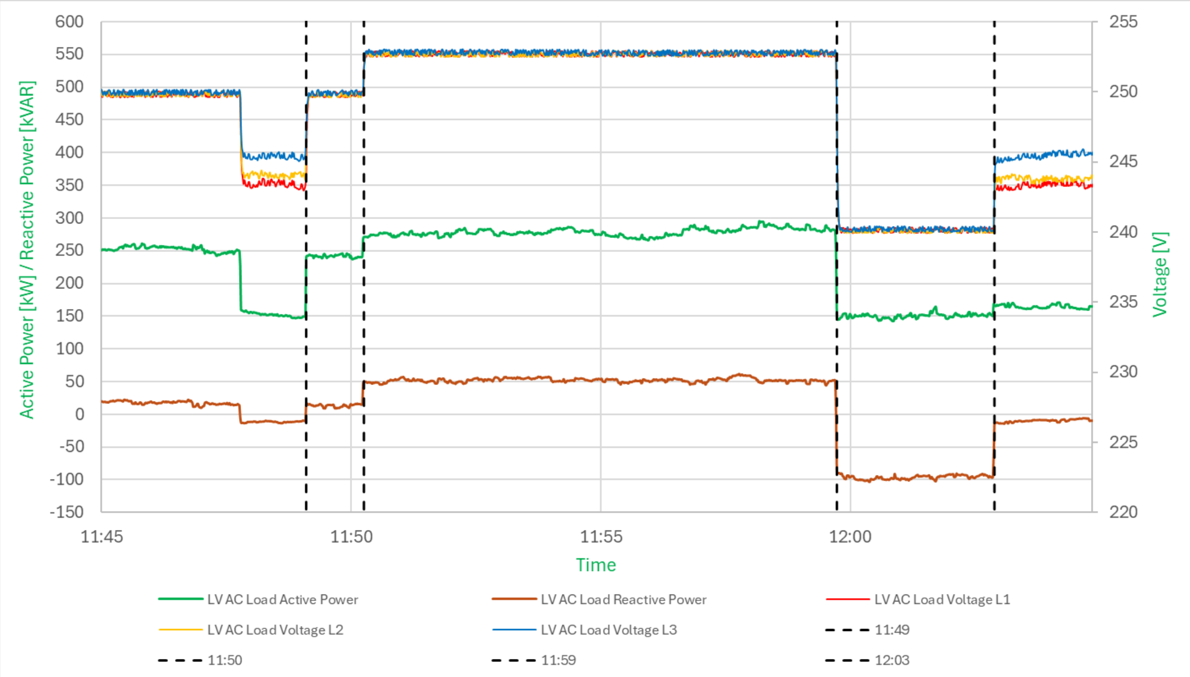

Figure 20 – Network configuration during the capacity sharing test between Smith DIY and Market Street

Time	Voltage Setpoint [V]	Change in Voltage Setpoint [V]	Change in Active Power [kW]	Change in Reactive Power [kW]
11:49	250	6	91	26
11:50	253	3	33	38
11:59	250	-13	-135	-149
12:03	253	3	13	83

Table 5 – Change in active and reactive power w.r.t change in voltage setpoints during the capacity sharing test between Smith DIY and Market Street

6.1.5 Capacity sharing between Crescent Road, Market Street, and Smith DIY

The capacity sharing test between Crescent Road, Market Street, and Smith DIY substations was carried out between 12:03 and 12:46 on 11 October. The circuit breakers for Crescent Road – Market Street interconnection, and Market Street – Smith DIY interconnection were closed at 12:05 as shown in Figure 21.

Once the circuit breakers were closed, the UPFCs at both Crescent Road and Smith DIY were put in voltage control mode and provided with different voltage setpoints throughout the test and the resulting changes in active and reactive power were assessed.

The active power, reactive power and the LV AC Load Voltage at the Crescent Road substation are shown in Figure 22, and the same quantities during this time period at Smith DIY are shown in Figure 23.

A consolidated table containing timestamps when the setpoints were changed at either Crescent Road or Smith DIY is shown in Table 6. Similar to the other test demonstrated in this section, a rise in voltage at the substation results in a rise in both active and reactive power and vice versa.

If it was only Crescent Road and Smith DIY sharing the capacity, a rise in power exported by one substation would result in an equivalent decrease in power exported by the other substation. However, this does not seem to be the case in Table 6, because the Market Street substation is also sharing the capacity and the measurements for power at Market Street are not available. The results shown in Table 6 lead to the conclusion that any change in power exported by Crescent Road or Smith DIY results in an equivalent change at Market Street substation.

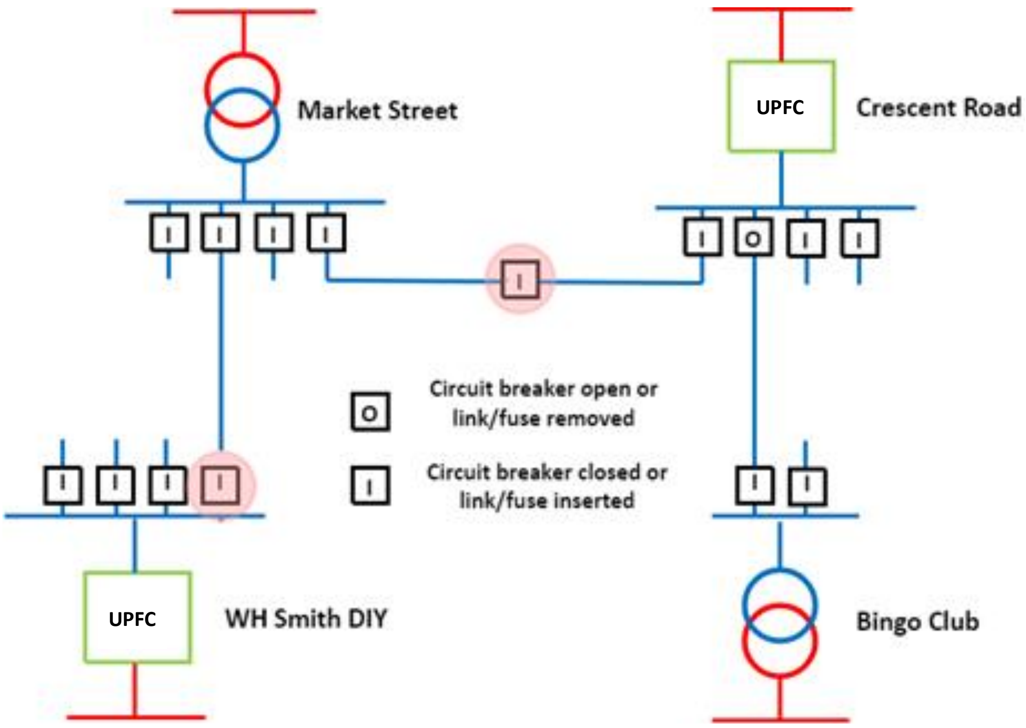

Figure 21 - Network configuration during the capacity sharing test among Crescent Road, Market Street, and Smith DIY

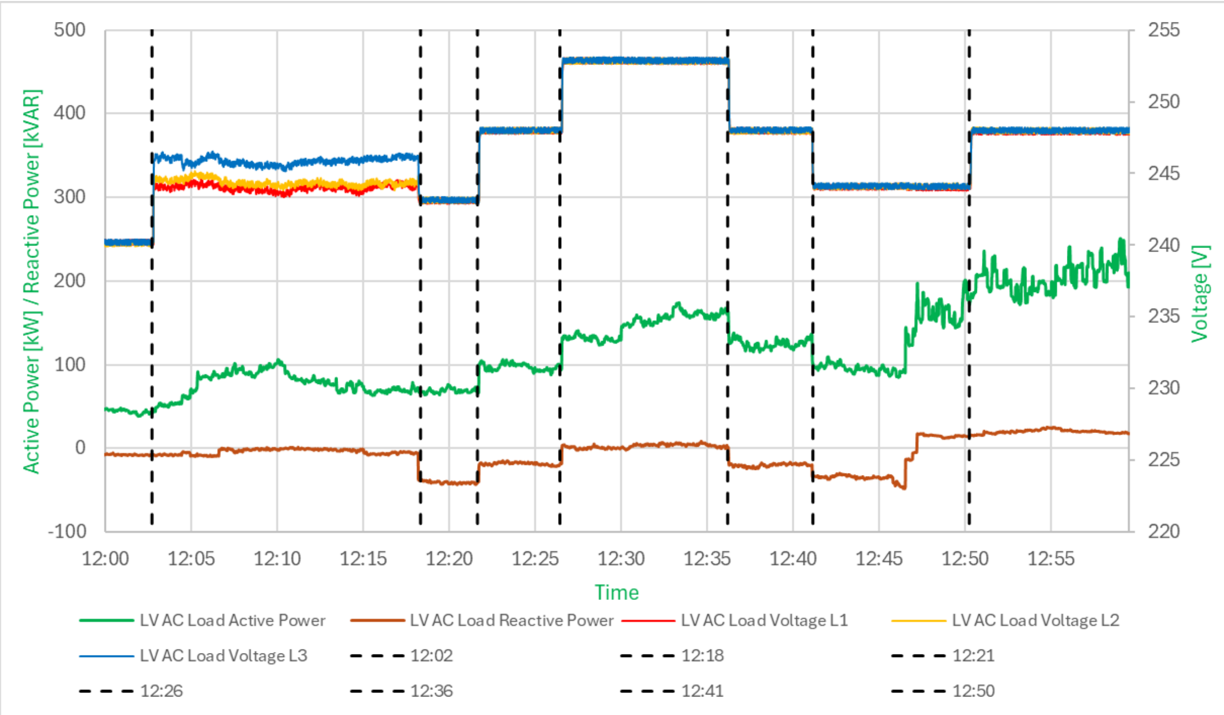

Figure 22 – Output Active power and voltage at Cresent Road during the capacity sharing test among Crescent Road, Market Street, and Smith DIY

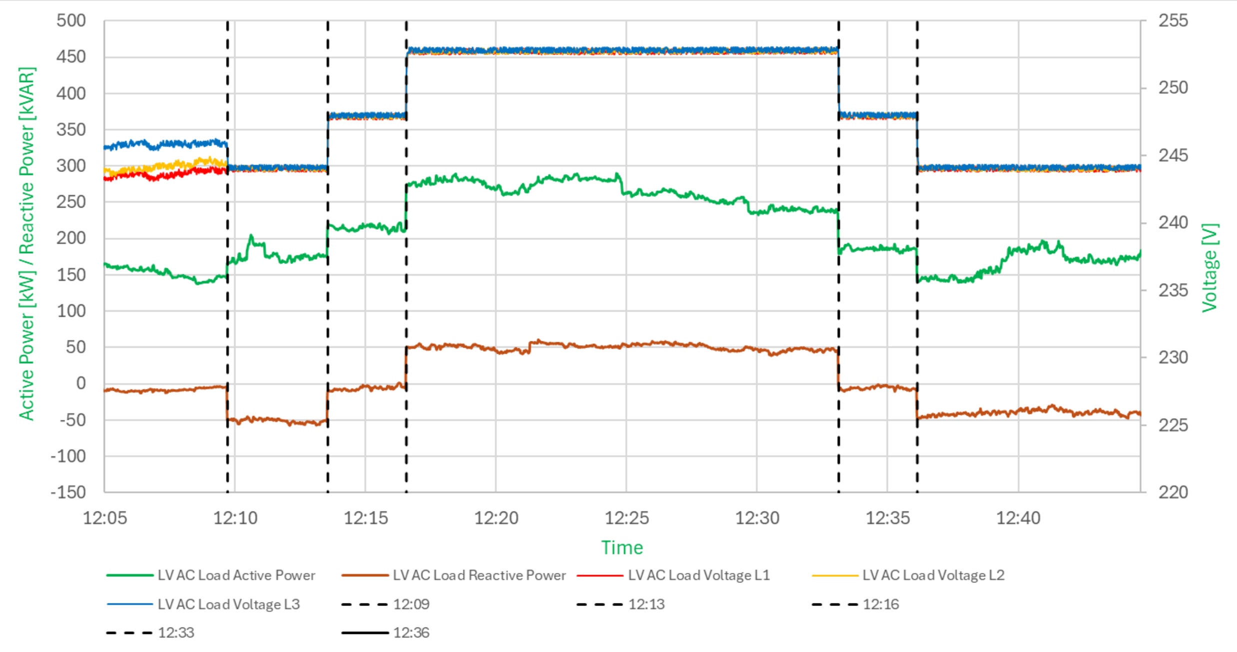

Figure 23 – Output Active power and voltage at Smith DIY during the capacity sharing test among Crescent Road, Market Street, and Smith DIY

Time	Crescent Road				Smith DIY			
	Voltage Setpoint [V]	Change in Voltage Setpoint [V]	Change in Active Power [kW]	Change in Reactive Power [kVAR]	Voltage Setpoint [V]	Change in Voltage Setpoint [V]	Change in Active Power [kW]	Change in Reactive Power [kVAR]
12:02	244	4	9	0	243	3	12	74
12:09	244	0	4	1	244	0	38	-45
12:13	244	0	-6	-1	248	4	38	45
12:16	244	0	3	2	253	5	62	56
12:18	243	-1	-2	-35	253	0	1	0
12:21	248	5	28	23	253	0	15	7
12:26	253	5	40	21	253	0	-1	-1
12:33	253	0	8	0	248	-5	-52	-53
12:36	248	-5	-31	-23	244	-4	-41	-37
12:41	244	-4	-26	-16	244	0	-10	-2
12:50	248	4	41	2	244	0	-5	1

Table 6 – Change in active and reactive power w.r.t change in voltage setpoints during the capacity sharing test between Smith DIY and Market Street

6.2 Crescent Road voltage control tests

LV Engine has the capability to regulate voltage for each phase independently. This functionality allows the UPFC to dynamically respond to varying load conditions or specific grid requirements, maintaining balance and optimising performance in real-time. By using the internal control algorithms, the UPFC adjusts each phase voltage to meet the required setpoints, ensuring stable operation even in scenarios where the phases are asymmetrical or subject to fluctuations.

Results of a test carried out to test LV Engine's ability to track user-defined voltage set points are shown in Figure 24. The results show that LV Engine closely follows the voltage set points and remains stable in case of step changes to the set points.

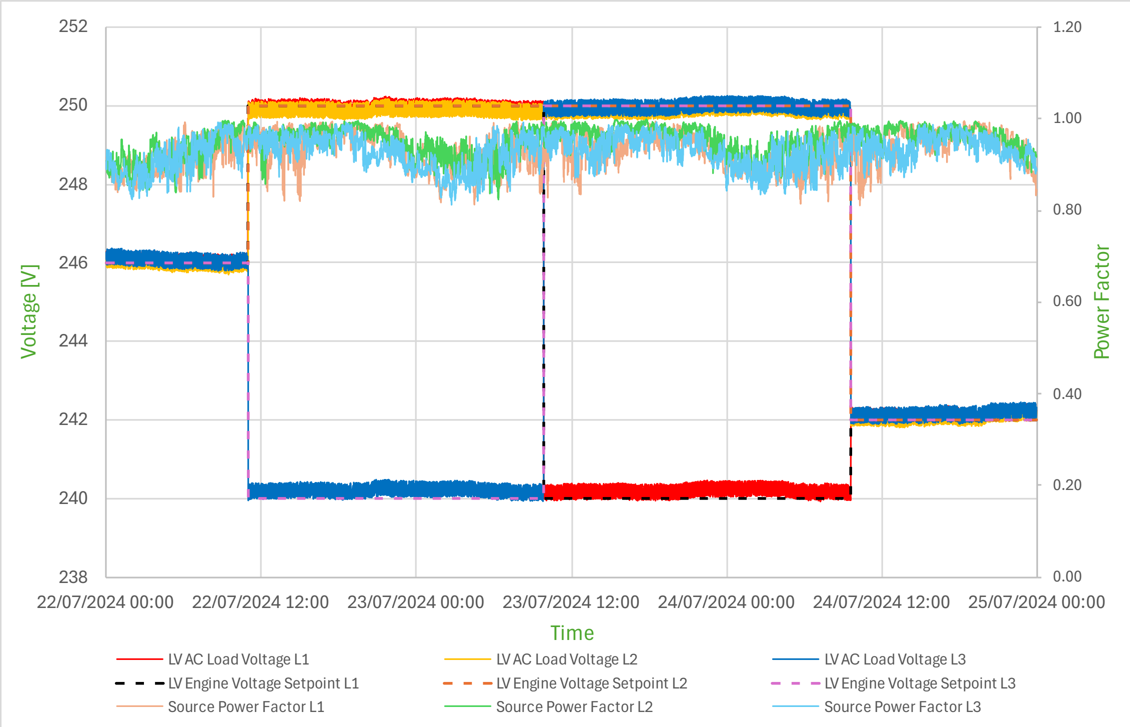

Figure 24 - Voltage set points tracking test for LV Engine system at Crescent Road
A quantitative analysis of LV Engine's ability to track the voltage set points is shown in

Table 7

Table 7 presents analysis of the difference between the voltage set points and the output voltages for three phases (L1, L2, and L3). For each phase, two metrics are shown: the average difference, and the maximum difference, both expressed as percentages.

The analysis was carried out over data spanning three weeks period from 15 July 2024 to 4 August 2024. This period includes the voltage step change test shown in Figure 24. The average difference between voltage set points and output voltage varied from 0.014% (for L3) to 0.042% (for L1). Since the accuracy of voltage measurements is 0.5% and the average percentage difference is much less that this value, it can be concluded that the LV Engine system accurately regulates the load voltage according to the set points without causing any significant deviations. This test demonstrates that the voltage control feature of the LV Engine system can be reliably used in as required by operation staff.

Phase	Average Difference Between Setpoint and Output Voltage [%]	Maximum Difference Between Setpoint and Output Voltage [%]
L1	0.04%	1.00%
L2	0.01%	3.08%
L3	0.05%	3.09%

Table 7 - Analysis of voltage set points tracking test for LV Engine system at Crescent Road

6.3 Crescent Road customer phase identification

Another purpose of the voltage control test described in the previous section is to perform customer phase identification, which aims to determine which customers are connected to each phase. This is achieved by varying the voltage on each phase at the substation and then comparing these variations to the voltage measurements taken by the energy smart meters installed at customers. By deliberately adjusting the voltage on individual phases, the resulting changes in voltage are observed on customers' smart meters. These measurements are then analysed to correlate the voltage variations with the specific phases, thereby identifying the phase to which each customer is connected. This mechanism ensures precise mapping of customers to their respective phases allowing improved visibility of the LV network and allowing future customers to be connected to phases with lower demand.

The voltage measurements taken by smart meters of customers connected to Phase 3 are shown in Figure 25. The voltage profile in Figure 25 closely matches the voltage profile of Phase 3 in Figure 24, leading to the conclusion that voltage control test is a reliable technique for identifying the phase to which each customer is connected.

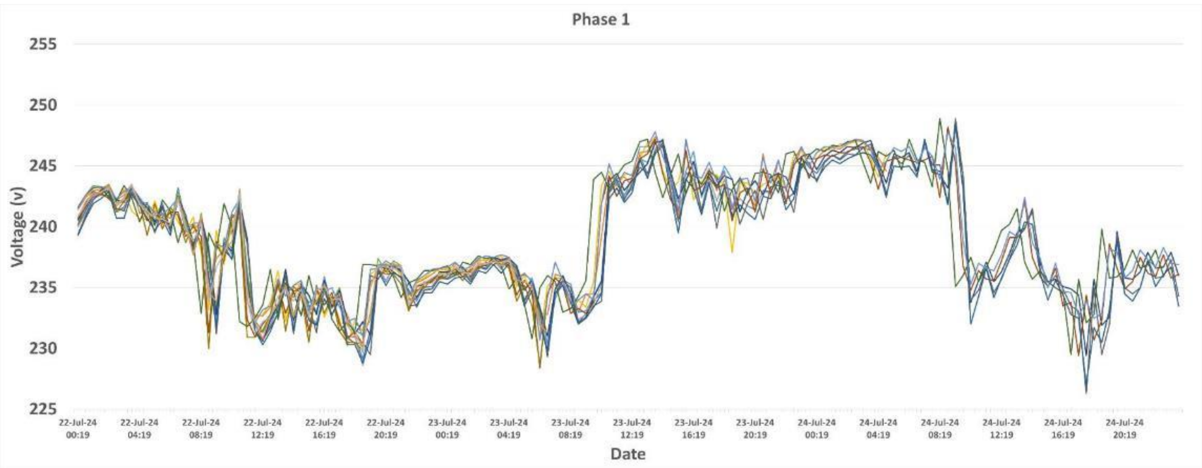

Figure 25 – Voltage measurements taken by smart meters of customers connected to Phase 3 of Crescent Road substation

This analysis was carried out for all three phases and the customers were mapped according to the phase they were connected to. The final results of the mapping process are shown in Figure 26.

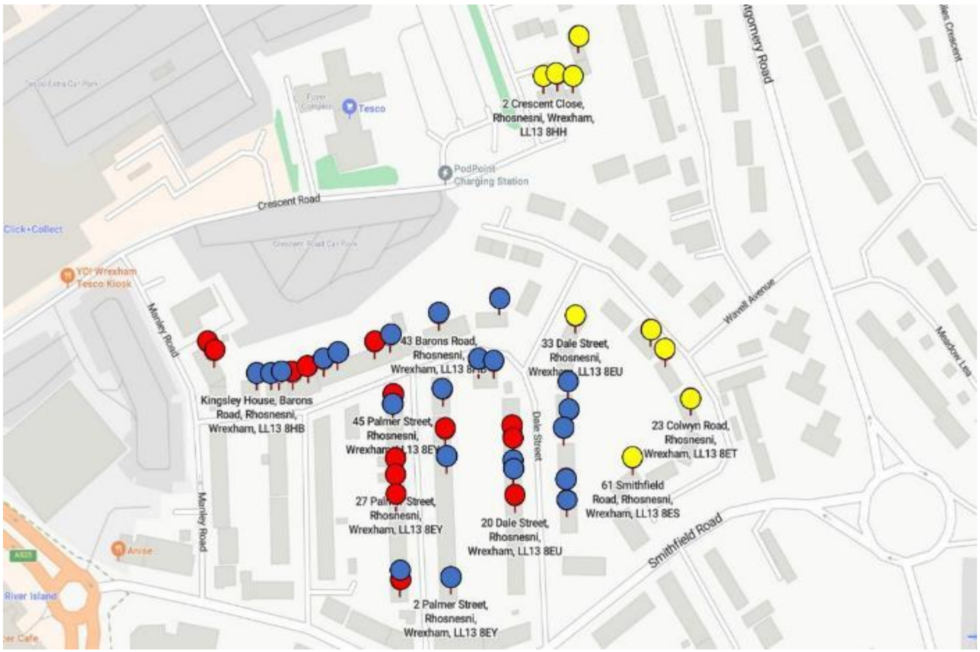

Figure 26 – Customers mapped to each of the three phases using the results of the voltage control test

6.4 Crescent Road phase imbalance / power factor correction test

LV Engine has the capability to cancel imbalanced loads across the three phases. When the load is unbalanced the UPFC adjusts the current drawn from the source in such a way that the source perceives a balanced load. This is achieved through advanced power electronics and control algorithms.

Tests to demonstrate LV Engine's capability to compensate for imbalanced loads were carried out on 30 May 2024 between 13:26 and 13:29, and on 12 August 2024 between 11:30 and 11:33.

The phase currents during the test carried out on 30 May on both source and load sides are shown in Figure 27. The impact of load balancing on power factor on the source side is shown in Figure 28. A quantitative analysis of the phase currents, current imbalance, and power factor before and during the load balancing test is shown in Table 8.

Prior to 13:26 the load and source current on each phase of the UPFC are unbalanced (L1, L2 and L3 currents are different). The source currents on each phase are slightly higher than the load currents to account for the losses in the UPFC.

At 13:26 load balancing / power factor correction mode is enabled. The load currents remain unbalanced, as expected, as they are a function of the customer loads on the network. However, the UPFC source currents all become equal and the neutral current is significantly reduced. The quantitative analysis shows that before the load balancing event, the average current among the phases is different and the neutral line is carrying an average current of 45 A. During the load balancing event, the current across all the three phases becomes equal and the neutral current drops to 9 A, demonstrating a significant improvement.

Prior to 13:26 the power factors on each source phase were also different and varying. At 13:26 these all equalise to the same steady value.

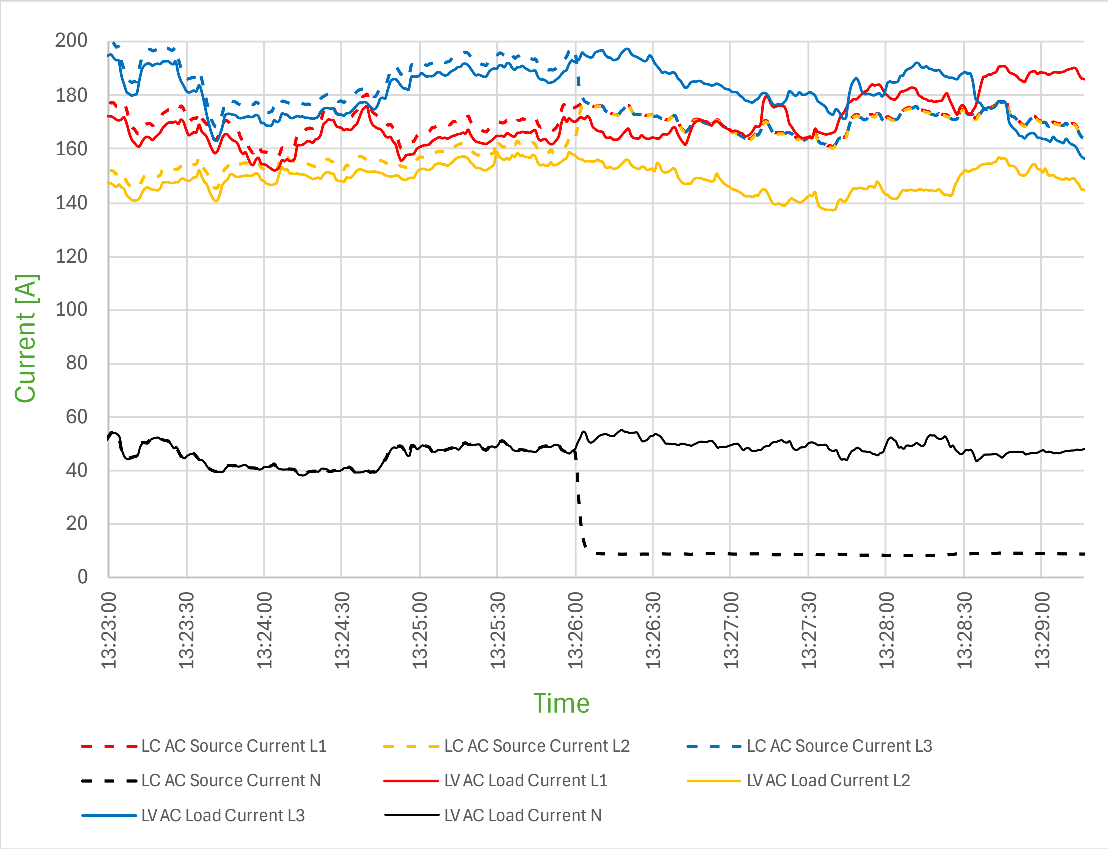

Figure 27 - Phase and neutral currents on the source and load side of the UPFC during the imbalanced load test performed on 30 May

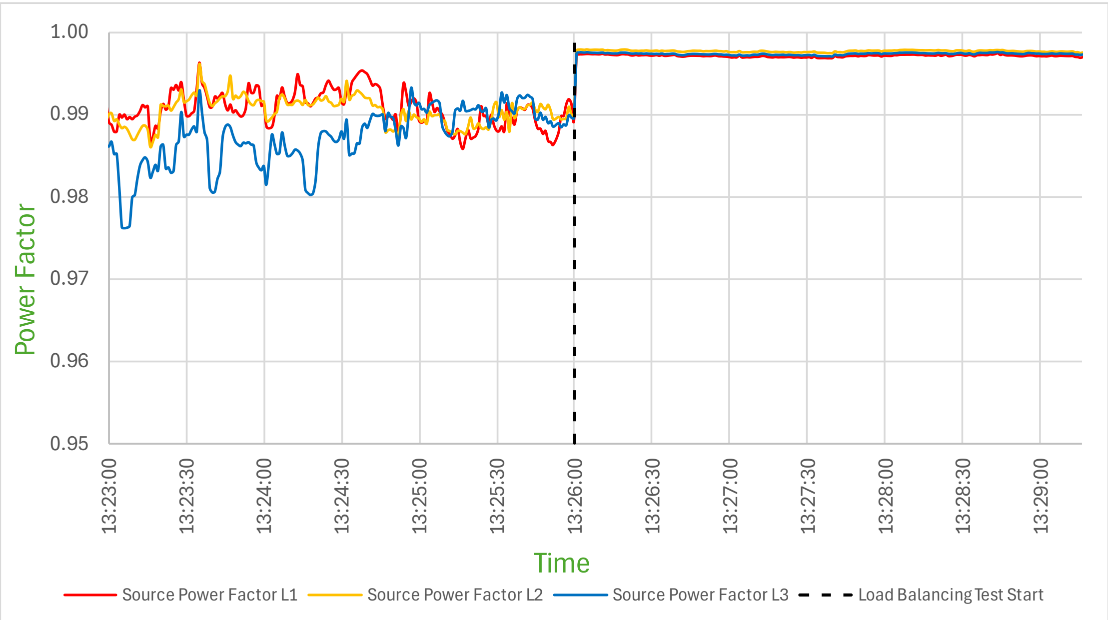

Figure 28 – Power factor on the UPFC source side during the imbalanced load test performed on 30 May

Phase	Before the Load Balancing Test			During the Load Balancing Test		
	Average Current [A]	Difference from the Average 3-Phase Current [%]	Average Power Factor	Average Current [A]	Difference from the Average 3-Phase Current [%]	Average Power Factor
L1	165	2.78%	0.99	170	0.09%	1.00
L2	150	8.85%	0.99	170	0.03%	1.00
L3	179	8.77%	0.98	170	0.09%	1.00
N	45	--	--	9	--	--

Table 8 – Quantitative analysis for the imbalanced load test performed on 30 May (UPFC source side)

Phase imbalance cancellation test was also carried out on 12th August, see Figure 29. The impact of load balancing on power factor on the source side is shown in Figure 30 and the quantitative analysis of the phase currents, current imbalance, and power factor before and during the load balancing test is shown in Table 9.

The difference between the currents on the three phases and the magnitude of neutral current drastically reduce when the load balancing is enabled. However, in this case there is still some imbalance among the three phases and the reason is the extent of imbalance among the three phases before load balancing was enabled.

A comparison between Table 8 and Table 9 shows that on 30 May, the maximum current imbalance before the test is 8.85% which reduces to 0.09% during the test. On the other hand, on 12 August the maximum current imbalance before the test is 28.19% which is significantly reduced to 6.79% during the test. The reason the UPFC could not make the current of three phases exactly equal is that the imbalance of 28.19% is very close to the UPFC's 30% maximum load imbalance cancellation capability.

The two tests have demonstrated that LV Engine can improve the network power factor and load imbalance on the source side of the UPFC.

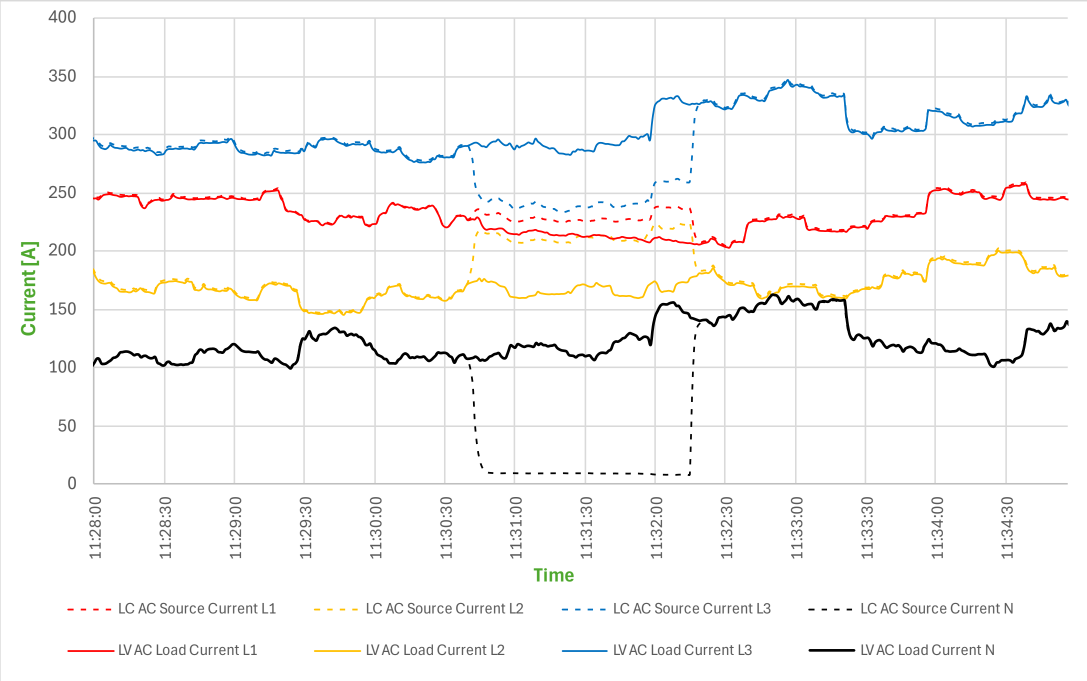

Figure 29 - Phase and neutral currents on the source and load side of the UPFC during the imbalanced load test on 12 August

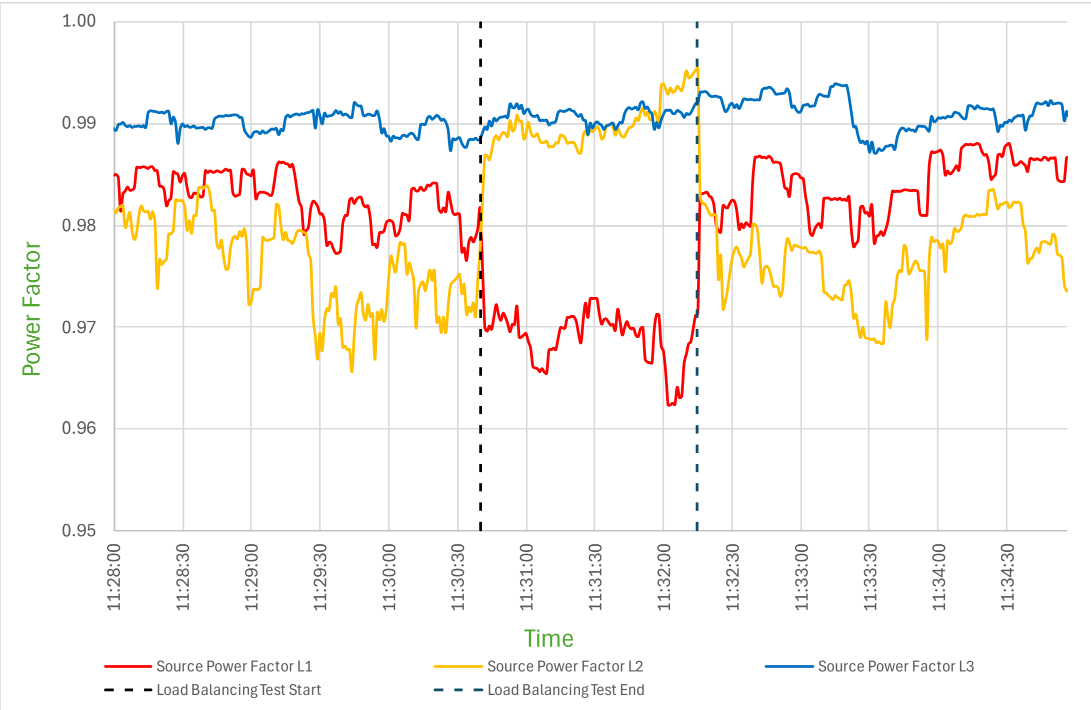

Figure 30 - Power factor on the UPFC source side during the imbalanced load test performed on 12 August

Phase	Before the Load Balancing Test			During the Load Balancing Test		
	Average Current [A]	Difference from the Average 3-Phase Current [%]	Average Power Factor	Average Current [A]	Difference from the Average 3-Phase Current [%]	Average Power Factor
L1	235	3.73%	0.98	227	0.82%	0.97
L2	160	28.2%	0.97	209	6.79%	0.99
L3	280	24.5%	0.99	239	5.99%	0.99
N	110	--	--	9	--	--

Table 9 – Quantitative analysis for the imbalanced load test performed on 12 August

6.5 WH Smith DIY voltage control tests

Similar to the test carried out at Crescent Road from 22 July 2024 to 24 July 2024, a voltage control test was carried at WH Smith DIY substation on 25 June 2024. Voltage set points for the three phases along with the corresponding load voltages are shown in Figure 31.

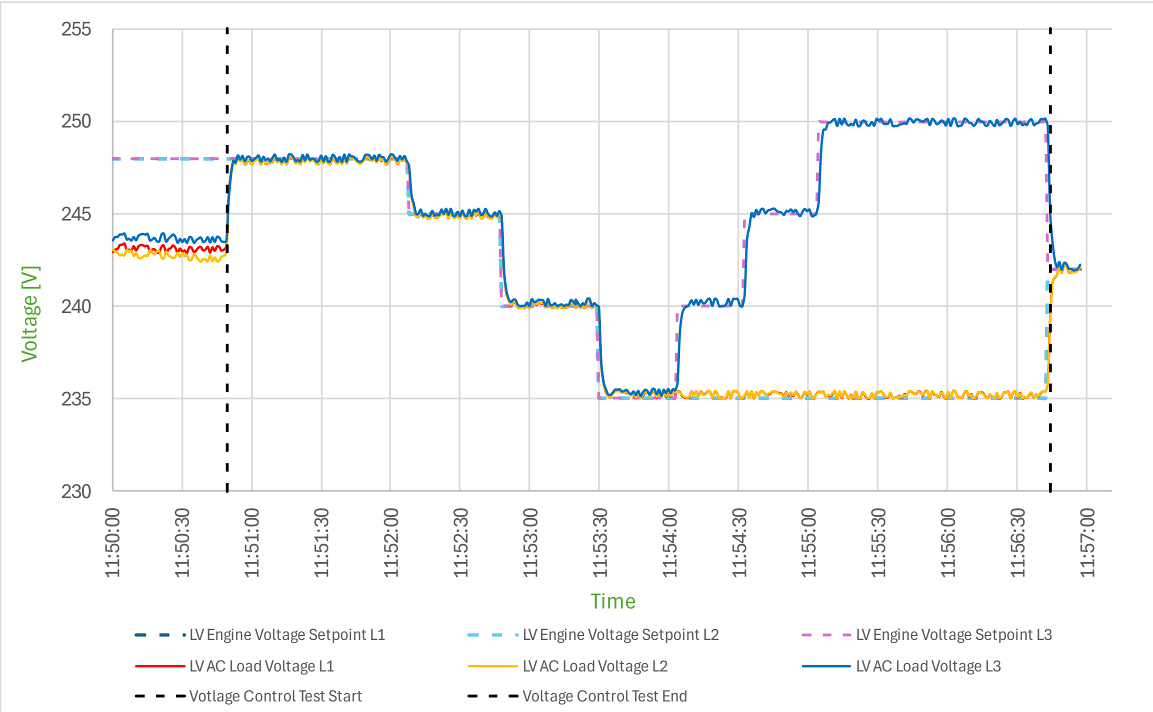

Figure 31 – WH Smith DIY voltage control tests

The graph in Figure 31 shows the voltage regulation conducted at WH Smith DIY substation. A quantitative analysis of this voltage control test is provided in Table 10. This presents analysis of the difference between the voltage set points and the output voltages for three phases (L1, L2, and L3). For each phase, two metrics are shown: the average difference, and the maximum difference, both expressed as percentages.

The average difference between voltage set points and output voltage varied from 0.010% (for L2) to 0.12% (for L3). Since the accuracy of voltage measurements is 0.5% and the average percentage difference is much less that this value, it can be concluded that the UPFC accurately regulates the load voltage according to the set points.

Table 10 - Analysis of voltage set points tracking test for LV Engine system at WH Smith DIY

Phase	Average Difference Between Setpoint and Load Voltage [%]	Maximum Difference Between Setpoint and Load Voltage [%]
L1	0.11%	2.56%
L2	0.10%	2.58%
L3	0.12%	3.18%

6.6 Conservation Voltage Reduction Test

Conservation Voltage Reduction (CVR) is a technique used to lower the voltage supplied to loads in order to reduce energy consumption while maintaining acceptable voltage levels for end-use equipment. The UPFC can deliver this service by allowing voltage control at the substation. By dynamically adjusting the voltage set points, the UPFC can reduce or increase the voltage supplied to the load.

The CVR test was performed between 06:45 and 08:30 on 11 October. The active power and reactive power along with the LV load voltage during the test are shown in Figure 32 and Figure 33 respectively. The test was performed by switching the voltage setpoints between 240 and 250 several times during the test and measuring any change in power both before and after an increase or decrease in voltage.

A scatter plot showing relationship between change in active power and change in voltage in shown in Figure 34, and the same for reactive power is shown in Figure 35. Each point on the scatter plot corresponds to the point in time when the voltage changes. The plot shows a consistent directly proportional relationship between the change in power and change in voltage. In other words, a rise in voltage results in an increase in power consumption and a fall in voltage results in a decrease in power consumption. The CVR factor which is defined as ratio of percentage change in active power to percentage change in voltage was found to have an average value of 1.06.

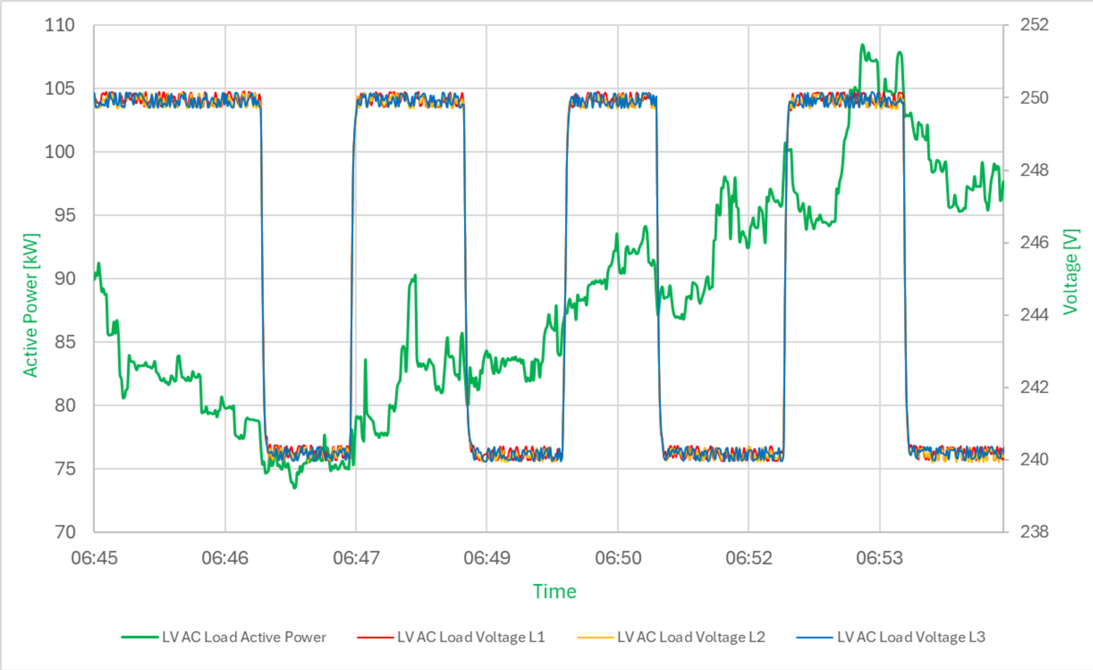

Figure 32 – LV AC load voltage and active power during the CVR test on 11 October

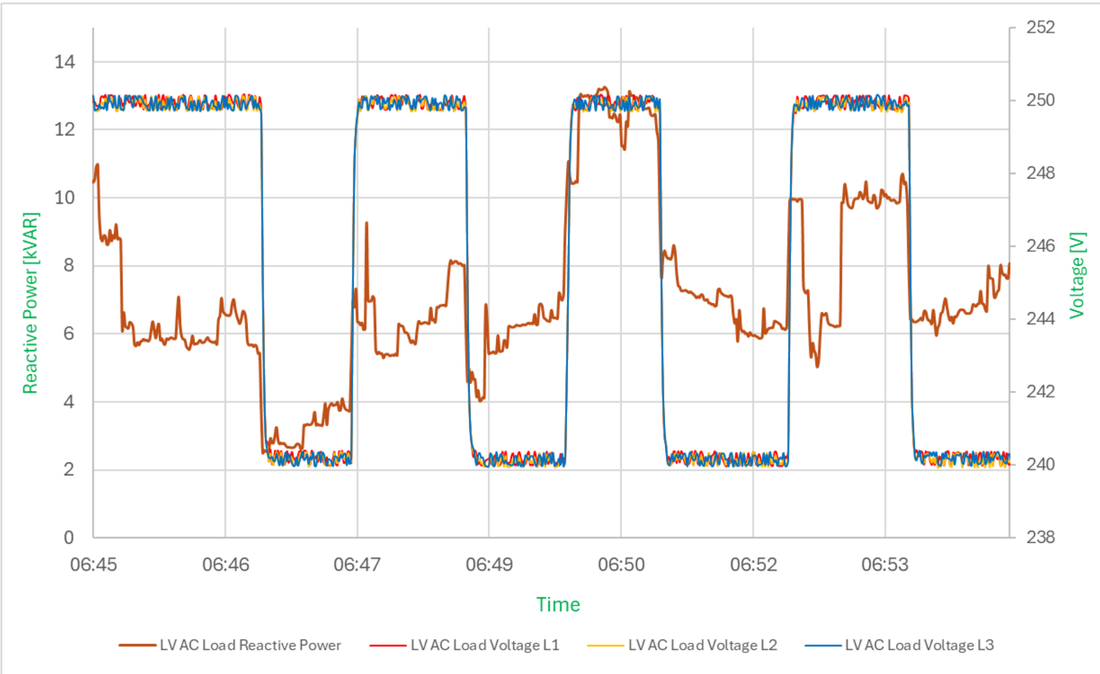

Figure 33 – LV AC load voltage and reactive power during the CVR test on 11 October

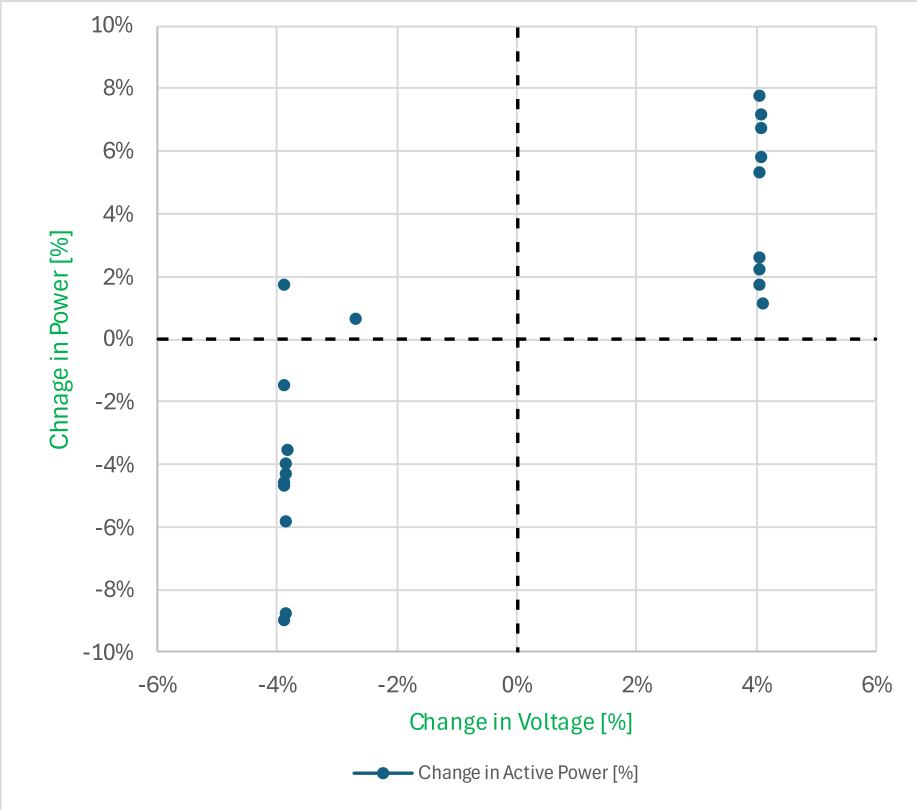

Figure 34 – Relationship between change in active power and change in voltage

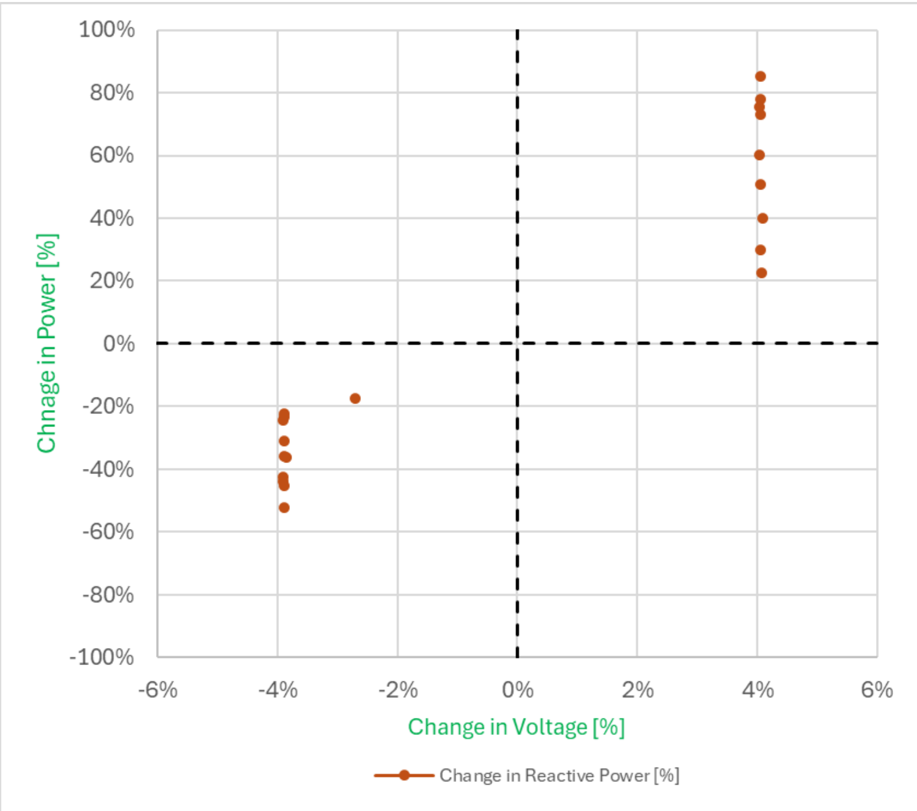

Figure 35 – Relationship between change in reactive power and change in voltage

6.7 UPFC Losses

Losses in the UPFC can be assessed by measuring the difference between the active power measured on the source side and active power measured on the load side. Losses in the UPFC are attributed to switching and conduction losses in the UPFC's power electronics and losses due to control circuitry and auxiliary components. From this, the efficiency of the UPFC can be assessed.

The UPFC AC Load active power and UPFC losses at Crescent Road between 5 August 2024 and 12 August 2024 are shown in Figure 36. The comparison between these two quantities show a clear correlation between the load active power and the losses within the LV Engine system as expected i.e. the losses increase as the load active power increases.

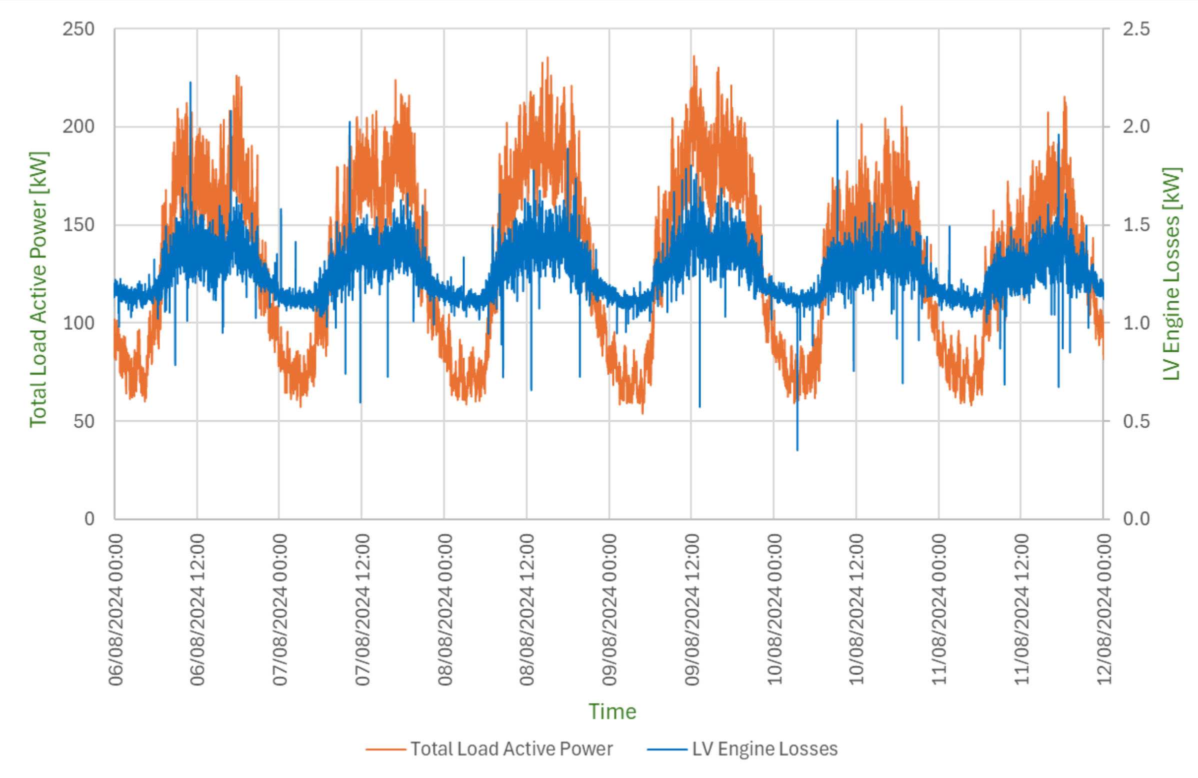

Figure 36 Total load active power and UPFC losses at Crescent Road from 05/08/2024 to 12/08/2024

To further investigate the efficiency of the UPFC as a function of the load active power, a graph of load active power, and UPFC losses as percentage of the load active power is shown in Figure 37. The percentage losses within the UPFC were found to have an average value of 1.1%, varying from a minimum value of 0.1% to a maximum value of 2.0%. Moreover, the percentage losses have an inverse relationship to the load active power, leading to the conclusion that the UPFC is most efficient when operated at its full capacity. This behaviour is due to the overheads resulting from the control circuitry and auxiliary components whose power consumption is not proportional to the output power.

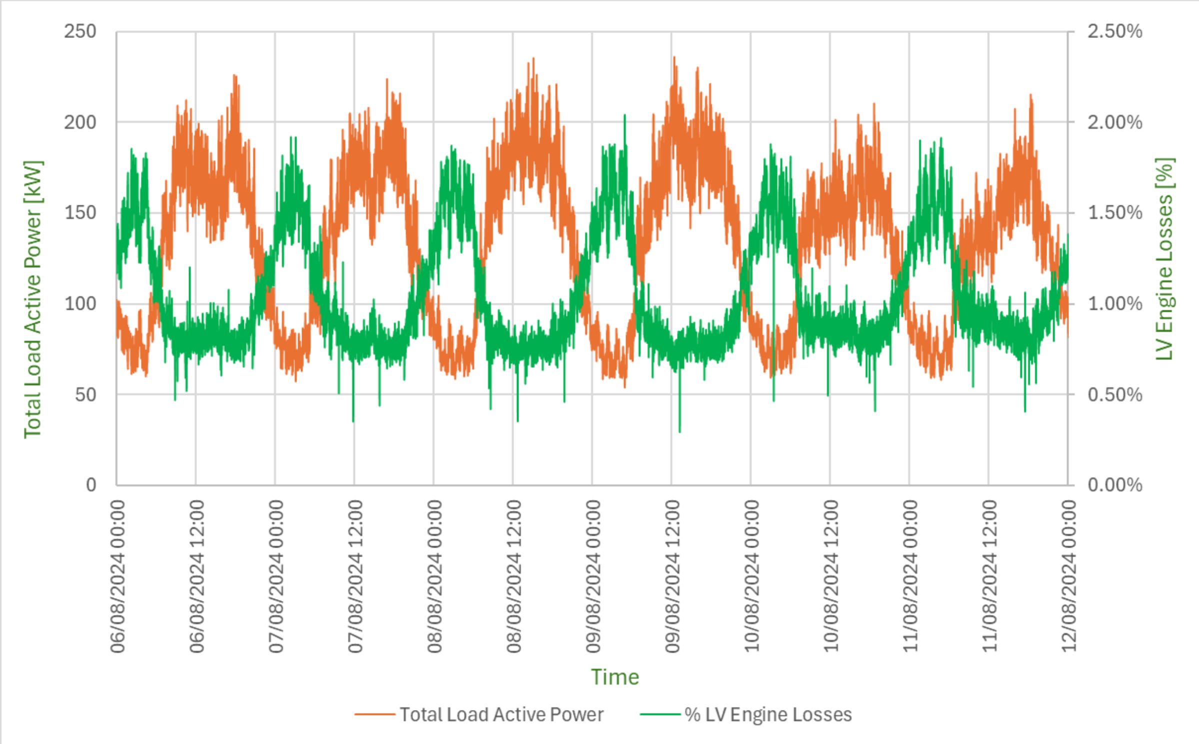

Figure 37 Total load active power and percentage UPFC losses at Crescent Road from 05/08/2024 to 12/08/2024

To further study the losses within UPFC, an analysis of losses was carried out while the UPFC was in bypass mode. This analysis has been carried out over the period spanning 8 June 2024 to 12 June 2024. A graph showing voltage setpoints and the LV load voltages for all three phases during this period in shown in Figure 40. It can be seen that the LV Engine is not regulating the load voltage to the setpoints confirming that the UPFC is in bypass mode.

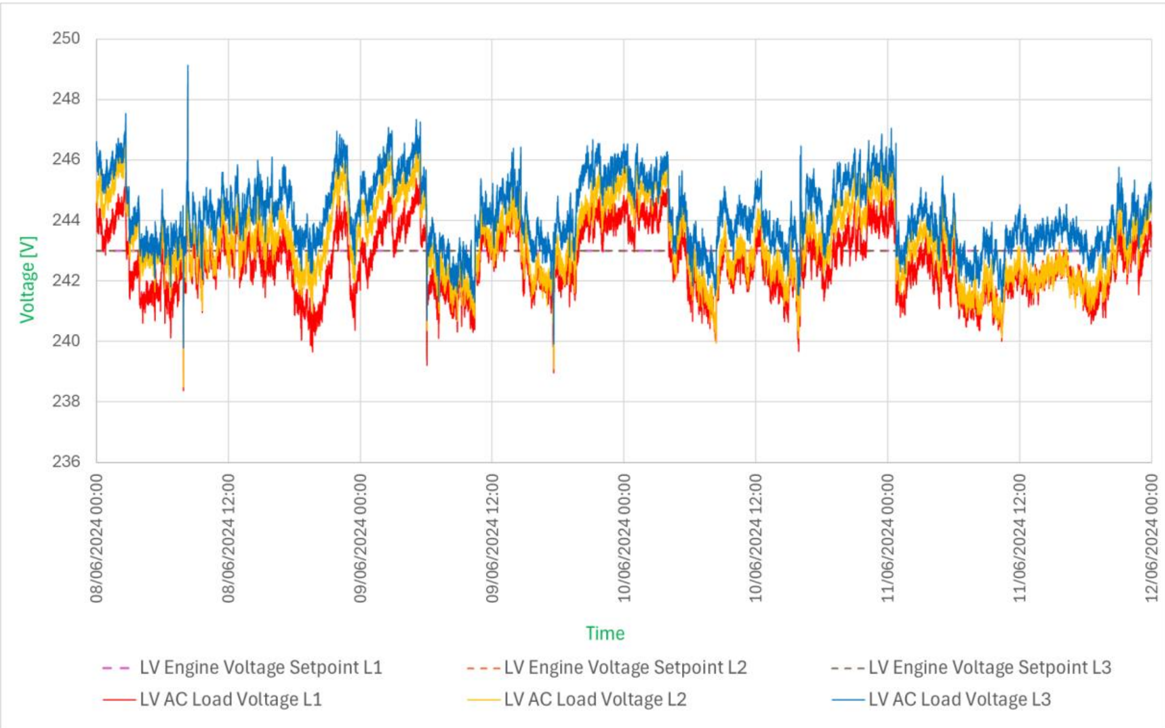

Figure 38 – LV Engine voltage setpoints and LV AC Voltages when the UPFC is in bypass mode

The total load active power at Crescent Road and the UPFC losses during this period are shown in Figure 39. Average losses during this period were found to be 120 W which can be attributed to control circuitry and auxiliary components within the system.

Figure 39 shows some correlation between the load power and UPFC losses as the losses appear to decrease and increase with the load profile, but this correlation is not as strong as the case when the UPFC is in active mode (Figure 36). Since the UPFC is not performing any control functions during the period, this variation in losses can be attributed to powering the UPFC auxiliary systems.

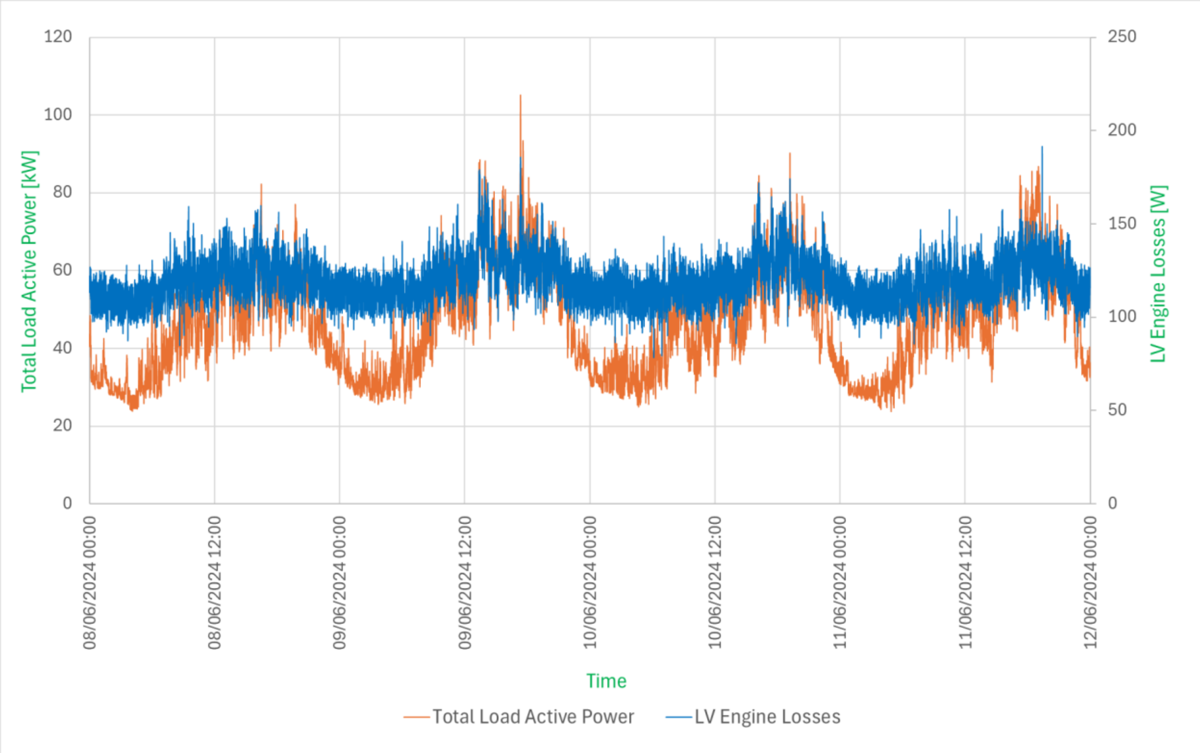

Figure 39 - Total load active power and LV Engine losses at Crescent Road while the LV Engine System is bypassed

7 Falkirk Trial

The Falkirk site trials the performance of one LV Engine substation providing an LV DC supply to a single EV Charger, Figure 40. The LV DC cable from the substation to the EV Charger and the EV charger itself are owned by the customer.

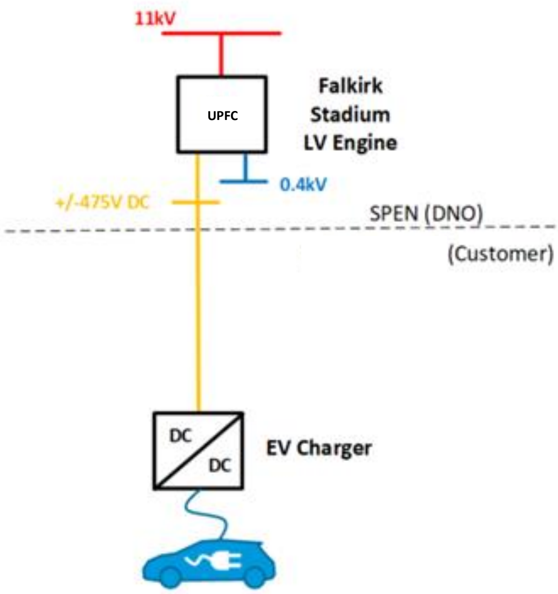

Figure 40 – Falkirk Stadium LV Engine network

The make-up of the SST substation at Falkirk Stadium is shown in Figure 41. It is similar to the LV Engine substations in Wrexham but with the following differences:

- The UPFC LV DC Load terminal is connected to an LV DC switchboard.
- The LV AC switchboard only supplies power to substation auxiliaries (lighting, protection, telecoms). There is no customer connected to AC switchboard. However, a new AC connection is being connected to the substation at the time of writing this report.

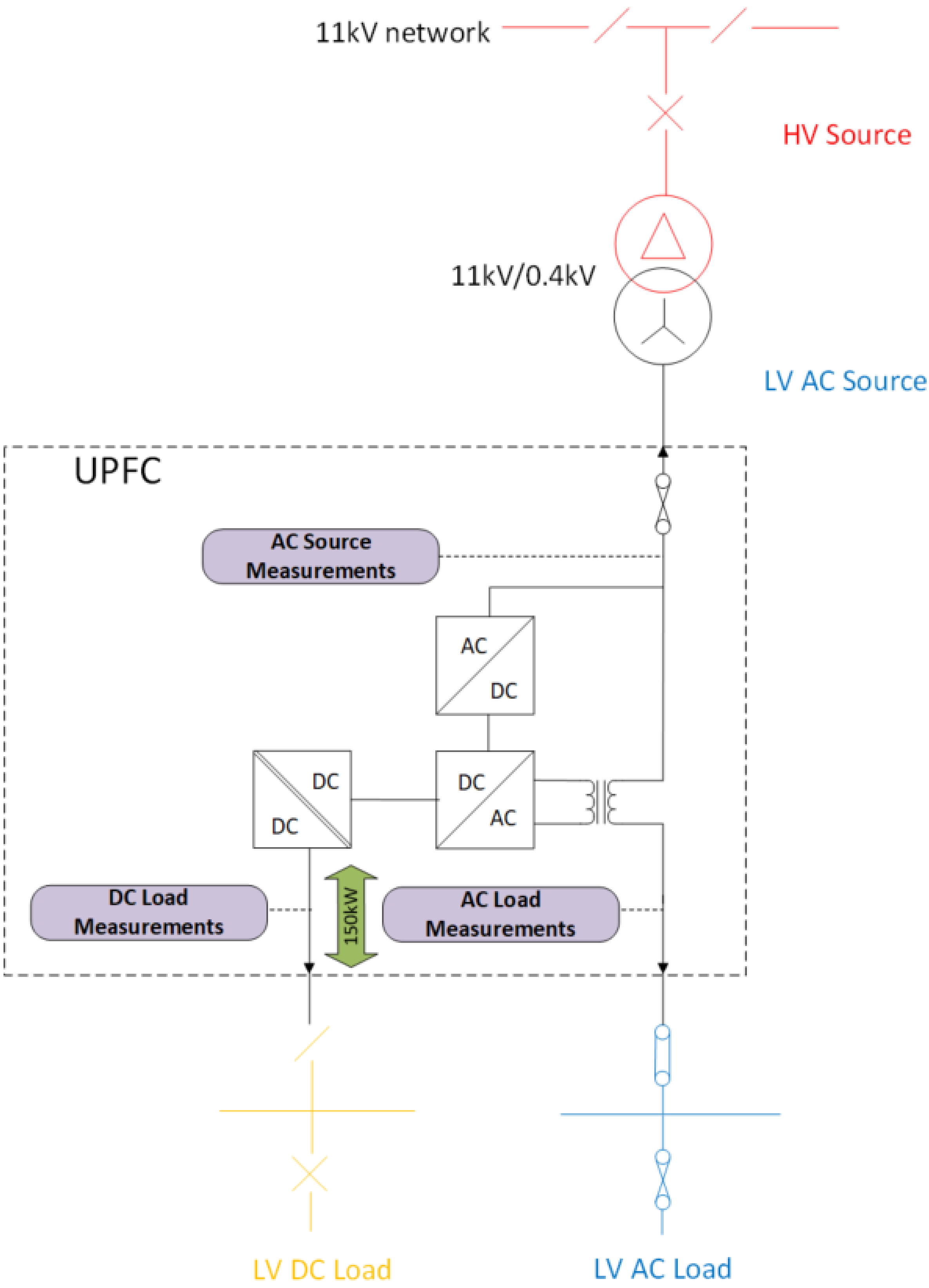

Figure 41 – LV Engine substation at Falkirk trial site

8 Performance Analysis – Falkirk

To assess the performance of the system, the UPFC LV DC Load power is compared to the UPFC LV AC Source power allowing the efficiency of the conversion process to be determined. The LV AC Source voltage is also analysed, before and during charging to examine whether source voltages are affected during charging. Short duration tests were carried out on 6 August 2024, Figure 42.

When the UPFC is not supplying LV DC Load, it draws around 1.7 kW of power from the source which is due to the idle losses resulting from control circuitry and auxiliary components within the UPFC and the substation auxiliary load. When LV DC power is being supplied, the average efficiency of the LV Engine system was found to be 92.5%. A comparison between the source phase voltages and the DC power supply patterns shows no significant correlation between the two quantities, leading to the conclusion that the use of DC power supply function within the LV Engine has no adverse effect over the source network.

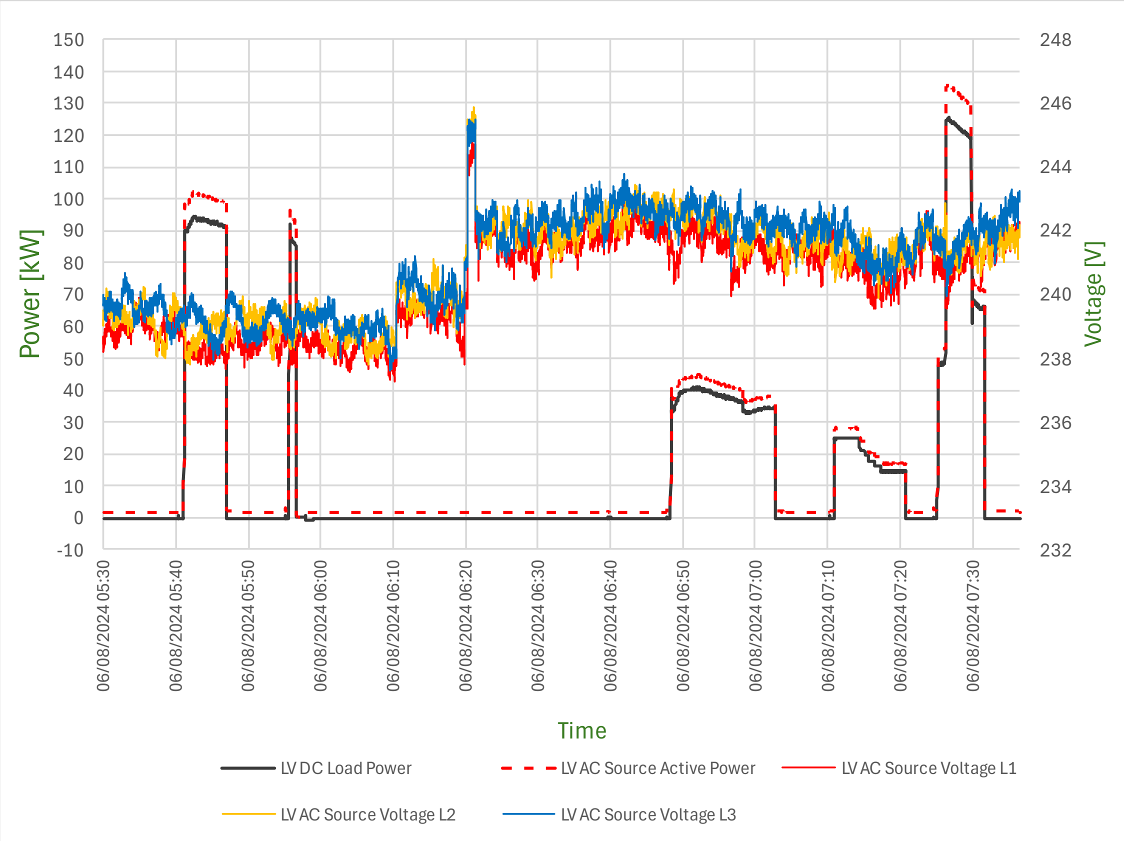

Figure 42 Performance of the UPFC when providing DC for EV charging

A graph showing DC load power and the DC load voltage during EV charging is shown in Figure 43. The graph shows that the voltage at positive and negative poles of the DC supply is very closely regulated to it nominal values of +475V and -475V.

Figure 43 reveals that in the event of a step change in DC load (due to the connection/disconnection of an EV charging load), the voltage at the terminals undergoes oscillations with maximum peak-to-peak amplitude of 6V which is 1.26% of the nominal voltage of 475V. It can also be observed that when the DC load rises to 120kW, the voltage on negative pole undergoes a rise of approximately 10V which is 2.1% of the nominal voltage of 475V. This is the result of droop functions set in the DC/DC converter.

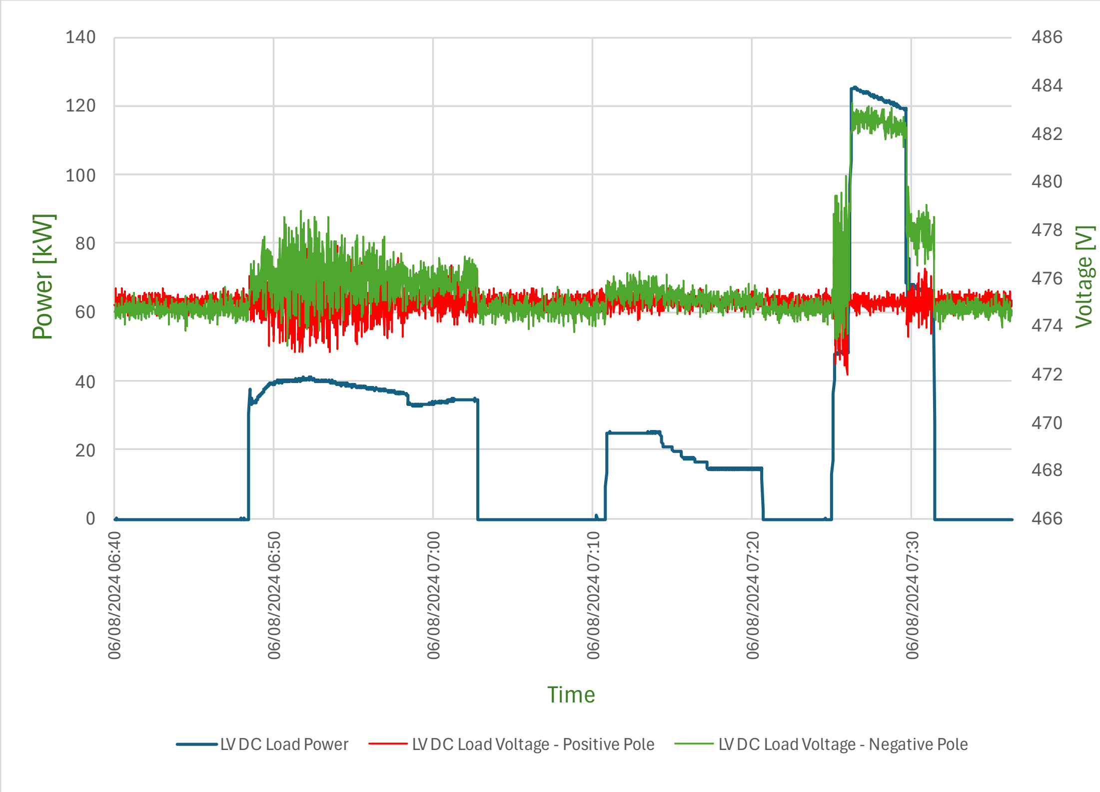

Figure 43 - LV DC voltage supply and LV DC power output at the UPFC during EV charging

To further analyse the performance of the LV Engine system installed at Falkirk, EV charging was also performed from 25/09/2024 to 03/10/2024. EV charging power profile along with the AC source voltage on all three phases is shown in Figure 44. EV charging power profile along with the DC load voltage on positive and negative poles is shown in Figure 45. Similar to the discussion provided above with reference to Figure 43, when the DC output power reaches its rated value of 150 kW, the voltage on the negative pole undergoes an increase of approximately 10V.

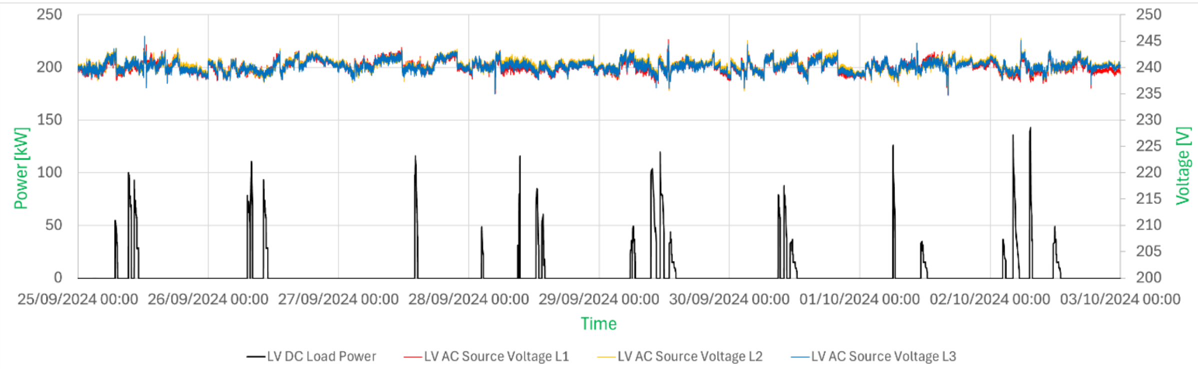

Figure 44 - EV Charging power profile and the AC Source Voltage profile from 25 Sep to 3 Oct 2024

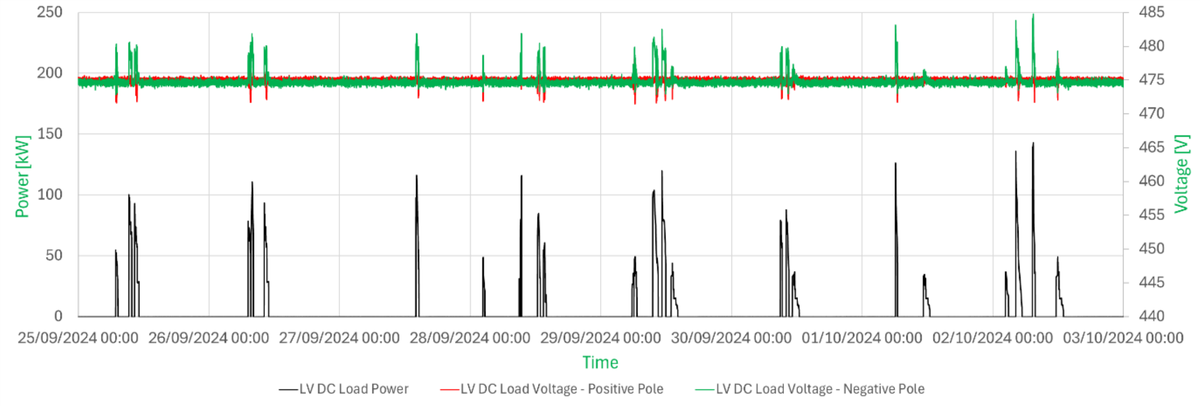

Figure 45 - EV Charging profile and the DC Load Voltage profile from 25 Sep to 3 Oct 2024

9 DIgSILENT PowerFactory model for the SST

The LV Engine solution using UPFC is designed to perform two key functions: first, it balances an unbalanced three-phase load by making it appear as a balanced load on the source side, and second, it allows for the setting of individual voltage set points for each of the three phases at the output. Building on learnings gathered from performance monitoring, a simulation model has been developed in DIgSILENT PowerFactory specifically for load flow studies. This model enables detailed analysis of the system's ability to balance load distribution and control voltage levels independently across all three phases. Through these load flow simulations, the effectiveness of the UPFC in improving power quality and maintaining grid stability can be thoroughly evaluated under various operational scenarios.

The PowerFactory model for the UFC is shown in Figure 46. Although the UFC was designed based on Topology 2 (Section 4.3), the PowerFactory model has been constructed similar to Topology 1. Constructing the model like Topology 2 would require modelling of internal control system within the UPFC and then the model would only be applicable to dynamic simulations in DIgSILENT PowerFactory. Because the main purpose of the model is to run steady-state simulations such as load flow and short-circuit studies within the SPEN network incorporating the LV Engine system, this modelling approach was chosen.

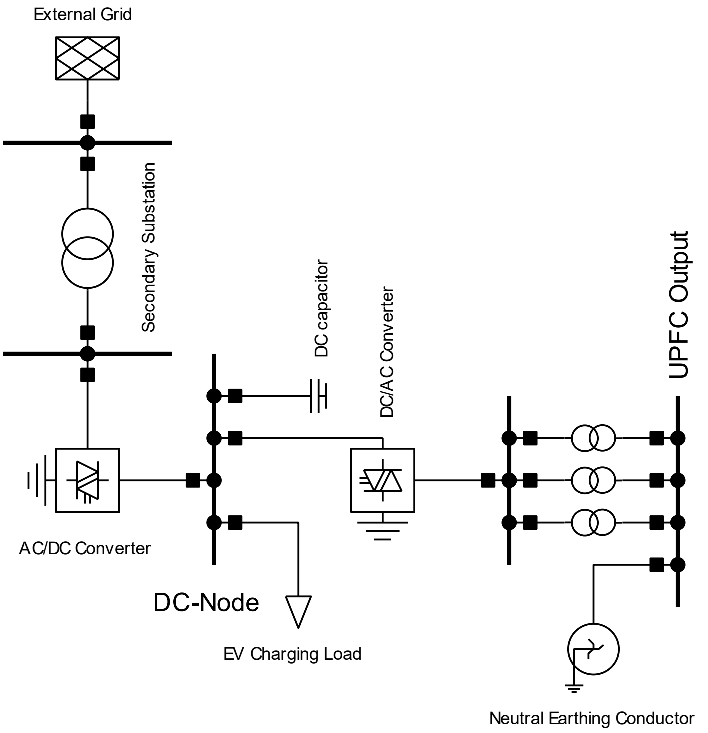

Figure 46 – UPFC (equivalent) model in DIgSILENT PowerFactory for steady state studies

The model shown in Figure 46 consists of an AC/DC and a DC/AC converter connected through a DC link. This DC-link serves two purposes – 1) it makes unbalanced load appear as a balanced load to the secondary substation transformer and 2) It allows for DC EV charging load to be connected to the DC node. Between the DC/AC converter and the UPFC output, there are three ideal single-phase transformers with zero impedance. These transformers are equipped with automatic tap changing functionality and they regulate each phase voltage according to the setpoints at the UPFC output. A neutral earthing conductor with zero impedance is connected to the UPFC output busbar to connect the neutral terminal to ground. This is an important part of the model and without this, any phase-to-earth loads connected downstream would cause errors in simulation.

9.1 Simulation Results

The PowerFactory model for the UPFC was incorporated into the Crescent Road substation and its corresponding LV network. The loads in the network model were modelled with known daily consumption profiles at those nodes. The current on each phase at the UPFC output is shown in Figure 47. The load profiles show that the load distribution across the three phases is unbalanced. The current in each phase on the LV side of the secondary substation transformer during the same period is shown in Figure 48. The load profile in this case shows exactly the same magnitude of current across the three phases. This shows that the load balancing function of the SST can be incorporated into steady state simulations by using this UPFC model.

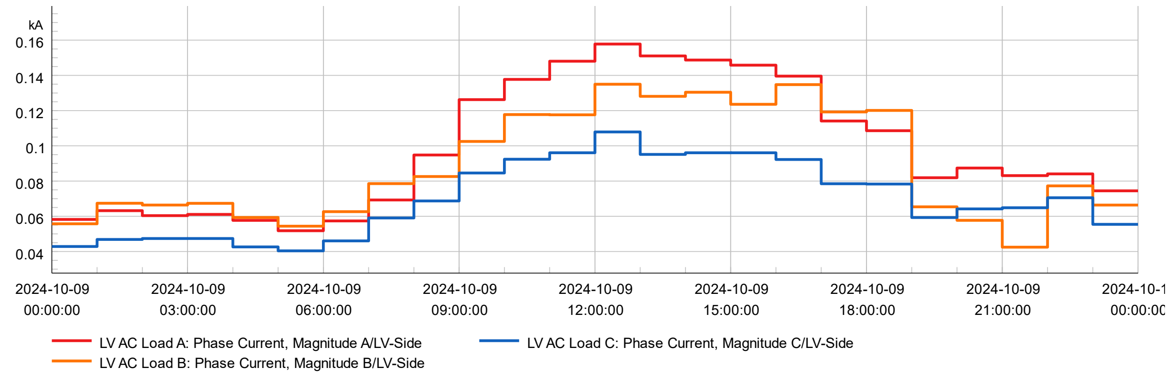

Figure 47 – Current magnitude for each phase at the output of the UPFC

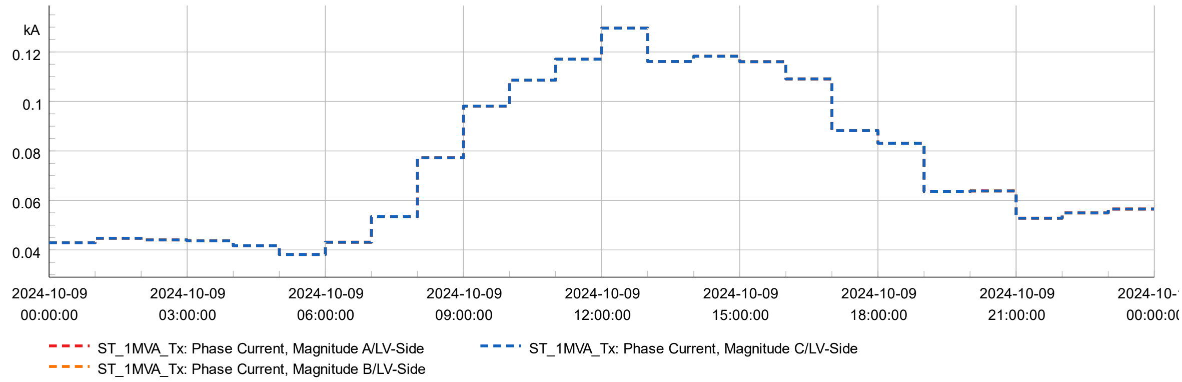

Figure 48 - Current magnitude for each phase on the LV side of the secondary substation transformer

Voltage control function of the UPFC can also be performed using this UPFC model. The simulation test for this function was run by providing different voltage setpoints to each phase over a specific period. The test schedule is shown in

Table 11. The voltage profiles for phases A, B and C over the period of this test are shown in Figure 49, Figure 50, and Figure 51 respectively. The dashed black lines in all the graphs show the voltage at UPFC output and all the other lines show the votlage at endpoints of the feeders downstream of Crescent Road substation. An SLD for the Crescent Road substation and the feeders downstream with end points of the feeders marked is shown in Figure 52.

The results show that when voltage at the UPFC output changes according to the schedule shown in

Table 11, the voltage at the endpoints of the feeders also changes proportionally. This shows that the voltage control function of the SST can be incorporated into steady state simulations by using this UPFC model.

Table 11 – Test procedure for voltage control function in PowerFactory model

Phase	Voltage Setpoint	Start Time	End Time
Phase A	1.03	12:00	13:00
Phase B	0.98	12:00	13:00
Phase C	1.03	14:00	15:00

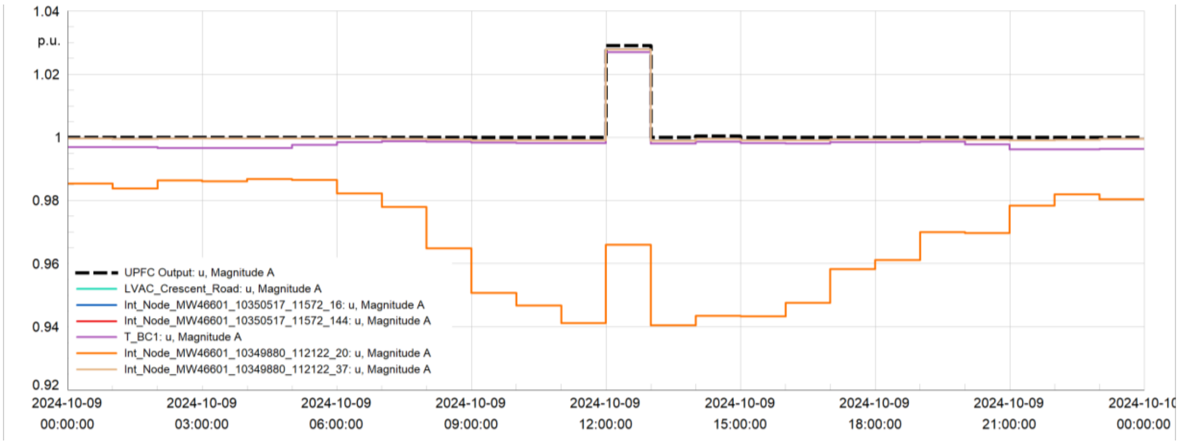

Figure 49 – Voltage profile for phase A at UPFC output and endpoints of the feeders

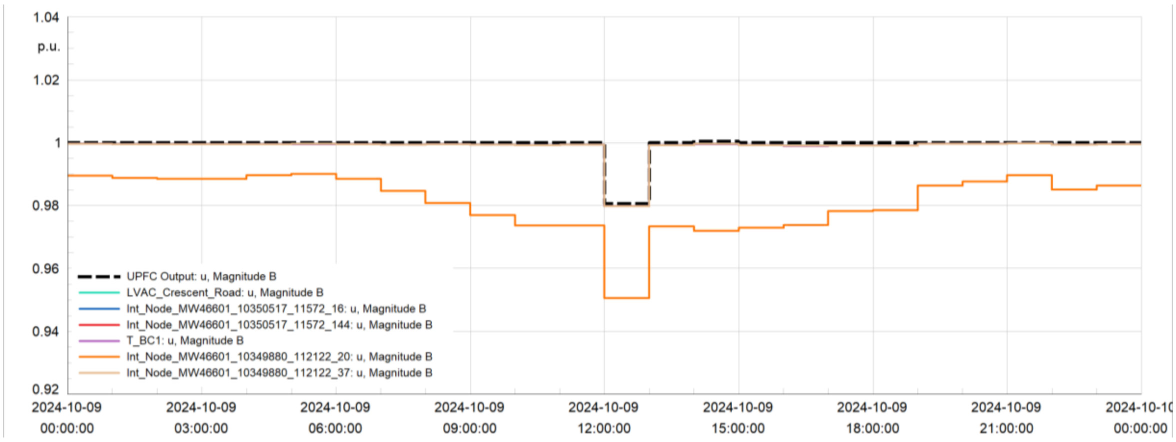

Figure 50 – Voltage profile for phase B at UPFC output and endpoints of the feeders

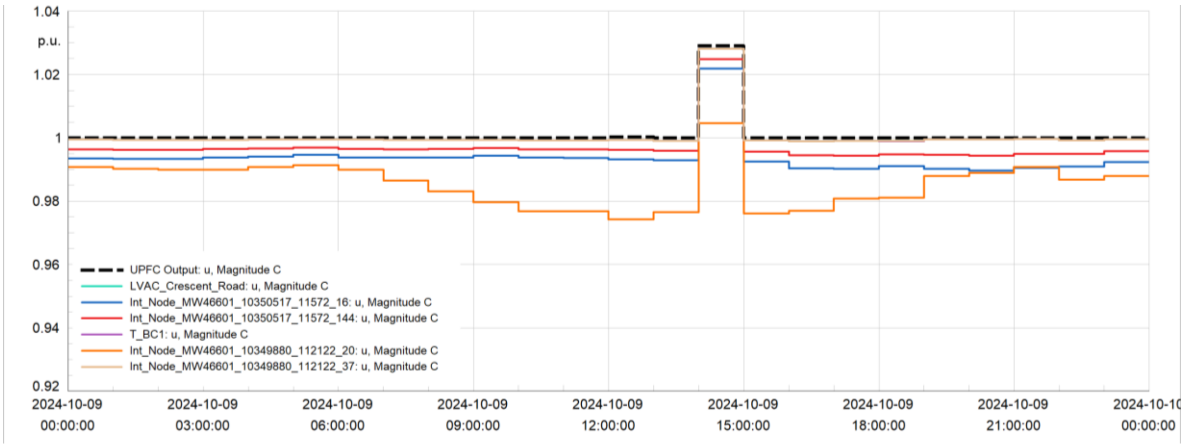

Figure 51 – Voltage profile for phase C at UPFC output and endpoints of the feeders

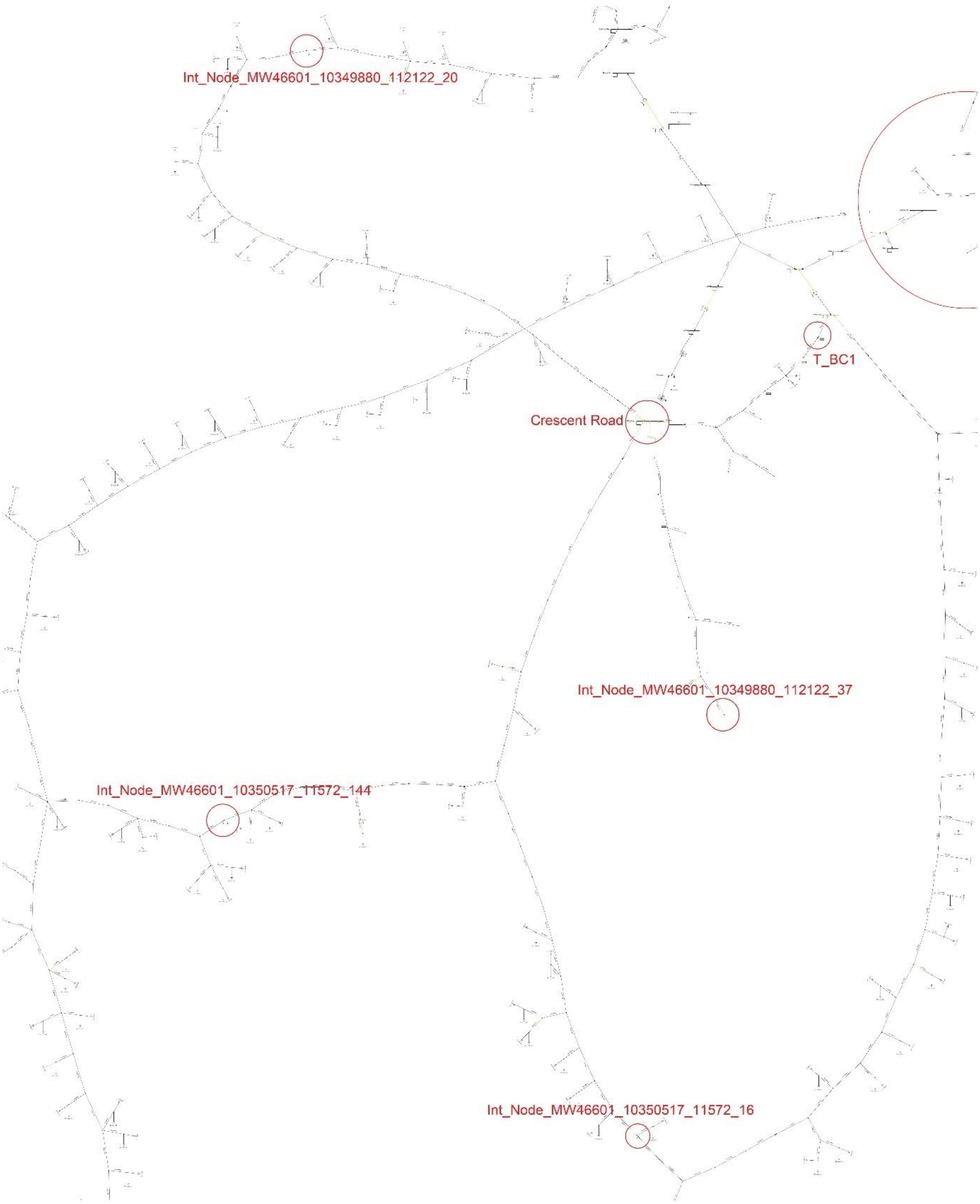

Figure 52 – SLD of the Crescent Road substation and the feeders being supplied by Crescent Road

10 Maintenance and Service Requirements of the UPFC

Maintenance of the UPFC is split into two categories: Scheduled and Preventative.

10.1 Scheduled

The following scheduled maintenance should occur at six month intervals:

1. Inspect and clean any dust and debris from all external air louver panels;
2. Inspect and clean any dust and debris from the rear mounted heat-sink fins.

The UPFC must be turned off and de-energised prior to performing these tasks (as described in section **Error! Reference source not found.**). Ali – De-energising would seem unnecessary for t his cleaning/dusting task. Is this the procedure being followed?

10.2 Preventative maintenance

Preventative maintenance must only be carried out with the UPFC turned off and de-energised. Preventative maintenance comprises:

1. Replacing the fuses if warranted by a recent overloading event. The location of these three fuses and the three spare fuses are shown in Figure 53.
2. Checking the AC Bypass option using the GERUI laptop application or the switch on the Service Panel.
3. Check that there is sufficient liquid coolant in the reservoir by observing the coolant level using the sight glass, Figure 54. The floating ball must be at the top of the sight glass, indicating proper fill level. The sight glass is visible through a hole in the rear access panel, Figure 55. The reservoir is a sealed system and does not require servicing to maintain the proper fluid level.

Figure 53 – Fuse panel with spares

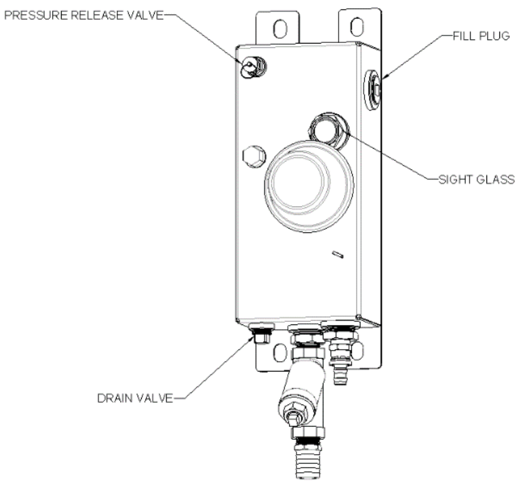

Figure 54 – Liquid coolant reservoir

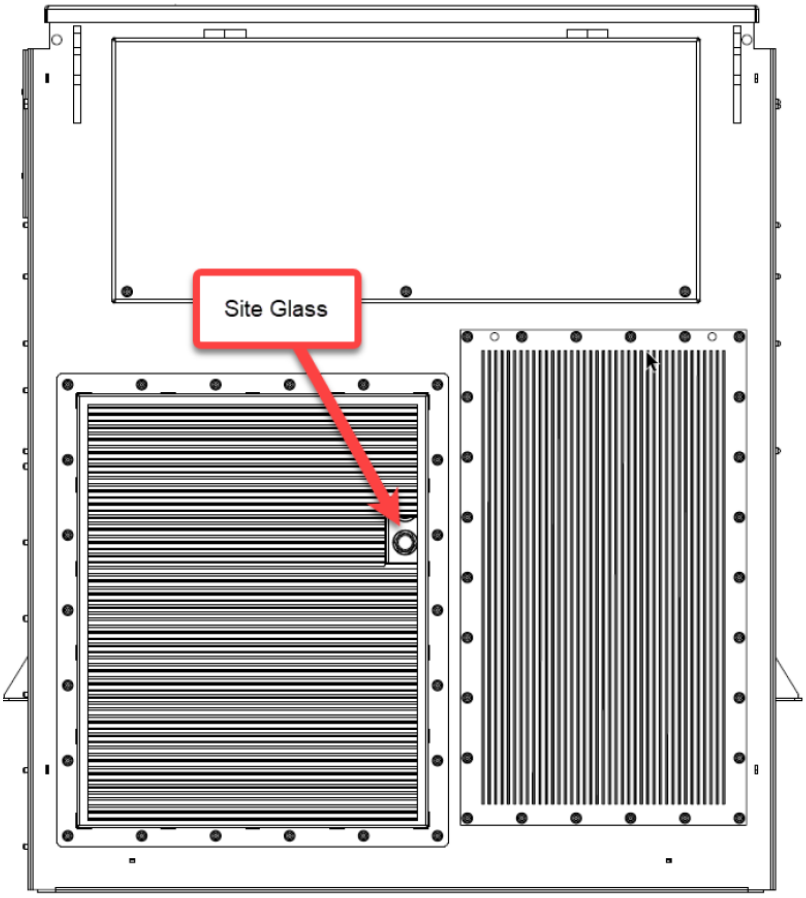

Figure 55 – Site glass location on rear of UPFC

10.3 Warnings requiring preventative maintenance

If a fault or alarm happens on a recurring basis, it is generally an indicator that something is wrong in the system; faults and alarms should not occur regularly.

The following conditions (both AC and DC) are typically revealed as faults or alarms:

- Undervoltage;
- Overcurrent;
- Over temperature.

If one of these faults recurs, then a technician needs to be sent to site for inspection and troubleshooting. Whilst awaiting service the UPFC should be set to AC Bypass mode.

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