LV ENGINE

Equipment Manufacturing – Deliverable #3

About Report		
Report Title	:	LV Engine Deliverable #3 - Equipment Manufacturing
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Report Summary & Disclaimer

This report details the activities carried out for the manufacturing, installation and commissioning the LV Engine solution that forms Deliverable 3 of the LV Engine project in line with LV Engine project direction.

The LV Engine project is 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 based 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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Contents

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 electronics technology to significantly enhance the functions delivered at a secondary substation. LV Engine provides 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 tested as part of LV Engine development. This report contains learnings and information about the key devices designed and manufactured for the LV Engine solution demonstration.

This report intends to satisfy LV Engine deliverable #3: "the equipment for LV Engine has now been manufactured, factory tested, delivered, and commissioned on site".

2 LV Engine Overview

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

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

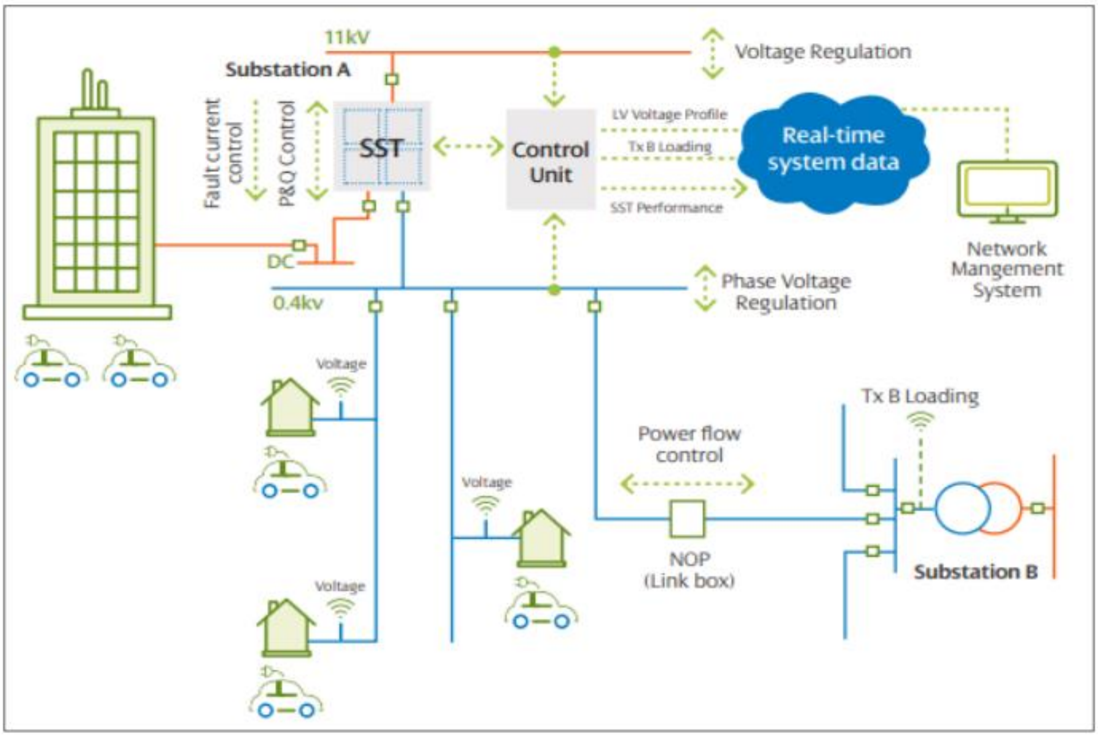


Figure 1 LV Engine project concept

3 LV Engine Power Electronics Products

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.

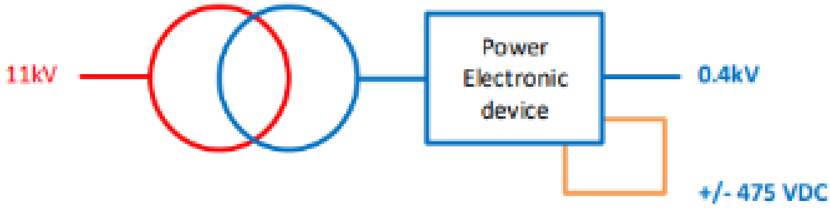


Figure 2 SST Topology 1

- 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.

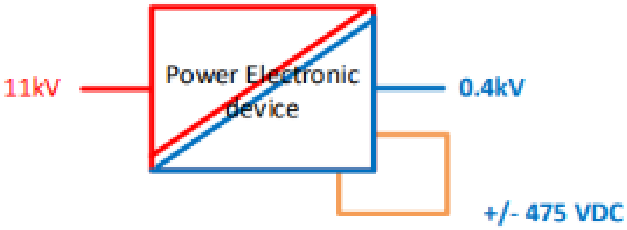


Figure 3 SST Topology 2

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 LV Engine key equipment

There are three key pieces of equipment that were designed, manufactured, and tested in the LV Engine project:

1. Solid State Transformer (SST) Topology 1 / Unified Power Flow Controller (UPFC)
2. LV DC Switchboard
3. Display panel and telecoms cabinet

1- **SST Topology 1/Unified Power Flow Controller (UPFC)** – SST Topology 1, also known as the UPFC, was designed and manufactured in collaboration with ERMCO as part of LV Engine project (see Figure 4). The UPFC comprises a 250 kVA AC/DC converter connected through a DC-link to an 80 kVA DC/AC converter (**Error! Reference source not found.**). 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 voltage through the phases to adjust the parameters such as voltage, power factor, and reactive power. A key feature of this design is that 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 vehicle charging.

2- **LVDC switchboard** – Designed and manufactured in collaboration with Schneider Electric, the LVDC 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 carried out at the Power Networks Demonstration Centre (PNDC). See Figure 6 for the general arrangement of the LV Switchboard.

3- **Local Control System (LCS)** - This is an alarm display panel and telecoms cabinet, designed specifically for LV Engine. The aim of this alarm panel is to provide an overview about the status of the various devices in the substation. The router, communicating the monitored data, was installed in this cabinet.

Figure 4 – The Unified Power Flow Controller (UPFC) – the power electronic device used in Topology 1

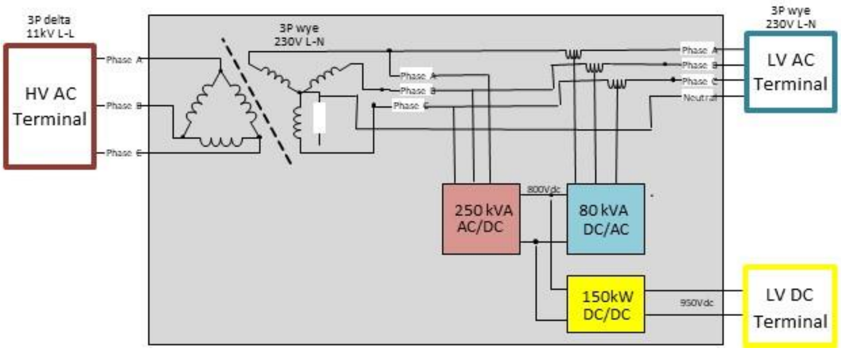


Figure 5 - SST Topology 1 , UPFC

Figure 6 – UPFC (left) and LVDC distribution board (middle), LCS (Right)

5 Equipment & Design for LV Engine

5.1 Process for design and manufacturing

The equipment deployed in LV Engine has undergone thorough design, manufacturing and testing process. For each equipment the following process was carried out collaboratively with the respective manufacturers:

- **Project inception** – Reviewing technical specifications, identifying the critical technical requirements, understanding the relevant policies and standards requirements and developing initial high-level solutions.

- **Initial Design** – Identifying the trade-offs in the design and optioneering, conducting limited desktop simulations (depending on the product), mechanical design and thermal management requirements.

- **Enhanced/critical design** – Developing components specifications, control and protection strategy development, terminations and network interfaces, detailed mechanical design, supply chain identifications and ordering components.

- **Prototyping** – Conducting benchtop and component testing, confirming mechanical design and thermal design validations, completing the firmware developments, and preparing the factory acceptance testing schedule.

- **Manufacturing** – Building and testing mechanical enclosure, system assembly and component fitting, factory testing, independent laboratory testing, completing operation and maintenance documentation.

One of the key challenges in this project was to ensure the equipment developed separately by different manufacturing partners works together in harmony to deliver against the LV Engine objectives. For this reason, the core SPEN project team had significant involvement in facilitating the design interface requirements between the different equipment.

5.2 LV Engine SST Topology 1 (UPFC) manufacturing

The UPFC designed for LV Engine was the first of its kind globally, to the best of our knowledge, to be manufactured and tested. Similar to other innovation projects, while we endeavoured to cover all the functional and technical requirements in the design and benchtop testing stages, there was always risks of failure during the factory testing of this product.

In order to i) reduce any risk of programme delay as the results of factory testing failure ii) build further confidence in the blueprints for unit assembly, and iii) have the opportunity for parallel testing, ERMCO proposed to build four initial engineering units which were similar, if not the same, to the final products but these engineering units would be used only for testing at the factory and independent test centres. The summary of manufacturing steps to reach the final product is as follows:

Step 1 – Building and testing E1, E2, E3 and E4 engineering units. These units went through various tests including (but not limited to) dielectric test, thermal test, normal operation and functional tests, impulse test, and maximum short circuit test. During these tests, three key issues were identified that resulted in upgrading the engineering units and repeating the factory tests:

1- Bypass system – The solid-state relay (SSR), designed to bypass the device in fault/overloading conditions, did not fulfil the initial factory tests. Consequently, ERMCO team redesigned, built the new SSR and tested in various stages. The second prototype also did not pass the tests due to higher speed of data processing and sampling required to detect the overload conditions activating SSR. However, the third attempt for the design was successful and final build was established.

2- Thermal issue – The operation of UPFC under full load resulted in an uncontrolled temperature rise in the isolation transformer in the DC/DC converter. Therefore, a new engagement with the DC/DC transformer supplier started in parallel with new market research for transformers. Eventually, a new design for transformer with extra cooling pipes was agreed with the original supplier. After a number of tests on new design, ERMCO confirmed that the new design and equipment met the target thermal rating.

3- DC-link failure – During various factory tests, DC capacitors forming the internal DC-link failed. The diagnosis was that the presence of excessive DC ripples resulted in extra thermal stress on the capacitor and consequently failure. A new type of capacitor with improved specifications was identified and purchased. The capacitors have a cubical shape whereas the original capacitors were cylinder shape.

Step 2 – Building the first field unit (S1) – The learning from tests on the four engineering units provided adequate confidence to build the first fully operational UPFC which can be potentially deployed in the field and shipped to the UK. In line with the project programme, SP Energy Networks, in collaboration with the PNDC team, carried out integration testing on S1. In this test, S1 was tested in normal operating and fault conditions extensively. The results of these tests have been published in LV Engine Deliverable #4 in details. We identified a number of control and firmware issues during S1 testing and how this unit should work with the existing LV networks protection arrangement.

Step 3 – Building the second field unit (S2) – Following the learning gathered from tests on S1, ERMCO built an improved unit (S2) and shipped to the UK. SP Energy Networks and the PNDC team repeated the integration tests on S2 to confirm all issues have been addressed and the unit is ready for network deployment. After S2 successfully passed all the tests, S2 was transported to a newly built and designed substation in Scotland. S2 was successfully commissioned in November 2023 and is still operational at the time of writing this report.

Step 4 – Building the third and fourth field units (S3 and S4) – Successful commissioning of S2 gave the team confidence to manufacture further units for deploying in other trial sites, earmarked for the project, in Wales. S3 and S4 units were successfully commissioned in two separate substations in February and April 2024, respectively. S3 and S4 are still operational with no issue at the time of writing this report.

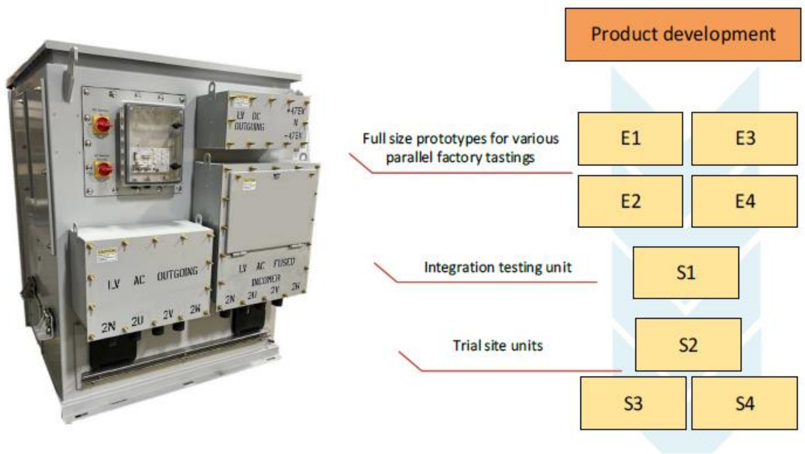


Figure 7 The process for developing final products that were deployed for live trial

5.2.1 UPFC key functional specifications

The key functional specifications of the UPFC design for LV Engine is shown in Table 1 and also reflected on the unit nameplate shown in Figure 8.

Table 1 SST Topology 1 , UPFC, key functional specifications

Function	Specification
Incoming AC voltage rating	400 V L-L +/-15%
Outgoing AC voltage rating	400 V L-L +10% -%6
DC voltage output	+/- 475V +/- 1%
Current rating	725A
Maximum current before going to bypass	980 A
Maximum imbalance current cancellation	%30 from average current
Maximum var compensation	75kvar per phase

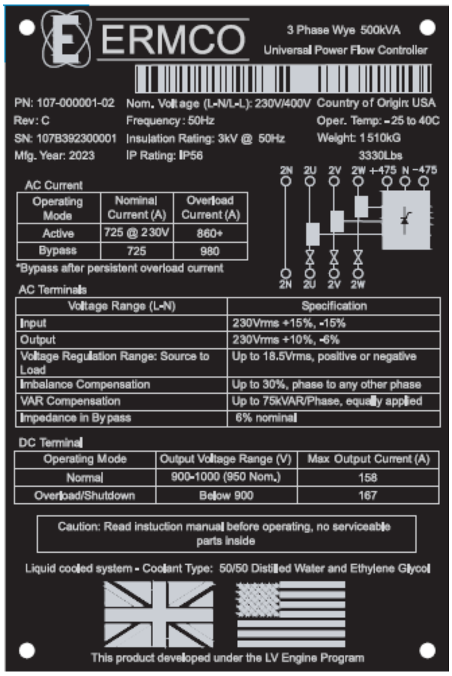


Figure 8 UPFC nameplate

5.2.2 Key factory tests

The following tests were successfully carried out and all tests passed at ERMCO's manufacturing facilities prior to shipment to the UK and SP Energy Networks sites:

Functional tests

These are extensive tests to confirm UPFC delivers the core services including voltage control, power factor correction, imbalance load cancellation and DC supply. These services were tested at different loading conditions (including at UPFC rating) and different environment conditions up to 40 ºC ambient temperature, see Figure 9.

Protection system tests

One of the key requirements for UPFC is to not compromise the existing LV network protection arrangement and also be able to protect itself in case of external or internal faults. The bypass system designed and manufactured for UPFC to protect/bypass the unit at the time of external fault was tested under short circuit scenarios. One of the key specifications that was tested was the thermal withstand capability of the bypass system in relation to upstream time link fuses at ring main unit and downstream LV way fuses (315A gg).

Short circuit withstand tests

Short circuit withstand for up to (~15kA rms) which is the same requirements for the 500kVA distribution transformer was tested at an KEMA independent laboratory, see Figure 9.

Lightning Surge Immunity Test

Lightning Surge Immunity Testing is a set of tests that are performed to qualify the power system's ability to withstand a voltage surge that models a lightning strike or switching surge. The testing is typically performed by applying a 1.2/50 usec voltage surge pulse of an operator's elected amplitude in positive and negative polarities with the expectation of no impact to the system under test.

High potential tests

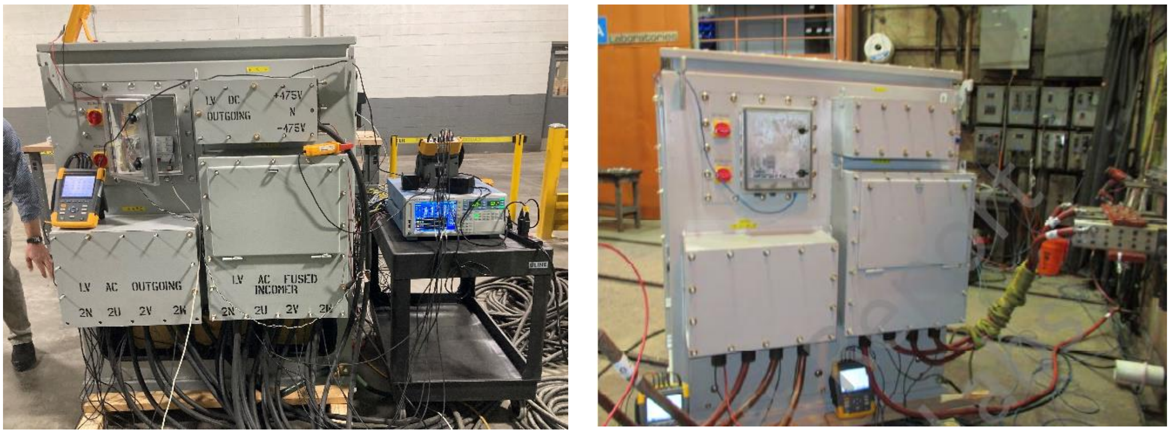
Dielectric tests for up to 3kV were successfully passed and confirm the adequacy of insulation design.

Harmonic Testing

The operational resilience was tested by confirming the UPFC normal operation and at regulation when connecting to a grid with 8% voltage total harmonic distortion (THD).

Graphic User Interface (GUI) tests

A GUI developed for UPFC during LV Engine project, see Figure 10. This GUI can be installed on a user laptop and allow users to connect via ethernet to the device locally to interrogate the UPFC internal databases and alarms. GUI was tested during all operation scenarios to confirm correct information communicated and available to the user.



(a) (b)

Figure 9 (a) SST Topology 1 prototype under various tests in Ermco-Gridbridge facility (b) SST Topology 1 under short circuit tests in KEMA facility

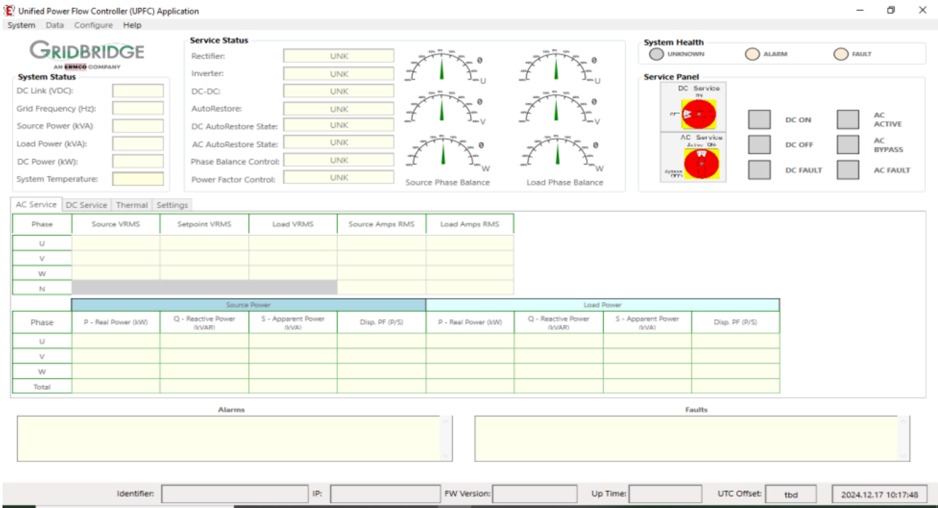


Figure 10 GUI designed for UPFC manufactured in LV Engine project.

5.2.3 UPFC operational and maintenance manual

One of the important documents developed and published was the Operation and Maintenance UPFC document which contains all the information for normal operation, safety requirements, commissioning, inspection, periodic maintenance, and working with GUI. General drawings with adequate explanation of each part of UPFC were also produced, see Figure 11 showing some of general arrangement drawings.

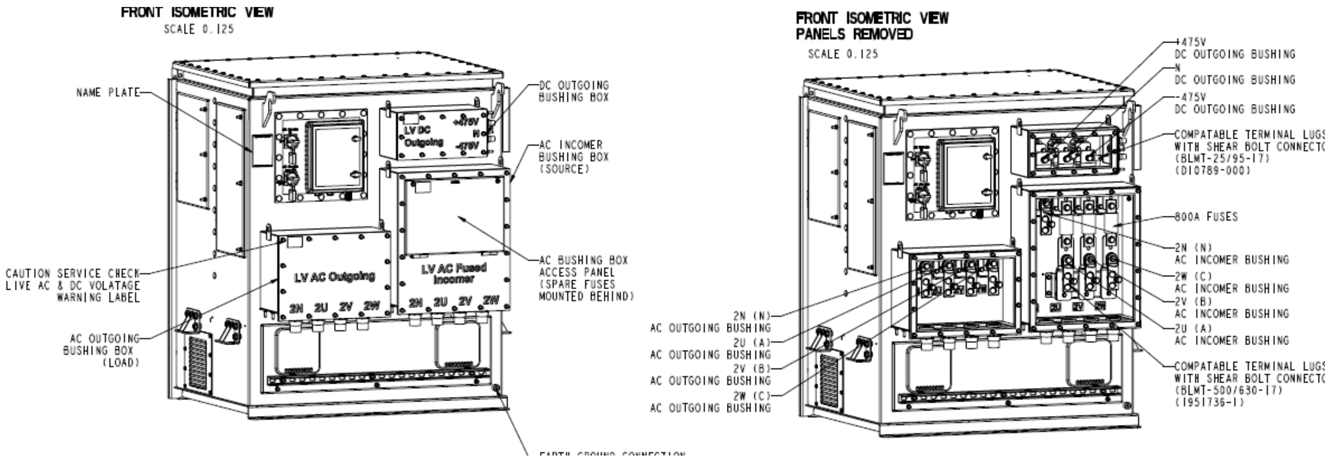


Figure 11 UPFC general arrangement drawings

5.3 LV Engine LV DC switchboard manufacturing

An LVDC switchboard designed and manufactured by LV Engine project for the first time in the UK. LV DC switchboard provides the following key functionalities:

- Point of isolation from customer's LV DC cable circuit which supplies one 150kW DC charger
- Point of isolation from UPFC
- Protection against faults on LV DC cable circuit or residual current by isolating/de-energising the customer

5.3.1 LV DC protection arrangement

Due to the use of power electronic based rectification, the UPFC DC output cannot provide sustained fault current in excess of its rating (158kW or 166A). Therefore, typical LV AC protection schemes based on overcurrent devices such as fuses or thermo-magnetic devices in moulded case circuit breakers (MCCBs) are not suitable for this application. However, the UPFC automatically switches off the DC supply if it experiences any current beyond its rating (see the appendix on UPFC DC fault management).

The customer's cable (EV charger) is connected to SPEN's LV DC switchboard where a DC MCCB provides point of isolation between customer's cable and LV DC switchboard. The LV DC switchboard supplies the customer's EV charger by a three-core cable which carries the supply positive (+475V), negative (-475V) and earth. The EV charger does not have a mid-point connection, although the DC system mid-point is solidly bonded to earth in the substation.

The MCCB is fitted with a shunt trip release that may be triggered by one of the following conditions (shown diagrammatically in Figure 12):

- Undervoltage on the positive pole, triggered by a control relay in case of loss of voltage i.e. DC supply switches off
- Undervoltage on the negative pole, triggered by a control relay in case of loss of voltage i.e. DC supply switches off
- Earth current leakage detection by a Residual Current Monitor (RCM), in case there is any current flowing between the DC mid-point and Earth.

- An inter-trip issued by the EV charger based on their internal protection logic e.g. someone opens the EV charger door.

Figure 12 shows the tripping arrangement within the DC charger.

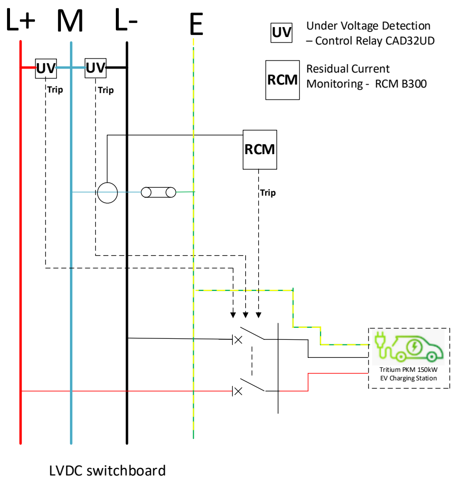


Figure 12 – LV DC Switchboard protection arrangement

5.3.2 Key factory tests carried out

The following tests were carried out and successfully passed at Schneider Electric factory in Scarborough, UK:

- General visual inspection – checking any damage, dimensions, general wiring arrangements, equipment positioning and overall built quality.
- Dielectric, insulation and impulse tests
- Temperature rise tests – operating at the maximum rating and confirming that temperature at different points of LV DC switchboard stabilises and does not rise further after a period (temperature became stable after 6 hours)
- Inter-trip checks and contacts – various checks on normally open and normal close contacts to ensure alignment with protection strategy, also testing residual current relay contacts and wiring.

5.3.3 LV DC switchboard general arrangement

An operation and maintenance manual document was developed for this newly designed and built LV DC switchboard. The document contains inspection requirements, periodic maintenance, safety precautions, installation and commissioning requirements, and drawings including general assembly (see Figure 13) and wiring diagrams.

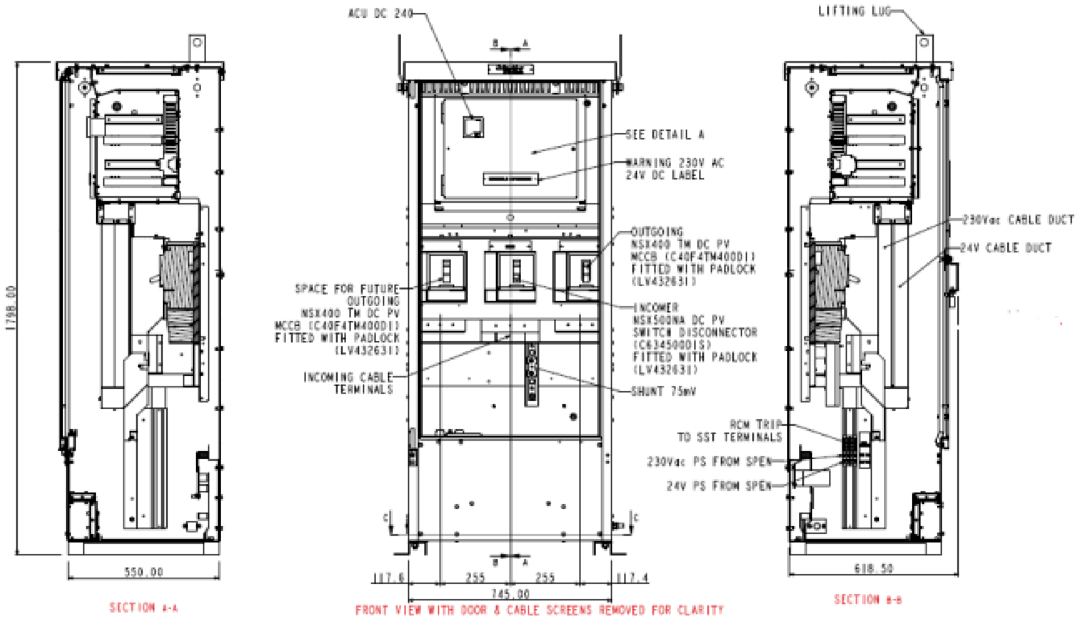


Figure 13 General arrangement drawing of LV DC Switchboard

6 Installation and commissioning

6.1 Delivery of equipment

After passing all the tests, including the integration testing which is reported in LV Engine Deliverable #4, all key LV Engine equipment were delivered to SP Energy Networks trial sites for installation on the dates shown in Table 2.

Table 2 Dates that equipment delivered to LV Engine sites for installation

Item	Delivery Date	Target Trial site
UPFC S2	23 Oct 2023	Falkirk
UPFC S3	23 June 2024	Wrexham
UPFC S4	29 Jan 2024	Wrexham
LV DC Switchboard	23 Oct 2023	Falkirk

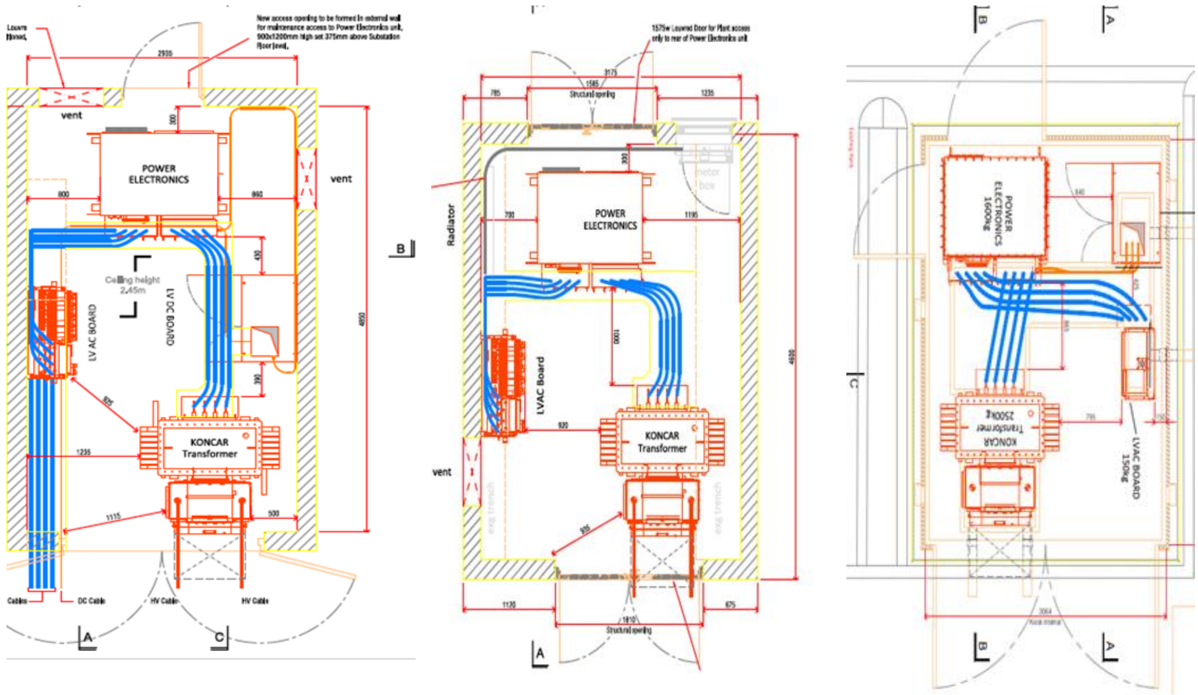
6.2 Substation layouts and electrical arrangement

Extensive work carried out within LV Engine team to establish the substation layout for each trial site to ensure operational safety and no risk during installation. Each trial site was unique in terms of site dimensions and requirements for acquiring the land. We had to also consider access to different sides of UPFC to allow for inspection and maintenance. This was included in the design by considering an access door at the rear of UPFC.

- Wrexham trial site 1, see (a) – This is a brick-built substation supplying mainly residential customers. The substation layout design includes LV AC and LV DC switchboard although the LV DC supply did not eventually materialise at this substation during LV Engine project.
- Wrexham trial site 2, see (b) – This is a brick-built substation supplying mainly commercial customers. This substation has the smallest dimensions among the three LV

Engine trial sites. Substation does not provide LV DC supply and only provides AC functionalities.

- Falkirk trial site, see (c) – This is a substation with an enclosure specifically designed for LV Engine. The Glass Reinforced Plastic (GRP) enclosure design for this site provides an indoor environment to protect power electronic and other indoor rated switchgear against ingression.



(a) (b) (c)

Figure 14 LV Engine substation layouts

The electrical connectivity and earthing arrangements of the substation are shown in the schematic in Figure 15. Note that due to the absence of any approved DC meter for energy billing purposes, we decided to fit the CT metering within the LV cable box of the distribution transformer which measures overall AC and DC total consumptions. As a results, our substation at Falkirk where DC is trialled, has been a dedicated substation for only one customer.

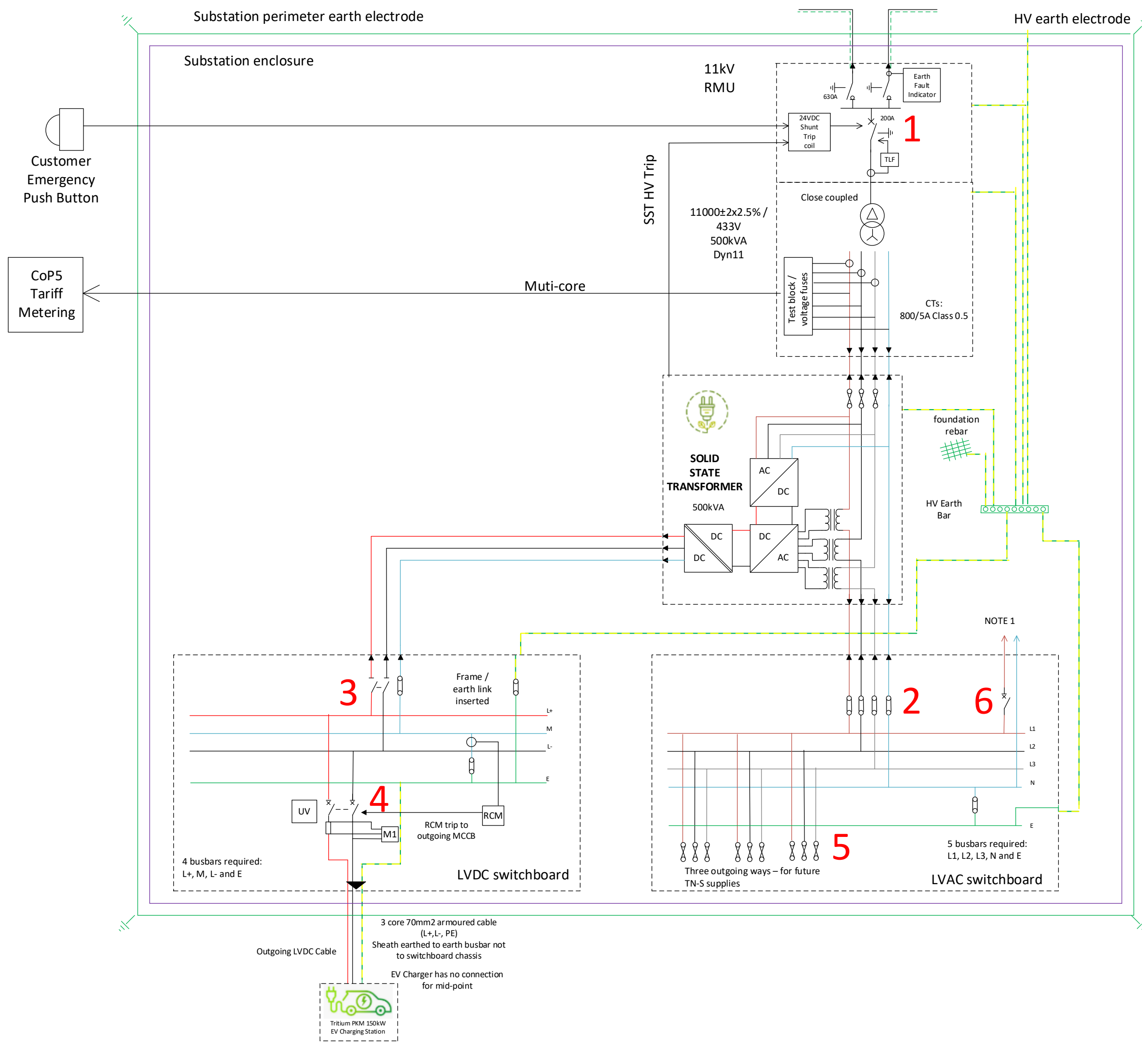


Figure 15 - Electric schematic diagram at Falkirk substation – other trial sites use similar electrical arrangement.

6.3 Commissioning and installation

Prior to site work, a commissioning an installation method statement was developed and shared with the installation team. Online and in-person training sessions were also carried out to ensure all the risks are captured and mitigation plans are in place. This is particularly essential for work on new equipment and installation in a small space close to public pathways.

We also inspected all the equipment with the installation team at the depot before transferring them to the site. That exercise generated questions around fitting and securing the equipment that could then be planned for in advance of installation day.

The commissioning method statement document includes the following technical and operational guidance:

- Safety Precautions
- Substation layouts
- Civil design
- Manual handling
- Electrical connections

- Terminations and cabling requirements
- Earthing requirements
- Small wiring schematic
- System start-up and energisation procedure
- Inter tripping and alarms tests and checks
- AC services and voltage regulations tests
- DC services energisation procedure

Figure 16 and Figure 17 show the installation at Falkirk and Wrexham trial sites respectively.

Figure 16 - Installations at Wrexham trial site

Figure 17 - Installations at Falkirk trial site

7 Safety Precautions

Power electronics devices and LV DC technologies that contain capacitive equipment maintain electrical charge even when they are isolated. To avoid any risk of electric shock or danger from stored energy, a procedure was developed and published as part of operational technical guidance. The following three steps should be taken prior to any work on LV Engine power electronics technologies:

- Isolate the device
- Measure and discharge stored energy
- Test and prove not live

The following process is adhered to:

- Isolate the UPFC from the LV DC switchboard by opening the switch-disconnector (isolation point 5).
- Isolate the UPFC from the LV AC switchboards by removing the links (isolation point 2).
- Isolate the UPFC from the incoming supply by opening, earthing and locking off the HV circuit breaker on the RMU (isolation point 1)
- Ensure safety documents have been issued with further precautions on stored energy, reflecting the processes for proving not live.
- After the UPFC isolation, the stored energy will be discharged automatically via the bleeding resistors internally fitted to the device, Figure 18. Measure the DC internal stored energy by using a multi-meter at the DC Bus Measurement Port on the UPFC front panel. In normal operating conditions, the internal capacitor is charged up to 800V which is equal to 8V at the DC Bus Port (100/1 ratio). After isolation, the voltage is discharged internally (internal bleeding resistor), wait until voltage at the DC Bus Port is as close as to 0 Volt. (~3 minutes).

Figure 18 – Measuring the internal stored energy of the UPFC via the DC Bus Port

- Use a discharge rod to earth the UPFC LVAC source, LVAC load and LVDC load terminals. Each phase can be discharged one at a time, keeping a connection to earth for 2 seconds. Confirm the voltage at each terminal is discharged (almost zero) using multi-meter. If cables from the UPFC to LV DC and LV AC switchboards are traceable, then discharging and measurements can be carried out at the incomers of these switchboards, in this way there is no need to open the UPFC cable box front panels to access its terminals. When discharging the stored energy, insulated rubber gloves shall be worn at all times.

Discharging stored energy at the LV DCSwitchboard incomer terminal

Connect the discharge rod to the substation earth system by clamping to the earth point on side of the switchboard.

Keep the discharge rod in contact with terminations at incomer terminal. Repeat this for all 4 terminals at the incomer switch disconnector.

Discharging the stored energy at UPFC AC source / incomer terminal

Connect the discharge rod to the substation earth system at one end.

Keep the discharge rod in contact with terminations at both sides of UPFC fuses for 2 sec. Repeat this for all three phases.

Figure 19 Store energy discharging procedure

8 Conclusions and key lessons

LV Engine equipment have been successfully manufactured, tested, and commissioned. All LV Engine trial sites were live and operational at the time of writing this report. The intention is to keep these substations in service as long as there is not any unexpected major operational or safety issue. We're working with manufacturers to establish inspection and maintenance plans for these substations beyond LV Engine substation lifetime. There are a number of key learnings from the manufacturing that can be considered for future innovation projects:

- We encountered several issues for design or manufacturing SST Topology 2, the key challenge was to design and manufacture a product with enough maturity for a safe trial in the network. SST Topology 2 had several unresolved issues including reliability, stability, HV impulse withstand and compatibility with existing LV protection arrangement.
- The UPFC design is preferable over the back to back (AC/DC/AC) design for SST Topology 1 solution. As the UPFC design offers a more efficient, smaller footprint, more reliable and less expensive solution than the back to back design. In addition, UPFC does not limit the fault current to the LV network which makes it more compatible with existing LV Protection arrangement.
- Early manufacture engagement is very important when development of a new technologies is intended. This allowed identifying the manufacturing challenges and project risks and clarify SPEN expectation from the project at early stage before procurement. We engaged with at least 8 manufacturers prior to procurement. That engagement informed us to make decision for pursuing two SST topologies in parallel for de-risking LV Engine project delivery.
- For a product development, a very close collaboration between the manufacturer and DNO is required to overcome different challenges. Manufacturers, especially non-UK ones, need to fully understand the grid interface requirements and UK standards which can be mainly achieved by communication between two parties throughout the development albeit those requirements have been reflected in the initial technical specifications.
- In a DC network, the fast transient overvoltage should be well understood/studied as this depends on topology and design of all converters connected to a DC network. SST components shall be able to withstand these transient behaviours. We needed to upgrade the DC/DC converter capacitors to ensure adequate margin with the maximum transient voltage.
- SST should be able to operate autonomously without any need for regular set points issued to it. The existing LV control, operation and safety procedures within most of the UK DNOs does not allow active LV control practices. In order to give SST a better chance of success for the roll out, our design allows locally setting fixed control parameters for SST through a user interface application.
- Having multiple prototypes manufactured and ready for parallel testing was a sensible decision to allow simultaneous progress in various testing and de-risk programme delay. The manufacturer also better understood the final assembly blueprints.

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