LV ENGINE

Project Progress Report

Work carried out during 2021

About Report

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Report Progress

Created by	:	Ali Kazerooni
Reviewed by	:	Michael Eves
Approved by	:	James Yu

Contents

1 Executive Summary

1.1 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 2023.

The LV Engine innovation project intends to trial Smart Transformers (ST) within secondary substations as the central point of an active and intelligent 11kV and LV distribution network. The ST trialled during the project will bring together sophisticated power electronic hardware with intelligent network monitoring and control to maximise the performance and efficiency of the distribution network.

This is the fourth in the series of annual progress reports for the LV ENGINE project, covering the project reporting period January 2021 to January 2022, the “reporting period”.

1.2 LV Engine overview

A ST consists of a Solid-State Transformer (SST) and a Smart Control System (SCS). SST uses power electronic technologies to deliver several functionalities, SCS, however, provides the control set points to SST based on data gathered and analysed from different monitored points in the network. LV Engine aims to demonstrate the following Core Functionalities can be delivered by deploying SST at secondary substations:

- Voltage regulation at LV Networks;
- Capacity sharing with other substations;
- Cancelation of LV imbalance load seen by the HV network;
- Reactive power compensation and power factor correction at secondary substations;
- Provision of LV DC to supply rapid and ultra-rapid EV chargers.

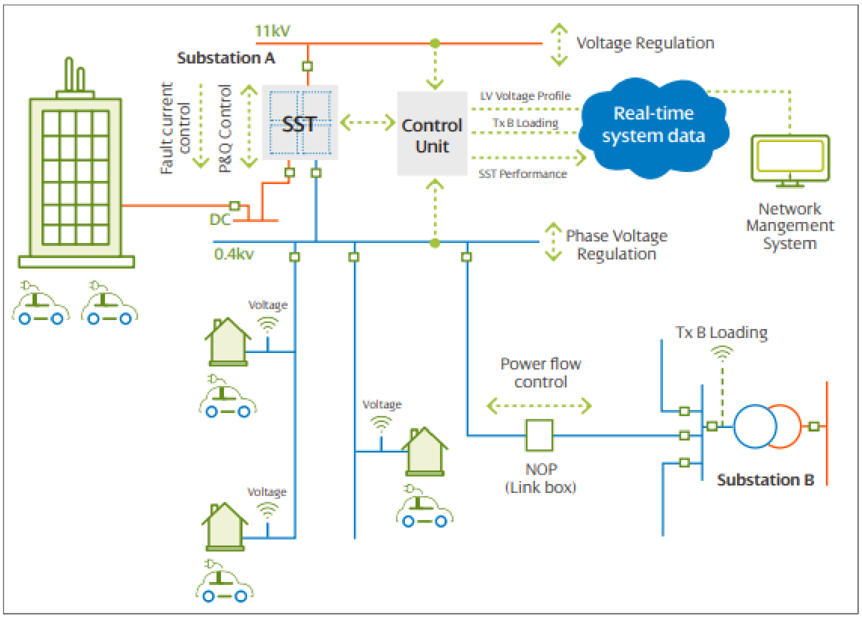

Figure 1 LV Engine project concept

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LV Engine power electronics products

As the focus of the LV Engine project is to demonstrate the performance of the Core Functionalities required by the network, different SST innovative topologies may provide these Core Functionalities in an efficient and reliable manner at secondary substation. There are different possible SST topologies which have been considered as products of LV Engine:

- ***Topology 1*** - *Topology using a conventional low frequency 50Hz (LF) transformer* –This topology uses power electronics devices at the secondary side of conventional LF transformers (11kV/0.4kV). The power electronic devices can be added to the existing distribution transformers to deliver the Core Functionalities of LV Engine. The aim is to enhance Technology Readiness Level (TRL) of this product from 6 to 9.

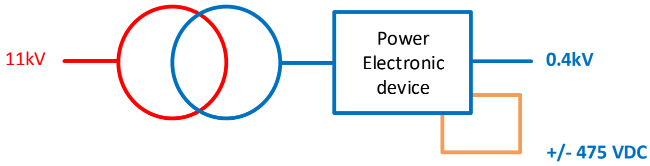


Figure 2 SST Topology 1

- ***Topology 2*** - *Topology 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. SPEN recognises that this topology may require a larger effort for design and manufacturing compared to the approach of retrofitting an LF transformer with power electronics. The aim is to enhance TRL of this product from 5 to 8.

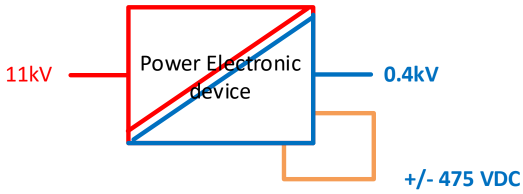


Figure 3 SST Topology 2

1.3 Project Highlights

The project highlights in this reporting period are as follows:

- **SST Prototyping and testing** – The main focus in 2021 was progressing on prototyping and testing SST Topology 1. The design and material ordering for SST Topology 2 were also progressed.
    - **SST Topology 1** - Enclosure designed has been finalised after completion of the detailed design and also building a number of test enclosures to create learnings for the final assembly. Different power electronic units and their associated control system have now been tested in separation. The initial system level tests that includes connecting all the power electronic modules together and operating them in low power have started in January 2022. The test rig for final factory acceptance tests in full power and fault conditions is now being set up. The next major milestone for SST Topology 1 is to pass all factory acceptance tests which is currently scheduled for March 2022.

- **SST Topology 2 –** The detailed design of this topology further progressed with main focus on the requirement for impulse voltage withstand to protect the power electronic equipment. Also, the layout, assembly and cooling system has been further progressed to inform the final enclosure requirements and physical layout. The key materials for building this product have been also ordered. The next major milestone for SST Topology 2 is to pass the module tests and enclosure built which are currently scheduled for Oct 2022.

- **Trial sites preparations** – In order to reduce the risk of delay in site installation, LV Engine team progressed on all legal, civil works, LV and HV cablings required in the selected trial sites.

  - **Wrexham Trial sites (AC schemes) –** Site preparations for the two substations located in Wrexham were progressed significantly to ensure that the majority of site work are completed in advance of installation and commissioning. One of the sites is now energised with LV Engine design to allow an unexpected new connection for a large commercial customer, we managed to de-risk losing the site for LV Engine trial. Adequate space and access have been provided to position SST when it is delivered to the site.

  - **Falkirk Trial site (DC Schemes) –** All legal and contractual arrangement with the customer (our project partner Falkirk Council) is now settled. Falkirk Council have also appointed a UK based contractor who will install the DC cabling and DC EV charger. Progress in LVDC protection strategy has been another major activity conducted during 2021.

- **Procurement and appointments –** We progressed on number of procurements and market research. Kelvatek was appointed as the LV automation project partner providing LV circuit breakers for the project. Cherry and White (in collaboration with Avara) have been appointed for provision of smart router which will be used for data management within the substation and communication with SPEN LV monitoring platforms. LVDC switchgear tendering is currently in the last contract negotiating stage. The preferred enclosure supplier has been also appointed.

- **System Integration** – In order to monitor LV Engine solution performance, and in line with LV Engine deliverable #5, we progressed on design of LV Engine system architecture, developing a complete I/O schedule and end to end data flow arrangement, and also requirements on display platforms.

- **BaU Integration** – Business as usual integration has been one of the pillars of each activity within LV Engine. We continued to raise awareness about the project, explored the deployment of the solution within RIIO-ED2 period, progress in developing documentations required for business adoption such as operation guidance, technical specifications and policy documents.

- **Project Dissemination –** In spite of Covid-19 pandemic limitations, the project successfully disseminated its learnings through various media including a presentation in ENIC, IET AC/DC conference, IEEE journal, ENA and CIRED working groups. One the main highlights was LV Engine’s strong presence during Cop26, where we had the opportunity to showcase our work and British led innovation to world leaders.

1.4 Project Issues

We have encountered the following project issues in this reporting period, nonetheless there is no Material Change to be reported at this stage:

- Covid-19 Pandemic – The risk of the pandemic and its impact worldwide was not expected during LV Engine programme development. The recent pandemic has introduced a number of issues to the project:
    - Supply chain – The lead times for procuring some of the components have been significantly longer than initially expected. In some cases, the suppliers temporarily suspended all or part of the orders due to shortage of raw materials.
    - Staff unavailability – Staff availabilities became unpredictable due to health issues affecting themselves or their families, and childcare, especially during lockdown periods.
- Semiconductor supply chain issue – unpredicted high demand for semiconductors and electronic chips was another reason to delay the delivery of the key components needed for the SST prototyping and manufacturing.
- Test failure – one of the key components for the cooling system failed under the pressure test. Consequently Ermco-Gridbridge reengaged with the original supplier and carried out a fresh market research to identify a supplier who can comply with the technical specification within a reasonable lead time delivery.
- Resource change – Some of our key resources within the project partner's team changed jobs. Although we keep record of all learnings and properly document the design decisions, some key staff develop unique knowledge and understanding about our challenges that replacing them is inevitably required additional effort for recruitment and handover.

1.5 Key lessons learnt

- Procurement and market research can offer a better value for money and understanding of the available products for innovation projects, however, this can be a relatively longer process (sometimes with unpredicted challenges) compared to procurement for conventional products. Longer procurement time for innovation projects will inevitably have an impact on the overall project delivery timeline.
- Although turned key contractual arrangements can pass the overall liabilities to the vendors, however, it is likely that DNOs are less exposed to design and implementation details. This may result in a weak(er) knowledge transfer during implementation and more difficulties for the roll out. Being the lead in detailed designs in LV Engine, has allowed us to better understand the challenges and solutions for business-as-usual integrations.
- In a DC network, the fast transient overvoltage conditions should be well understood/studied as these behaviours depend on topology and design of all the 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.

1.6 Summary of key activity in next reporting period

In the next reporting period, the project's critical path will be:

- Completion of manufacturing and factory acceptance test of SST Topology 1;
- Start prototyping SST Topology 2 with benchtop testing completed;
- Test the first SST Topology 1 at the Network Integration Testing centre focusing on DC protection strategy;
- Installation and commissioning the DC site at Falkirk Stadium;
- Development of safety documents, operation and manual documents and deliver relevant training prior to any commissioning;
- Submission of LV Engine Deliverable #3 and #4.

2 Project Manager's Report

This section provides an overview on the project progress made in this reporting period (15th January 2021 – 16th January 2022).

2.1 Overview

The project's Work Packages were progressed well during this reporting period. The key project highlights are significant progress in the SST Topology 1 full size prototyping and testing, also development of an innovative protection strategy for a LVDC network. In summary, the following progress was made in each Work Package:

Work Package 2 (Project Partner Selection & Procurement):

There are number of unconventional switchgear and devices required for delivering LV Engine solution. The LV Engine team conducted full procurement exercises for purchasing the majority of this equipment to ensure a technically sound and best value for money product has been used in the project. The following new appointments took place in the project:

- Kelvatek – Kelvatek will provide LV circuit breakers that will be deployed for LV automation and monitoring within the project.

- Cherry&White in partnership with Avara – Avara will provide an intelligent communication gateway (router) for communicating monitored data from a number of smart devices supplied from different vendors.

A number of procurements are also ongoing and scheduled to be completed before end of Q1 2022:

- LVDC board – LV Engine team conducted extensive market engagement and reviewing of technical proposals from a number of capable suppliers, all the technical clarifications and non-compliances were gathered and discussed. A risk assessment is now being undertaken with the aim to conclude the technical evaluation and appoint the vendor by end of Feb 2022.

- Enclosure –As the housing requirements for the LV Engine substation is different from conventional secondary substations, following development of technical specifications for LV Engine substation enclosure, we have conducted full procurement process with a number of suppliers. We are now in the contract negotiation stage and aiming to award the work by end of Feb 2022.

Work Package 3 (Design and manufacturing SST):

The main focus in 2021 was progressing on prototyping and testing SST Topology 1. The design and material ordering for SST Topology 2 were also progressed.

- **SST Topology 1** - Enclosure designed has been finalised after a detailed design and also building a number of test enclosures to create learnings for the final assembly. Different power electronic units and their associated control system have now been tested in separation. The initial system level tests that includes connecting all the power electronic modules together and operating them in low power have started in January 2021. The test rig for final factory acceptance tests in full power and fault conditions is now being set up. The next major milestone for SST Topology 1 is to pass all factory acceptance tests, which is currently scheduled for March 2022.

- **SST Topology 2 –** The detailed design of this topology further progressed with main focus on the requirement for impulse overvoltage withstand to protect the power electronic equipment. Also, the layout, assembly and cooling system has been also further progressed to inform the final enclosure requirements and physical layout. The materials for building this product have been also ordered. The next major milestone for SST Topology 2 is to pass the module tests and enclosure built, which is currently scheduled for Oct 2022.

LV Engine control philosophy document was developed looking at different objective functions and network scenarios to identify the control challenges and potential benefit that can be achieved by opting different control objectives especially for capacity sharing function. Communications and ownerships required for a BaU adoption of the LV control solutions were also considered and discussed. One of the main learnings is the operation safety risks associated with any autonomous LV network reconfiguration control system, which may not be able to be fully adopted by UK DNOs until they've established a LV control room and procedures similar to those of existing procedures for HV and EHV networks.

Work Package 4 (Network Integration Testing):

Network Integration Testing is currently planned to be conducted in May 2022. We are currently working with Power Network Demonstration Centre to finalise the scope of testing and site arrangements/requirements. Following the studies and design conducted for LVDC protection strategy, we have decided to test the overall LVDC protection strategy, as our proposed methodology is very unique, innovative and first of its kind in the UK if not world. We are expecting to generate further learnings and results than was initially planned for this work package.

Work Package 5 (Live Network Trial):

In order to reduce the risk of delay in site installation, LV Engine team progressed significantly on various site preparation activities including site designs legal, civil works, LV and HV cablings. A summary of work is as follows:

- **Wrexham Trial sites (AC schemes) –** Site preparation for the two substations located in Wrexham were progressed significantly to ensure the majority of site work was completed in advance of installation and commissioning. One of the trial sites selected for the project should be commissioned in a short notice in response to a new demand application. That introduced a high impact risk to the project as we could lose the site and new effort for trial site selection would have required resulting in additional cost and resource allocation to the project. LV Engine team, however, managed to expedite the site preparation works, and commissioned the substation with LV Engine design so that SST can be connected to the rest of plants in future.

- **Falkirk Trial site (DC Schemes) –** The main progress on the LV DC trial site was the significant study and work we have been conducting for LV DC protection strategy. This is one of the rich learning exercises that we conducted during this reporting period. Also, the lease agreement has now been finalised via our Legal team. Our project partners, Falkirk Council and Tritium, are now in a contractual agreement for supply and installation of the first rapid LVDC fed charger. This has de-risked the project ensuring all the parties are contractually committed to this implementation. It should be noted SPEN cannot own and operate an EV charger based on our licence conditions.

- **System Integration –** Work has started to design and implement a system architecture to report the data monitored at the substation by various vendors to different SPEN platforms. The aim is to develop an interoperable solution that can be adopted by the business beyond LV Engine for monitoring the performance of smart solutions, similar to those of LV Engine, in the secondary substation.

Work Package 6 (Development of novel approach and BaU integration):

The BaU integration have been the pillar of all activities in other work packages, the solutions can be adopted by the business beyond LV Engine project completion, if technology proven to be successful. Nonetheless, specifically to work package 6 the following progress was made:

- Progress on development of safety documents in particulate for LVDC switchboard and power electronic devices;
- Install and commission further distribution transformers fitted with on-load tap changer (OLTC), and plan for further installations;
- Carry out performance analysis and system modelling to assess the impact and benefits of the distribution transformers with OLTC;
- Progress on preparation of the policy document and cost benefit analysis for deployment of the distribution transformers fitted with OLTC;

Work Package 7 (Dissemination and Knowledge sharing):

The project has continued to go beyond its obligation for dissemination and knowledge sharing by sharing the project learning through a series of external presentations and published articles, material development and conference attendance. It should be noted that Covid-19 pandemic did affect our plan for some of the in-person workshops and dissemination events.

In order to provide further learnings, some the key progresses have been discussed in more details in the following section.

2.2 SST Design and Manufacturing

Our SST manufacturing partner progressed on development of both SST technologies with the main focus on SST Topology 1 prototyping and testing. Based on the detailed design carried out in the last reporting period, all the components were procured and delivered to Ermco-Gridbridge since the start of 2021. The lead time for some components were much longer than initially expected, which was affected by the global shortage of chips and electronic materials. This delay subsequently delayed the development plan during 2021.

The following main activities were carried out during this reporting period:

- Module tastings in low power were completed for SST Topology1. The Rectifier (AC/DC), Inverter (DC/AC) and DC/DC converter have now been built and individually tested in low power, which has been significant hardware and software progress. Figure 4 shows the Ermco-Gridbridge low power lab where testing the major power electronics blocks is being conducted;
- Cooling system, including the water pump and cold plates, have been tested. Cold plates initially failed under a pressure test, therefore, Ermco-Gridbridge needed to carry out a fresh market engagement as the project team recognised that there is a risk to reengage with the initial supplier. Figure 5 shows an initial simple test arrangement for the cooling system with new cold plate and water pump;
- The enclosure's mechanical design and build have been finalised after a number of trials to learn the best way of building the enclosure and the accesses it required. Components are being fitted into the enclosure to form the first complete prototype. Figure 6 shows different fixings and components fitted within the enclosure;
- Building the test rig for high power and short circuit withstand tastings has been progressed in the main Ermco factory facility in Tennessee.

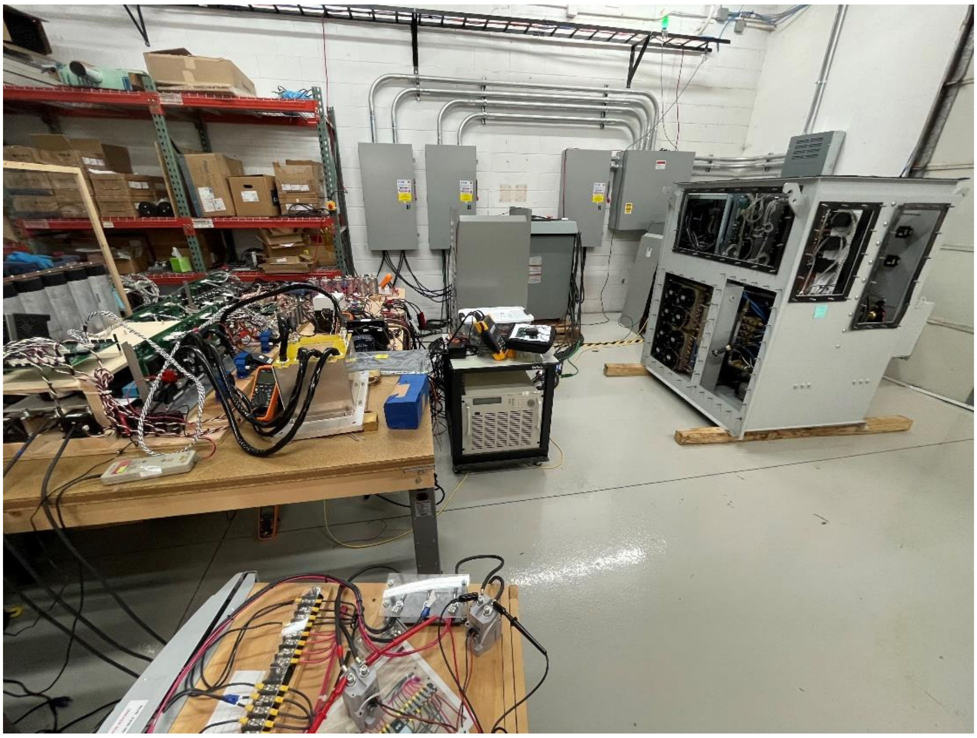


Figure 4 Ermco-Gridbridge low power lab where the power electronics are being tested and fitted within the enclosure

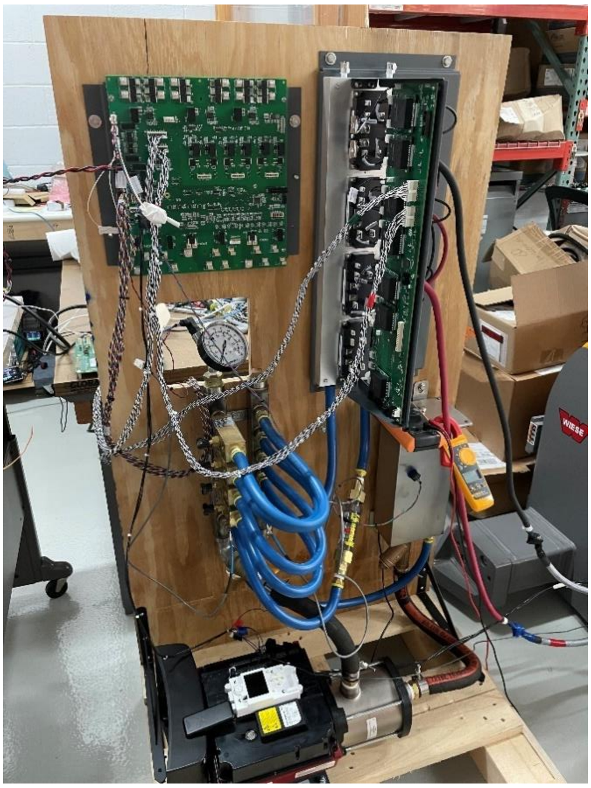


Figure 5 Initial test set up showing the water pump, cold plate and the control system

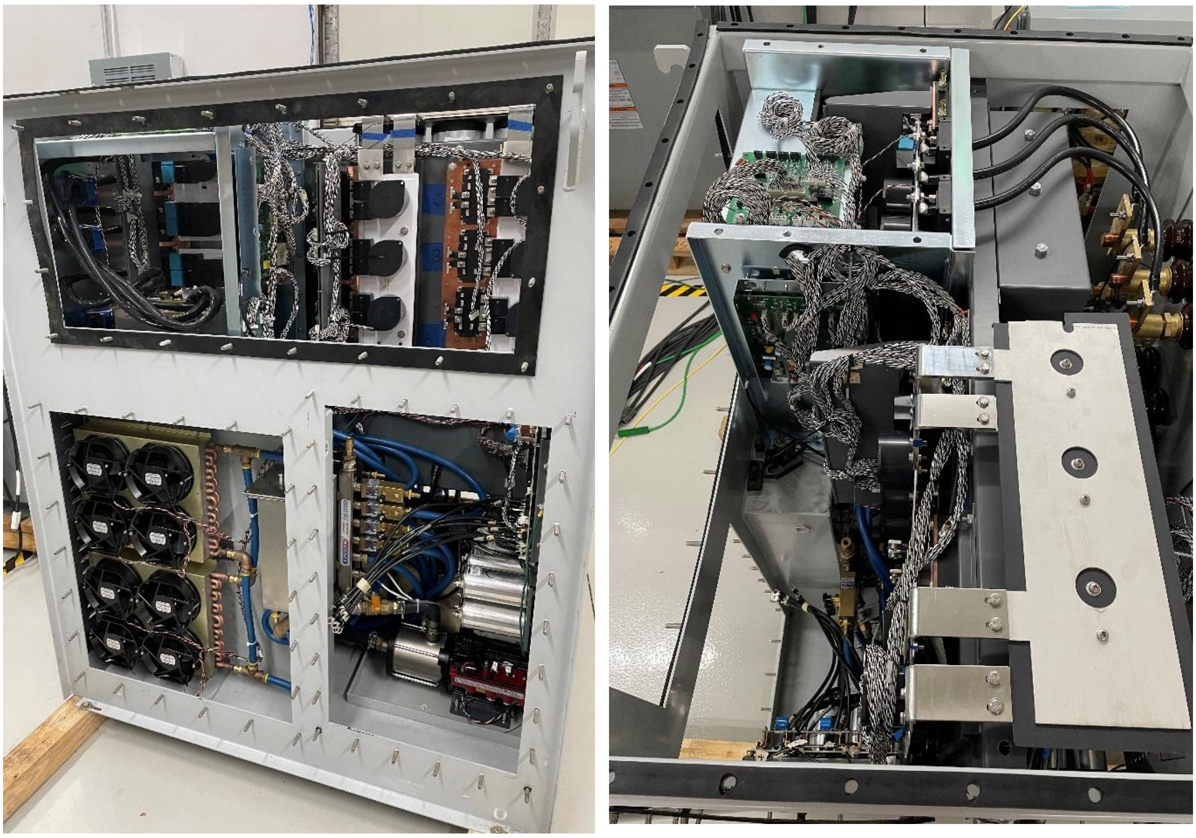


Figure 6 Components have been fitted (to date) within the enclosure for the first prototype

The following key activities for SST Topology 1 development are scheduled during the next reporting period:

- Carry out system level tests that demonstrate the functionalities of SST Topology 1 where the rectifier, inverter and the converter are connected to the same 800V internal DC link. This test has already started in low power arrangement and it will continue in high power testing arrangement in Q1 2022.
- Carry out factory acceptance tests (FAT) that includes high power and short circuit withstand tests. The full test plan and test schedule document is being prepared. The expected date for completion of the FAT is currently May 2022.

While the main resources allocated to the development of the SST Topology 1, SST Topology 2 design further progressed and key materials were ordered. The following key activities were conducted during this reporting period:

- The impulse voltage withstand has been one of the key challenges for SST Topology 2 to ensure HV network interface requirements is satisfied and power electronics are not damaged in fast transient overvoltage conditions. Detailed design of the HV interface were developed with two level surge arresters fitted between the HV terminals and the power electronic modules.
- Stackable high voltage (2.0kV) modules (SHVM) which will be connected in series (4 in each phase) to provide the nominal voltage capability have been designed. The move from 1.2kV to 2.0kV Sic Mosfet was decided in last reporting period when early release of these modules by Infeneon was confirmed for LV Engine project. Figure 7 shows the design of SHVMs.
- The physical layout of the HV stage has been designed considering the thermal management requirements and the connection between high voltage modules. Figure 8 shows the layout of the HV stage with SHVMs staked for the 3 phases.

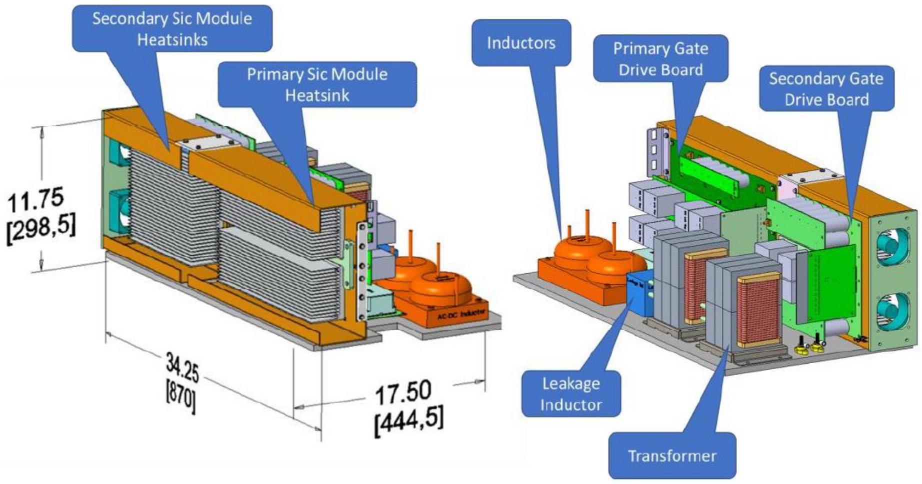


Figure 7 Stackable High Voltage 2.0kV Modules

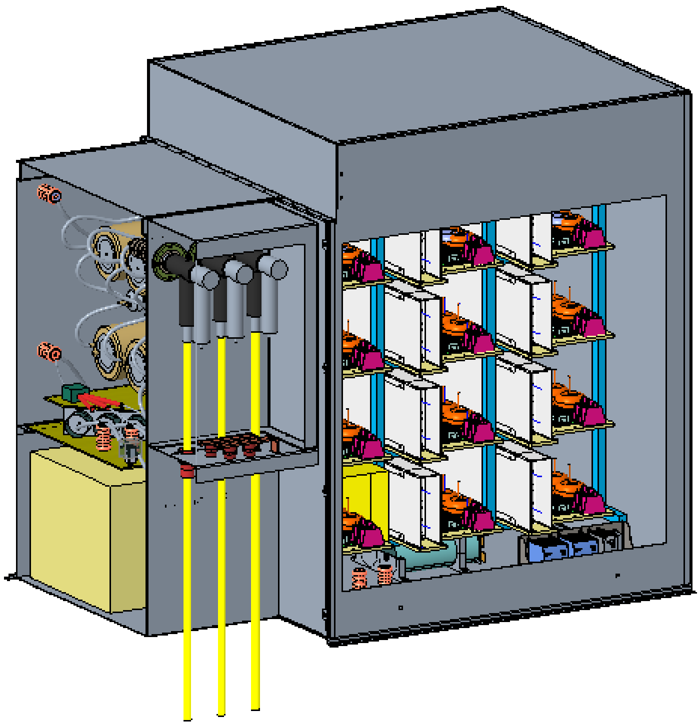


Figure 8 HV stage of SST Topology 2

The following key activities for SST Topology 2 development are scheduled during the next reporting period:

- Finalise the layout design to provide more flexibility for substation layout planning where the HV stage and LV stage can be separated and located at different locations within the substation;
- Carry out module tests and start assembly of the first prototype within the enclosure.

2.3 Trial site preparation

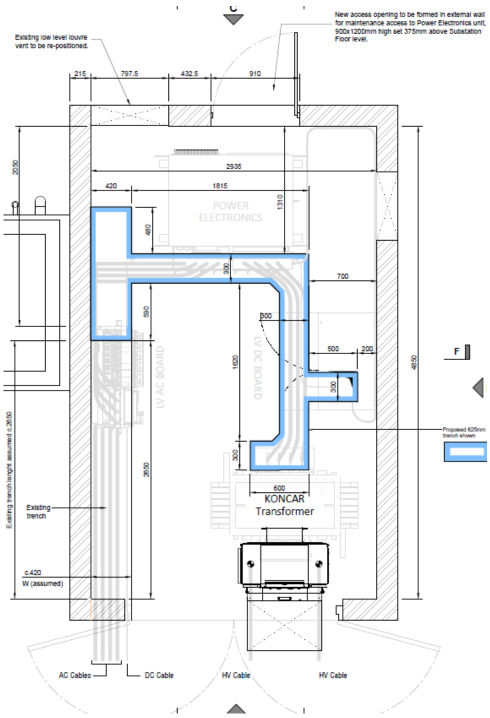
Considering the extra time and effort required for site preparations for a new technology compared to a conventional installation, we decided to start the site preparation works well in advance of SST delivery. We have progressed significantly in design and preparing the sites in Wrexham and Falkirk during this reporting period.

2.3.1 Wrexham

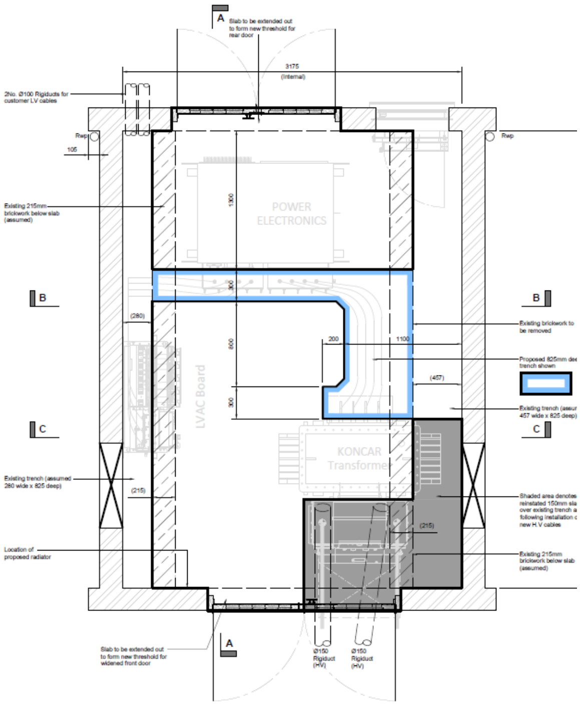
Wrexham trial sites are candidate for demonstration of LV Engine AC functionalities. LV Engine solution will be trialled in two secondary substations in Wrexham. These substations were initially LV Only substations which provide a "greenfield" opportunity for trialling a new technology and design. The following work carried out in Wrexham in this reporting period:

- Following an internal approval process and documentations, ordered and delivered cables and cable accessories that are required for LV Engine design;
- Upgrade a small section of LV network to de-risk any potential thermal stress on the network as a result of trial LV Engine solution, please see Figure 9;
- Completed civil designs in both substations, WH Smith and Crescent Road, after establishing substation layouts. please see Figure 10;
- Carried out civil and earthing installations at both substations. Also, additional access doors/inspection panels fitted at the back of substations to allow further access to the power electronic units if required, please see Figure 11;
- Energised one of the substations (WH Smith) with LV Engine design and without the power electronic technologies. WH Smith was offered for connection of a new large commercial customer as SPEN was required to offer a solution with minimum connection cost under regulatory obligations. In order to de-risk LV Engine project and also supply the customer, we decided to commission the site with LV Engine design, but with the provision to install a power electronic device at a later stage. Figure 10 and 11 shows a door at the back of substation which will be used to position the power electronic device within the substation without the need to relocate other switchgears.

Figure 9 Small section cable upgrade between Crescent Road and Bingo Club substation



Crescent Road considering both AC and DC supply



WH Smith only AC supply

Figure 10 As built substation layout for Wrexham trial sites

Civil installation

Cabling outside the substation

Finished work

Figure 11 WH Smith site preparation and installation

2.3.2 Falkirk

Falkirk stadium will host the first UK LV DC substation aimed to be delivered by LV Engine. Falkirk trial site progressed from various fronts to be prepared for installation and commissioning date, the following key progressed made during last reporting period:

- Our project partners, Falkirk Council and Tritium, are now in a contractual agreement for deploying and supply of DC fed EV charger. This has been an important milestone of the project to de-risk to ensure a DC fed EV charger will be purchased and operated by the customer (Falkirk Council).
- All contractual and legal matters between customer and SPEN including connection agreement, wayleaves, lease agreement are now settled. LV Engine team needed to

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conduct an extra environmental report for the site to ensure there is no contamination or other environmental issues in the allocated land for LV Engine substation.

- The HV connection and substation layout were re-designed to reduce the installation and operation risk, also overall cost of installation. Figure 12 shows the latest substation layout design at Falkirk.
- All the equipment including LV AC board, RMU and shunt trip coils, transformer, cables and cable accessories have been already ordered or delivered to our depot.
- As part of developing an enduring solution to ensure supply at Falkirk substation can be restored with minimum customer supply interruption. We have been working closely with SPEN operation staff to understand the requirements and we have purchased a number of spares for non-strategic equipment for which we experienced long lead time.
- One of the challenges for Falkirk LVDC substation is compliance with Guaranteed Standards of Performance (GSOP) as the conventional power restoration solutions such as emergency generator or backfeed are not possible to this only LVDC substation. After an extensive consultation across the business and beyond, we have decided to close the incident (thus closing any related alarms) and will leave a note in the Network Management System that this as an open fault, in this way our District team will not be unfairly penalised. We have also prepared a memorandum of understanding with the customer to appreciate that this is a highly innovative solution with little field experience therefore, there is a risk of failure although SPEN endeavour to avoid this by conducting varies tests prior to commissioning.
- Several sessions conducted with the delivery team to plan the sequence of installations as this is a unique substation (first in the UK if not EU or world, LVDC substation). A tender to appoint the civil contractor is now ongoing led by our District delivery team.
- We completed technical requirements and initial design for the enclosure to firstly allow provision of an indoor environment and secondly adequate thermal management within the housing. LV Engine enclosure design will consider two adjustable door size louvers at two sides of substation to allow adequate air flow through the substation, an inspection panel was also considered in the design to allow access to the side of SST. Please see Figure 13. We also carried out a competitive tender among our approved suppliers and we are now in a contract negotiation stage with our preferred vendor.
- We conducted extensive protection studies to assess our protection strategy as it has been one our key challenges for this trial site. With the support from our project partner, University of Strathclyde, Falkirk site were modelled to understand transient overvoltage and current behaviours in various fault events. In an LV DC network, the capacitors fitted in the converters, e.g. those fitted in SST and EV charger, may exchange energy upon a fault inception that causes some transient behaviours, see Figure 14 an example of pole to ground fault. These transient behaviours need to be fully understood and ensure that LVDC switchgears have adequate withstand capability in these conditions.
- An extensive market engagement and tendering exercise was carried out for purchasing the LVDC switchboard. In order to de-risk the project delivery, LV Engine team decided to focus only on commercially ready products. We conducted a competitive tender during 2021 and we have now completed the technical compliance assessment stage in line with technical specifications previously developed by LV Engine team. A contract negotiation stage is now ongoing with our preferred supplier.
- In addition to LVDC switchboard, we identified a number of LVDC relay and handheld clamps that will be used for protection and measurement of any leakage current between earth and midpoint of LVDC supply. We recognise it is essential to keep the leakage current close to zero. We purchased a number of these devices and they have gone under various independent tests to ensure their accuracy and maximum current withstand capabilities under certain fault conditions. Figure 15 shows the two DC earth leakage relays have been considered for deployment in LV DC substation.

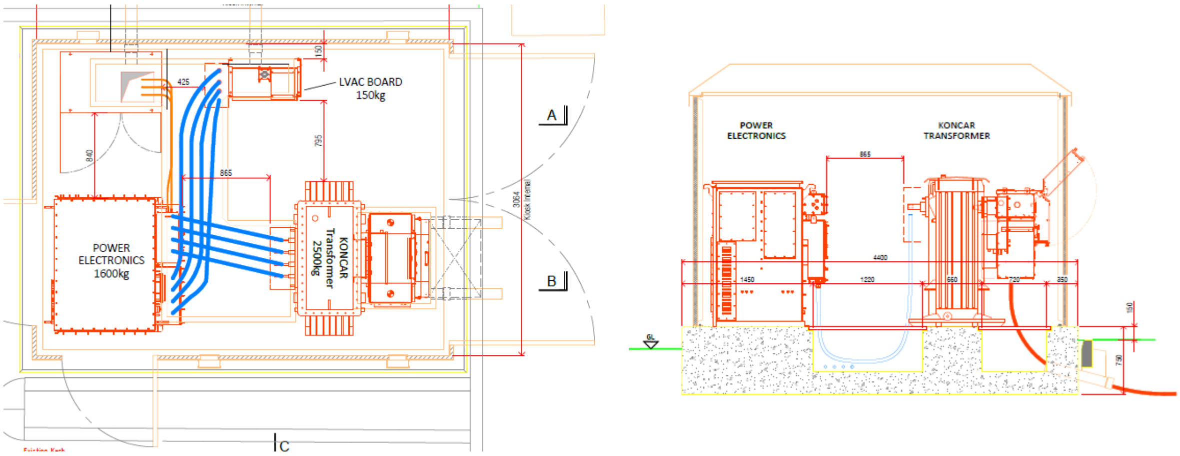

Figure 12 Falkirk Substation Layout

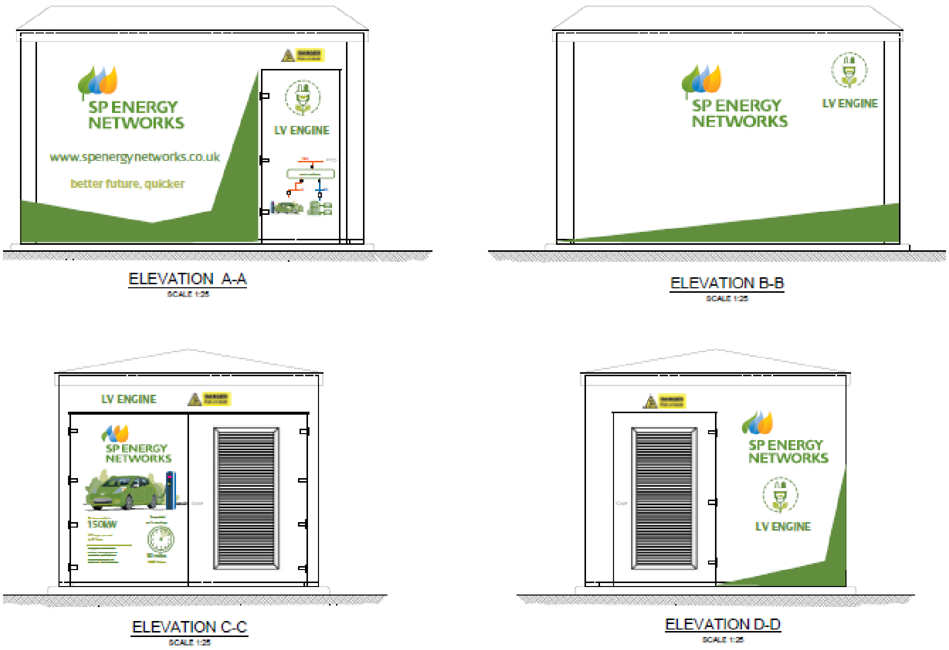

Figure 13 Falkirk enclosure initial design

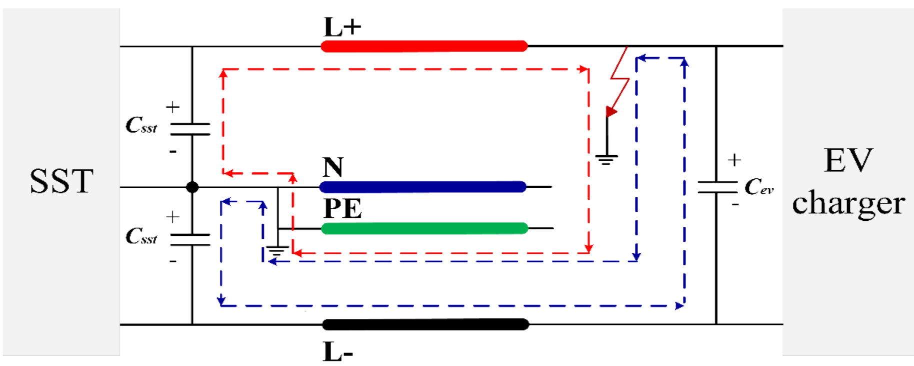

Figure 14 An example of pole to ground fault and exchange of energy between capacitors

Littelfuse EL731

Bender RCMB301

Figure 15 DC Earth Leakage Relays identified for potential deployment in LV Engine

2.4 Monitoring and system integration

In line with LV Engine deliverable #5, Establish the system architecture of LV Engine schemes, we have started design and development of the LV Engine system architecture. The intention is to build an enduring infrastructure to monitor the performance of the LV Engine solution via internal SPEN platforms. The majority of existing data recorded by LV monitoring solutions are hosted by the different vendors, we recognise that this will result in deploying various monitoring platform application suites and usually high operation costs for maintaining the data by different vendors.

SPEN set strategy to enhance LV monitoring during RIIO-ED2 by developing necessary infrastructure. In this way SPEN can own the data and data analytic platforms that will be vendor agnostic. We have aligned LV Engine with the overall SPEN strategy to ensure a better value for money and endurance for LV Engine solution. We are working on a system architecture that allows key LV Engine equipment within a substation report to the same platforms, which are under development for overall strategic SPEN's LV monitoring purposes.

Figure 16 shows a simplified system architecture which has considered for LV Engine. The following components of this architecture are currently under development. In order to establish this architecture, the following progress has been made:

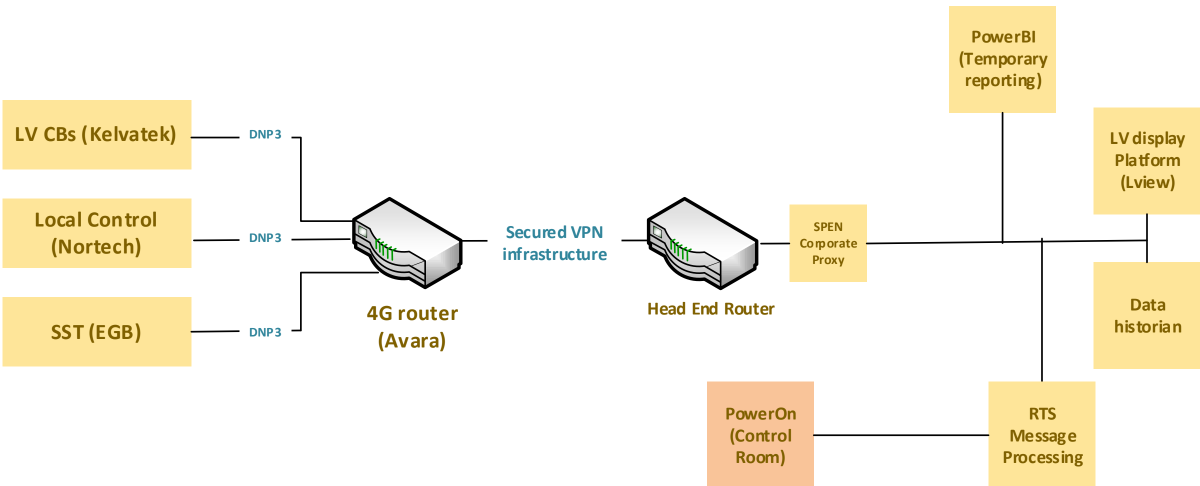

Figure 16 Simplified LV Engine system architecture

Level of confidentiality:
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- I/O schedule – an I/O schedule has been under preparation with inputs from all the vendors to reflect the end-to-end data flow, messaging and PI tags. We have setup a flexible I/O schedule that can be applicable to different substations where the substation identifications needs are different.
- 4G Router upgrade – We have commissioned Avara to update the firmware of their 4G router, which was previously used and tested in another application in SPEN. The firmware update includes a series of protocol conversion from DNP3 to SPEN approved protocols, adding the DNP3 master and slave functionalities and data storage capability.
- PI tags – We created PI tags for LV Engine analogue and alarms. PI is traditionally used for HV and EHV data historian, which do not require data to be recorded for each phase separately. LV network, however, is usually imbalance making the monitoring and storing data per phase more important. We created a new PI tag convention for LV parameters that can be used for future applications.
- Field Online development - This system will be used to publish key events from the field, which are of interest to internal IT/OT systems. Field online acts as a bridge between OT and IT to allow different monitoring and control equipment to communicate the necessary data through different protocols and method depending on the data volumes, frequencies, etc. We have appointed a team of software engineers to update this infrastructure for inclusion of LV Engine solution.
- LV display platforms – SPEN have been developing a customised and in house funded LV monitoring and operation management platform. We have developed the user interface requirements to this platform to include LV Engine devices.

LV Engine system architecture, use cases, data flows and details of system integration requirements have been reflected in LV Engine System Enterprise document. This document is currently in a draft version which will be finalised during next reporting period.

2.5 Voltage regulating distribution transformer (VRDT) performance studies

One of the objectives of LV Engine is to compare the performance of power electronic solutions with conventional distribution transformers fitted with on-load tap changer. This exercise will provide our design engineers with a better understanding and necessary policies to where and how a VRDT or power electronic technology may be used. The following activities were conducted during this reporting period:

- Installed second unit of VRDT in an area with high uptake of PVs. Also we have planned the installation of the third unit in Q1 2022 in a deprived area, where potentially we can demonstrate conservation voltage reduction (CVR);
- Conducted performance analysis and power system studies for the sites shortlisted for VRDT installations. The aim was to generate learnings on VRDT impact on quality of supply, demonstrate the potential reduction in customer's energy bills by operating in lower voltage and investigate if the acceptable controlled target voltage can be adopted without beaching the statutory voltage limits. Figure 17 shows an example of VRDT positive impact in an area with high uptake of PV, the green area shows the voltage measured by the smart meters during operation of VRDT and the orange area shows the expected voltage if VRDT was not deployed.
- Developed the first draft of VRDT policy to inform the design engineers for proposing VRDT. We are aiming to finalise this policy and propose to the business for internal approval.

It should be noted that the impact of our work on VRDT and learnings shared with the rest of business was the main driver for the plan to deploy further 10 VRDT units under the green recovery fund mechanism.

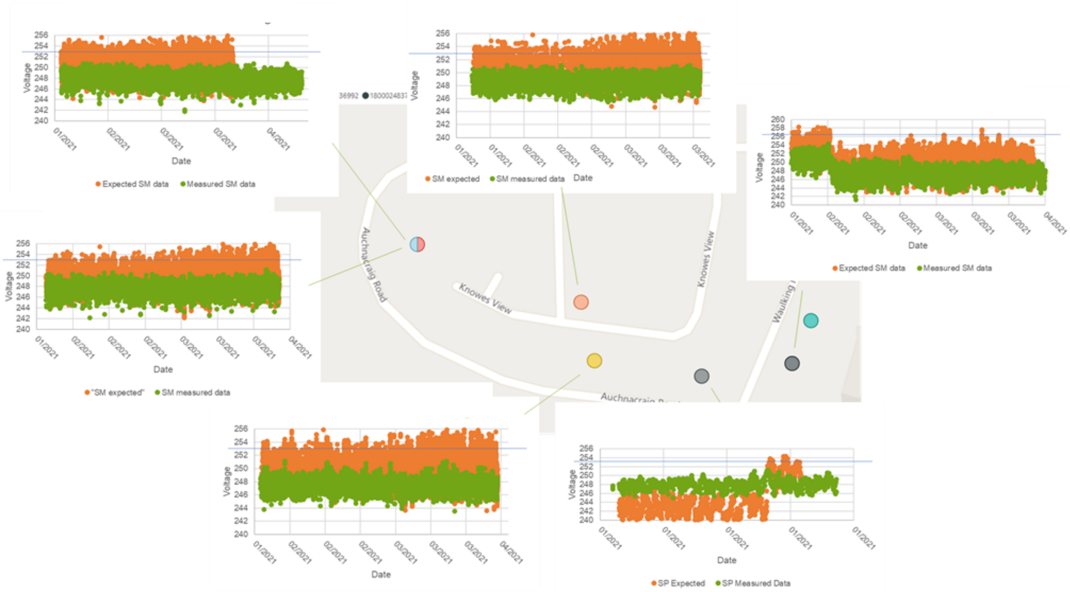

Figure 17 An example of VRDT deployment impact on voltage supplied to the customers in an area with high uptake of PV around Glasgow

2.6 Disseminations

Knowledge sharing continues to be in the core of LV Engine activities to ensure our internal and external stakeholders are aware of project progress, project learnings and challenges. Key highlights on dissemination activities during this reporting period are as follows:

Cop26 – Cop26 was a unique opportunity for LV Engine to raise awareness on the project and show case the government investment in innovation to achieve UK Net Zero target. LV Engine had a strong presence in both Cop26 Blue Zone and Green Zone:

Blue Zone – We prepared a world class holographic presentation of LV Engine with key benefits of the technology that we have been developing and the importance emphasise on UK leadership in driving innovations. Our stand was visited by the UK prime minister, several world leaders and key technology figures e.g. Bill Gates, where they learnt about LV Engine presented by our Scottish Power Chief Corporate Officer. The visits and presentations were widely published by our comms team through various channels.

Green Zone – Our SST Manufacturing Partner, Ermco-Gridbridge, joined SP Energy Networks supplier event to present LV Engine solution from their laboratory showing the audience the prototype and the progress.

ENIC – We had the opportunity to present the latest project learnings and some technical challenges during Energy Networks Innovation Conference in 2021.

IEEE Journal – The work conducted with one of our project partners, Kiel University, were published in prestigious IEEE transaction on Smart Grid. The title of the paper is Synchronization of Low Voltage Grids Fed by Smart and Conventional Transformers[1].

Power electronics community – In addition to an ongoing collaboration and support to Compound Semiconductor Application Catapult, we delivered a keynote talk as part of NMI Virtual conference 2021 organised by Techworks, which aimed to promote the application

[1] https://ieeexplore.ieee.org/document/9343312

of semiconductors and provide the challenges in this industry. We presented a talk titled Power Electronic Technologies Key Enabler for Net Zero Carbon Target.

IET AC/DC conference – The learnings captured from technical studies carried out for our LVDC protection strategy were presented in IET AC/DC conference under the paper titled Protection of LVDC Networks Integrating Smart Transformers: The case of LV Engine Falkirk Trial Site.

CIRED working group – As a member of CIRED working group on DC distribution networks[1] we have shared the learnings from LV Engine and provided inputs to the documentations prepared by the working group. The final report has been published and CIRED agreed that working group can continue the work under a new scope looking closer to LVDC technologies.

ENA working groups - LV Engine team in collaboration with Active Response project team (managed by UK Power Networks) proposed a new working group to Energy Networks Associate to develop guidance on testing the power electronic devices. The final report of this working group has been published in Jan 2022.

Internal staff awareness – We continue to share the project progress and lessons learnt with stakeholders within SPEN through various webinar events, raising awareness and preparing the business for the Smart Transformer and voltage regulation distribution transformer technologies.

[1] http://www.cired.net/cired-working-groups/dc-distribution-networks-wg-2019-1

2.7 Lessons learnt

In addition to the knowledge sharing presented by various sections in this report, the following summarises some of the additional learning made during this reporting period from each of the active work packages.

2.7.1 Work Package 2

- Procurement and market research can offer a better value for money and understanding of the available products for innovation projects, however, this can be a relatively longer process (sometimes with unpredicted challenges) compared to procurement for conventional products. Longer procurement time for innovation projects will inevitably have impact on overall project delivery timeline.
- Although turned key contractual arrangements can pass the overall design, installation and commissioning liabilities to the vendors however it is likely that DNOs are less exposed to design and implementation details. This may result in a weak(er) knowledge transfer during implementation and more difficulties for the roll out. Being the lead in detailed designs in LV Engine, has allowed us to better understand the challenges and solutions for business-as-usual integrations.
- Intellectual property and liability clauses are the most time-consuming items during contract negotiations. We suggest terms and conditions (T&Cs) of a contract are shared with the vendors at the start of tender and their responses to T&Cs are evaluated as part of technical compliance assessment phase.
- Most of existing framework agreements do not cover any design aspects. Innovation projects, however, usually have a design phase or an alternation to the existing approved products, therefore the existing frameworks will not suitable and that require a new form of contract.

2.7.2 Work Package 3

- 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.
- High speed sensing and fast acting solid state switches are required for bypassing power electronics and ensuring there is no damage to power electronics in case of any network fault.
- Impulse voltage withstand requirements for HV networks drives a larger enclosure for SST Topology 2 to include a number of surge arresters. These requirements may need to be revisited for power electronic devices connecting directly to cable underground cable networks. Moderating impulse voltage withstand for power electronic devices can have significant impact on cost and size of the final products.
- 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.
- We have been considering the voltage alarms issued by the Smart Meters as a suitable close loop control parameter for voltage control at secondary substation. However, it

should be noted that some of the voltage alarms may be as a result of progressive fault condition rather than any voltage violation due to generation or demand.

- As part of studies for developing the control philosophy we learnt that minimising total network loading in a meshed arrangement may have serious side-effects as the SST must output large amounts of reactive power, which increases voltages over limits and increases feeder and transformer loadings. Therefore, it would be a poor choice as an objective function.
- SST design considers a bi-polar (± 475V) supply arrangement, that was based on our initial market engagement at the start of the project and also the DC EV charger was available to us at that time. Our DC EV charger manufacturer partner also advised initially that their design will be based on a bipolar voltage. However, the design of EV charger changed later to remove the need for midpoint connection i.e. ability to accept 950V DC either bipolar or unipolar. This generated some learnings that there is a need for developing an engineering recommendation for a consistent approach across industry to define the supply arrangement and interfaces between DNOs and the customers.

2.7.3 Work Package 4

- The protection strategy developed and studied for LV Engine LVDC scheme is a unique protection approach that have not yet been implemented. We have decided to test this approach for various faults by replicating the exact arrangements in the Network Integration Testing centre.

2.7.4 Work Package 5

- The LVDC studies for Falkirk highlighted that the power electronic units (SST and the EV charger) are switched off in less than 1.0ms in the DC fault stage based on their built-in undervoltage protection. Following their disconnection, the fault response of the LVDC network is dominated by the resistive and inductive components of the feeder and the converters' smoothing capacitors. Owing to this, the duration of the DC fault transients is limited to a few milliseconds (<10 ms) in all fault cases.
- The maximum DC rating of the converter at our first LVDC trial site is very close to the demand (EV charger). Therefore, overcurrent protection is not adequate to be used as the only primary protection function. We have developed a new protection strategy relying on undervoltage and earth leakage tripping functions. The suitability of the protection strategy has been confirmed through detailed modelling and studies.
- One of the main barriers for wider deployment of power electronic devices in distribution networks, e.g. SST is their ability to provide adequate fault current during the fault so the conventional protection equipment can clear the fault within acceptable time. Creating high fault current provision capability will result in a larger size and more expensive SST, which introduces challenges in financial justification and deployment of these technologies. Instead, more intelligent/fast acting protection devices may be used to replace our conventional fuses. We are currently looking into possible solutions such as fast response fuses (typically used in automotive industry), solid state circuit breakers and tripping electronic devices.
- A staggered installation approach for trialling a technology in a number of trial sites allowing to capture learnings and applying them effectively from one installation to another.
- DC leakage may cause long term corrosion to the assets, this should be monitored and checked as part of commissioning procedure. LV Engine have identified and tested a number of handheld clamp meters can be used for testing during commissioning stage. DC clamp meters when measuring milli-amps need to be zeroed and kept in the same position prior to a measurement being made, due to effects from the earth's magnetic field.
- Existing commercially ready MCCBs are not designed to break the DC circuit when either of DC pole voltages exceeds 500 V. However, if the transient fault current reduces to zero

when MCCB opening contact some overvoltage on DC poles can be acceptable. This can be the case for most of DC fault currents when power electronic devices switch off and the current reduces to zero very shortly after fault inception, but overvoltage may persist for a longer time.

- The insulation value (U-Value) used for design of enclosure for typical indoor substations is usually 0.27 for walls and 0.2 for roofs. These values are close to the requirements for domestic residential properties. LV Engine Substation is an enhanced and modified Distribution Substation. It is not designed for occupation, therefore the U-value standards above are much too onerous. Following internal/external engagement, we decided to consider U-value of 0.7 for LV Engine enclosure design.

2.7.5 Work Package 6

- As LV networks are usually passive and there is no voltage regulating capability, we usually operate the LV networks at a voltage close to upper side of statutory limits, this may introduce risk of overvoltage during off peak condition especially if there is high uptake of PVs. Using VRDT will provide the opportunity to operate the network at a lower voltage level to avoid any voltage excursion at off peak and also reduce the overall customer's energy consumption
- LVDC supply restoration and compliance with regulatory obligations of Quality of Service Guaranteed Standards remain one of the challenges for LVDC network roll out. Unavailability of "back feed" arrangement similar to LV AC networks and emergency generators for LVDC supply are the main issue. We are currently investigating the possibility and technical specifications of the LVDC generator

2.7.6 Work Package 7

- Holographic technology used for presentation during Cop26 provided an attractive demonstration to a large audience for a better project awareness.
- ENA working groups should be more encouraged to capture learnings from innovation projects and reflect relevant learnings in ENA approved technical guidance documents for various technologies.

2.8 Project reports and materials

During the reporting period the following reports and materials have been generated to document the learning made within the project to date:

Document	Summary
Falkirk LV DC protection study	Include detailed transient study of protection strategy performance in Falkirk
Falkirk Protection Strategy Summary	Summary of DC protection strategy in Falkirk
Falkirk Substation Enclosure Supplementary design specifications	Supplementary requirements to conventional housing specifications based on requirements raised by LV Engine
Voltage Regulating Distribution Transformer performance	Performance analysis, network modelling and power system studies on three sites where VRDT either have installed or will be installed.
LV Engine control philosophy	System study and strategy for LV Engine control system embracing potential deployment of local and central control systems.
LV Engine Enterprise Architecture	A document that covers the system architecture, use cases, I/O schedule, communication protocols that will be used for monitoring of LV Engine performance – this document is still in draft version.
Earth Leakage Relays tests	Test procedure and results for verifying the performance of two DC earth leakage relays that will be potentially used in LV Engine.
Earth study reports and learnings	Earth studies in Wrexham and also learnings captured from these studies and literature reviews.
Layout and civil drawings for trial sites in Wrexham and Falkirk	Various design drawings for LV Engine trial sites showing substation layouts, civil designs, small wiring and 24V connections.

These documents can be made available to interested parties upon request, in line with SP Energy Networks Data Sharing Policy.

2.9 Project Issues

We have encountered the following project issues in this reporting period which are the main causes of the delay in the project to date:

- **Covid-19 Pandemic** – The risk of pandemic and its impact worldwide was not expected during LV Engine programme development. The recent pandemic has introduced a number of issues to the project, nonetheless, as reported last year we have been working to find alternative solutions and reduce the impacts where possible. The issues and the solutions are as follows:
    - Supply chain – The lead times for procuring some of the components have been significantly longer than initially expected. In some cases, the suppliers temporarily suspended all or part of the orders due to shortage of raw materials. That specially became an issue for the components required for manufacturing SSTs. Ermco-Gridbridge have reported several of the issues, however, they actively change the suppliers with larger stock availability and also ordered materials/components more than the volume needed for LV Engine to make the order more attractive to the suppliers. This has improved the delivery time however the lead times were still longer than what was initially expected.
    - Staff unavailability – Staff availabilities became unpredictable due to health issues affecting themselves or their families, and childcare especially during lockdown periods.

- **Semiconductor supply chain issue** – unpredicted high demand for semiconductors and electronic chips was another reason to delay the delivery of the key components needed for the SST prototyping and manufacturing.

- **Test failure** – one of the key components for the cooling system failed under the pressure test. Consequently Ermco-Gridbridge reengaged with the original supplier and also carried out a fresh market research to identify a supplier who can comply with technical specification within a reasonable lead time delivery. The outcome of that exercise was appointing a new supplier which provided a better quality product for the cooling system. Although the technical issue was resolved other tests and prototyping exercises were delayed.

- **Resource change** – Some of our key resources within the project partner's team changed jobs. Although we keep record of all learnings and properly document the design decisions, some key staff develop unique knowledge and understanding about our challenges that replacing them is inevitably required additional effort for recruitment and handover. Change of staff is particularly more challenging for innovation projects that the knowledge, skill sets and relevant experience cannot be offered by the same resource pot working on conventional developments.

2.10 Outlook to the next reporting period

In the next reporting period, the project critical path will be:

- Completion of manufacturing and factory acceptance test of SST Topology 1.
- Start prototyping SST Topology 2 with benchtop testing completed;
- Test the first SST Topology 1 at the Network Integration Testing centre focusing on DC protection strategy;
- Installation and commissioning the DC site at Falkirk Stadium;
- Development of safety documents, operation and manual documents and deliver relevant training prior to any commissioning;
- Submission of LV Engine Deliverable #3 and #4.

Furthermore, the following progress is planned in the next reporting period under different work packages:

Work Package 3 – Design and Manufacturing of SST

- Complete the factory acceptance tests in full power for SST Topology 1.
- Manufacture all the three SST Topology 1 units and shipment to the UK.
- Finalise the remaining design issues with SST Topology 2, start the prototyping and benchtop testing.
- Build the LV Engine local control system delivering data aggregation functionalities in DC substation.
- Prepare and submit LV Engine Deliverable #3.

Work Package 4 – Network Integration testing

- Finalise the testing schedule and all the preparation for SST Topology 1 in Power Network Demonstration Centre.
- Finalise testing DC earth leakage relays.
- Complete testing SST Topology 1 in network integration testing facility.
- Prepare a submit LV Engine Deliverable #4.

Work Package 5 – Live Trials

- Install and commission Falkirk DC trial site:
  - Install Civil, HV connections and enclosure.
  - Manufacture and test LVDC switchboard.
  - Install all the switchgears, cablings and wiring.
  - Establish Telecom and monitoring equipment.
  - Carry out site acceptance tests and commissioning.
- Progress on Wrexham site preparation and commissioning:
  - Progress on installation the first SST Topology 1 in Wrexham.
  - Continue engagement with local stakeholders for opportunity to trial LV DC in Wrexham.
- Progress on LV Engine monitoring system architecture.

Work Package 6 – Novel approach for transformer selection

- Finalise the safety documents required for commissioning and operation of LV DC and SST.
- Deliver necessary trainings to delivery and operation staff to adopt new technology.
- Install and commission an additional VRDT in Dumfries & Galloway District.

Work Package 7 – Dissemination

- Organise and hold UK DNO workshop to share lessons learnt.
- Technical papers for relevant conferences and articles.
- Share lessons learnt at ENIC (or similar event/conference).
- Continue to share project progress and lessons learnt with stakeholders within SPEN.
- Update the LV Engine website with the new document created by the project team.

3 Business Case Update

There has been no reported change to the Business Case submitted in the Full Submission Proposal (FSP) during the reporting period.

Level of confidentiality:

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4 Progress against plan

4.1 Key Achievements and project highlights

4.1.1 SST prototyping and manufacturing

Project successfully progressed on the SST design and prototyping. The following key highlights have been achieved:

- Module tests completion of SST Topology 1 and starting the system level test connecting all the major components to the internal DC busbar;
- Built the SST Topology 1 enclosure and started positioning different components inside the enclosure;
- Progress on the factory acceptance test rig set up;
- Progress on critical design of SST Topology 2.

4.1.2 Trial Site Developments

- All legal matters and technical designs completed for Falkirk LVDC substation;
- Extensive protection studies conducted for the DC protection strategy and some of the DC equipment were tested;
- Progressed significantly in LVDC switchgear tender and finalising the technical assessment
- Civil work completed in both Wrexham substations, and one of the substations has been energised with LV Engine design with adequate access to potion SST Topology 1 when it is ready;ready.

4.2 Project issues

Delay in Deliverable #3 and #4 due to delay in manufacturing and testing of SST. The project's issues were reported in detail in Section 2.9.

4.3 Key activities planned for upcoming reporting period (2022/23)

As summarised in Section 2.10, the key activities in the next reporting period are planned to achieve the following:

- Manufacture SST Topology 1 with all the necessary tests passed;
- Commission DC trial site at Falkirk Stadium;
- Conduct the network integration testing;
- Submit deliverable #3 and #4 of LV Engine.

4.4 Dissemination

The project team has a planned dissemination programme, aligning with UKPN's Active Response project. Key dissemination events include:

- Share lessons learned at ENIC and other relevant events;
- Submitting papers within academic forums;
- Holding DNO workshop to share lessons learned and obtain feedback.

5 Progress against budget [CONFIDENTIAL]

Level of confidentiality:

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6 Project Bank Account [Confidential]

7 Project Deliverables

The project deliverables set out in the Project Direction links with the Project Milestones and the identified targets directly. This project deliverables can be used to check the progress of the project delivery and position the progress against the original proposal.

Table 1 shows a summary of the LV Engine deliverables defined in the Project Direction.

Table 1 LV Engine project deliverables

	Project Deliverable	Initial target delivery date	Status	Expected delivery date
1	Technical specification of SST and functional specification of the LV Engine schemes' including relevant control algorithms	10/12/18	**Completed**	-
2	Detailed technical design of SST by the manufacturer and life cycle assessment	22/12/19	**Completed**	-
3	Manufacture SSTs for LV Engine schemes	11/01/21	**Delayed- In Progress**	30/06/2022
4	Complete network integration tests	28/09/20	**Delayed – In progress**	31/10/2022
5	Establish the system architecture of LV Engine schemes	20/06/21	**Delayed- In Progress**	31/12/2022
6	Demonstrate the functionalities of SST	20/06/22	**Not Started**	-
7	Best operational practices of SSTs	07/11/22	**In Progress**	-
8	Identify a trial site for replicating LV Engine solution within UK Power Networks	26/09/22	**Not Started**	-
N/A	Comply with knowledge transfer requirements of the Governance Document.	End of project	**Not Started**	-

SPEN confirm that adequate resources for project management and project delivery have been planned for upcoming deliverables. Resources are available internally in different parts of SPEN organisation and also additional supports will be provided by our project partners.

8 Data access details

The Publicly Available Data Sharing Policy is available via SPEN's website: https://www.spenergynetworks.co.uk/pages/data_sharing_policy.aspx. LV Engine website is accessible via: www.spenergynetworks.co.uk/pages/lvengine.aspx

9 IPR

LV Engine complies with the Ofgem default position regarding the IPR ownership and no further IPR is to report at this stage. However, we are working with project partners to finalise the list of IPRs and the type of IPRs generated in LV Engine. This list will be ready and reported in the next reporting period.

10 Risk Management [CONFIDENTIAL]

The summary of key risks and mitigation plans which are currently monitored in the project

11 Accuracy Assurance Statement

I therefore confirm that processes in place and steps taken to prepare the PPR are sufficiently robust and that the information provided is accurate and complete.

Signature: ___________________

Name (Print): ___________________

Title: ___________________

Date: ___________________

Signature: ___________________

Name (Print): ___________________

Title: ___________________

Date: ___________________

12 Material Change Information

None to report

13 Other

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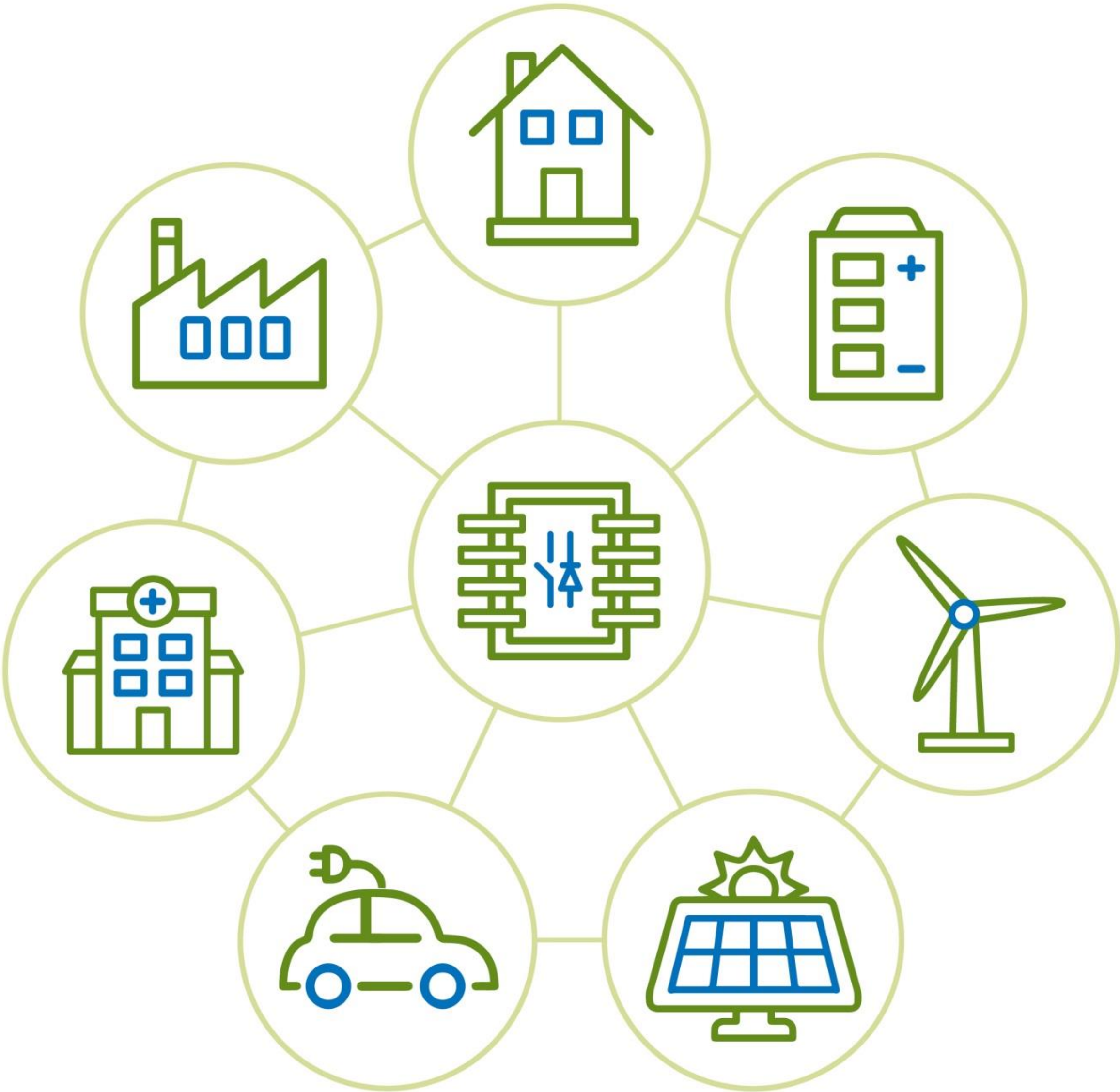

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