System Architecture – Deliverable #5

About Report

Report Title	:	System Architecture – Deliverable #5
Report Status	:	Final
Project Reference	:	LV Engine

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Report Summary & Disclaimer

This report provides the activities carried out for design and implementation of LV Engine system architecture that forms Deliverable 5 of LV Engine project in line with LV Engine project direction.

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1 Introduction

LV Engine, an innovation project funded through Network Innovation Competition (NIC) mechanism and led by SP Energy Networks (SPEN), aims to deploy power electronic technology to significantly enhance the functions delivered at a secondary substation. LV Engine provides a smart hybrid LV AC and LVDC supply offering a more efficient and improved quality of supply. There are several devices designed, manufactured, and tested as part of LV Engine development. These devices were integrated in an IT architecture to monitor their performance remotely.

This report contains learnings and information about the LV Engine system architecture design and implementation. This report intends to satisfy LV Engine deliverable #3 to show evidence on "Establish the system architecture of LV Engine schemes".

2 LV Engine Overview

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

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

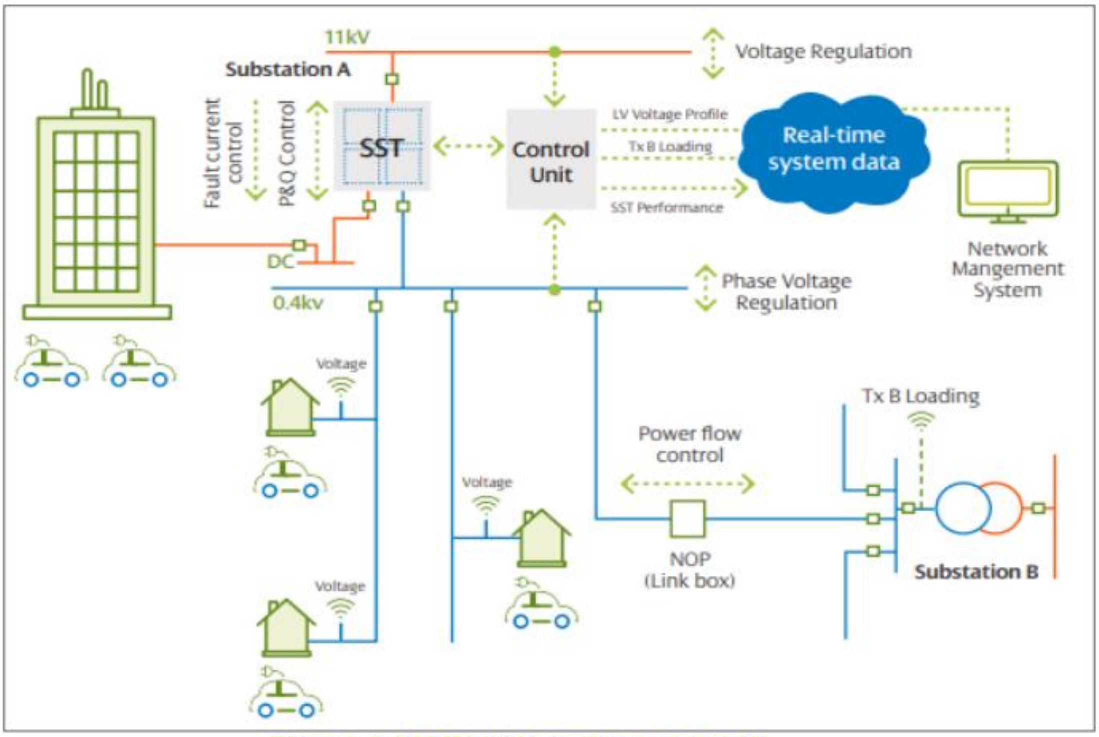

Figure 1 LV Engine project concept

3 LV Engine devices

LV Engine solution consists of number of devices that were developed and deployed for the first time in a secondary substation. The project aimed to monitor, and where possible, control these devices remotely. The key equipment newly deployed in the project and included in LV Engine system architecture are as follows:

1. Solid State Transformer Topology 1 /Unified Power Flow Controller (UPFC)
2. LVDC Switchboard
3. LV AC circuit breakers
4. Display panel and telecoms cabinet

1- **SST Topology 1/Unified Power Flow Controller (UPFC)** – This is Topology 1 of SST also known as UPFC, designed and manufactured in collaboration with ERMCO as part of LV Engine project (see Figure 2 the general arrangement of the UPFC). This device is key to delivering the smart functions planned in LV Engine project. UPFC has been designed to receive control commands (input data) or communicate performance and operation data (output data). This device communicates using DNP3 protocol over Ethernet.

2- **Local Control System (LCS)** - This is an alarm display panel and telecoms cabinet, designed specifically for LV Engine in collaboration with Nortech Management Ltd. The aim of this alarm panel is to provide an overview about the status of the various devices in the substation locally but also communicate them to SPEN's data historian and operation platforms. For example, the "normally open" contacts from the LVDC circuit breakers or HV circuit breaker have been wired to this panel. LCS collate this various status and communicate them using DNP3 protocol over Ethernet.

3- **LVDC switchboard** – This is designed and manufactured in collaboration with Schneider Electric. The switchboard accepts the DC output from the UPFC. The main function of the switchboard is to distribute power to DC customers. The LVDC distribution switchboard is fitted with disconnectors, Moulded Case Circuit Breakers (MCCB) and under-voltage release relays. Furthermore, a residual current monitor (RCM) is installed in the distribution board measuring current through the earth-neutral link. The contacts (normally open or normally close) from the MCCBS and RCM have been wired to the LCS for monitoring purposes and reporting.

4- **Controllable LV AC circuit** – These circuit breakers were deployed to allow controllable interconnection between substations and also monitor the voltage and load on each phase and each LV way of LV Engine substation. The gateway of these Controllable LV AC circuit breakers can receive control commands (input data) or send monitored data (output data) via DNP3 over Ethernet. These devices were supplied by Kelvatek.

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

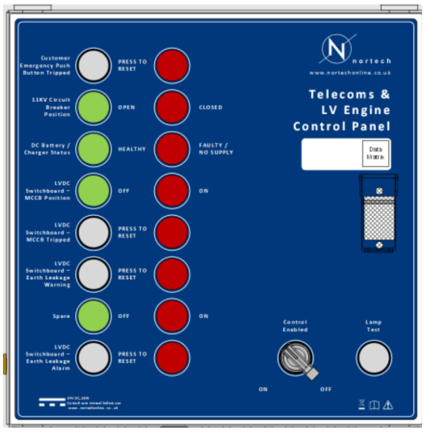

Figure 2 – UPFC (left) and LVDC distribution board (middle), LCS (Right)

Figure 3 Controllable LV AC circuit breaker (left) and their Gateway (right) collecting data from maximum 15 circuit breakers

4 Objectives of system architecture

4.1 Initial objectives

LV Engine initial objectives was to create an IT/OT system architecture that was able to deliver the following functionalities:

- Devices can be monitored remotely in near-time
- Monitored data are recorded in SP Energy Network's data historian for performance monitoring and data analysis.
- Suitable LV Engine symbol is created within SCADA to distinguish LV Engine substation from conventional substations
- Key monitored and alarms are available to LV operation team
- Residential customer's Smart Meter (SM) data are used for LV voltage control purposes.

At the time of developing project proposal, these functionalities were considered based on two key assumptions:

- SPEN's LV control room would have developed by the business and all the safety procedures for remote LV switching and control are being established in parallel with LV Engine development.
- LV Engine architecture design can meet all the cyber security requirements.

IT and OT projects are usually required significant effort with multi parties' involvements. In order to ensure that we can achieve a fit for purpose architecture that delivers the project objectives, we built a capable team of experts including internal IT and cyber security experts and external trusted consultants. In addition, all the project partners who manufactured LV Engine devices (Ermco, Kelvatek, Nortech) were involved to ensure an end-to-end working solution would be developed.

4.2 Challenges

Despite the preliminary design set out based on the initial system architecture objectives, LV Engine team encountered number of issues that raised risk to overall project programme. In order to mitigate the risks, we modified the design and prioritise the functions that can be practically developed and demonstrated within the project life-time with adequate learnings and best value for money. We encountered the following issues:

- Safety procedures for remote control of LV devices and establishing LV control room functions were not developed in SPEN adequately in parallel with LV Engine project progress. Development LV control room functionalities and organisational changes was not part of LV Engine scope of work and that requires extensive development which could have come with significant cost and time on LV Engine causing overspent and non-delivery risks.

- SPEN' IT infrastructure house communication, recording and analysis of LV networks monitored data. This is a strategic decision as much larger data volume communication and analysis is required for LV networks, compared to HV distribution networks for which data are captured and communicated to the real-time system (OT) infrastructure. Nonetheless, OT infrastructure hold the conventional remote-control functions which are well established in SPEN' control room for HV and EHV networks. For data monitoring and control at LV, even as a demonstrator, we had to create a bridge between IT and OT infrastructure which raised major cyber security issues. These issues could not be resolved only by LV Engine and even a stand-alone demonstration would have offered only little learnings that could not contribute to an enduring solution.

- During the project, there were issues with access to SM data and using them in "near-time" to input to a remote LV voltage regulation function. The issue was mainly related to infrastructure, data pulling rate and SPEN' interfaces with Data Communication Centre.

4.3 Modified objective

Considering the issues encountered and our aim to provide the best value for money for activities in LV Engine, we opted to remove the remote-control objective from the system architecture and build up LV Engine system architecture within IT infrastructure. SPEN' IT infrastructure was also strategically planned by the business to host all the LV monitored data. That could increase the chance of final LV Engine system architecture to be adopted by the business after project completion.

5 System architecture design

The overall system architecture is shown in Figure 4. Data reported from three devices (UPFC, LCS and LV CBs) are collated at secondary substation by a router acting as a smart hub. The router then sends the information via an IOT protocol over a private APN to a headend router which directs data to FieldOnline platform. This platform performs validation of events and stores the raw events for reporting and audit purposes before passing then to smart data integration platform where more extensive data analytic functionalities are available.

The monitored data then will be directed to SPEN's data historian, and they are also available to LView platform which is SPEN's customised design platform for visualising LV monitored data. It should be noted that when we started LV Engine architecture design, the overall LV monitoring project in the company had not started completely yet. Design of LV Engine monitoring system architecture was a test bed to provide guidance for an enduring LV monitoring system architecture. That was an example that an ongoing innovation project provided learning to a larger scale development in the business.

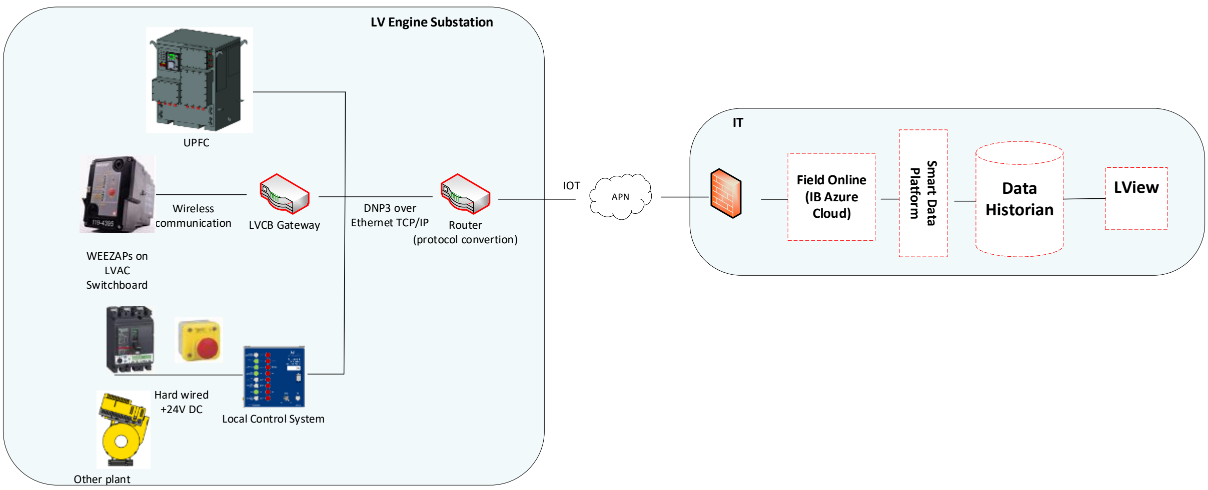

Figure 4 LV Engine system architecture

6 Work carried out

Extensive work was carried out to develop the system architecture and confirm end-to-end communications. The key works carried out were as follows:

- Router firmware design and development to act as a smart hub communicating with multiple devices in a secondary substation
- Established a comprehensive I/O schedule and IOT messaging sheet (DNP3 to IOT) which then set up in the router
- Upgraded FieldOnline firmware to be able to receive the messages from different substations
- Developed a complex end-to-end testing methodology prior to full commissioning
- Created and implemented PI (data historian) tags for LV Engine devices. It should be noted that we had to define tag's naming conventions at LV for a three phase system as no LV network tag was previously created/reported to SPEN's data historian
- Developed high level and then low-level designs of the system architecture with all firewalls setting, IPs and ports required for a fully workable architecture.

6.1 Substation Smart Hub

An approved router, which was previously passed the cyber security tests by SPEN, and has multiple Ethernet ports, was selected for the project. The router provides the following functionalities:

- Acts as an aggregator for measurements collected over DNP3 Ethernet within the substation
- Converts these measurements into IoT messages which are sent to SPEN's FieldOnline system over APN network
- Provide a local gateway for accessing and managing devices within substation

The overall router's architecture design is shown in Figure 4. In our initial design, the router was considered to act as both DNP3 master and slave to facilitate both monitoring and remote control. However, due to challenges we encountered for remote control of LV devices (explained previously), the DNP3 slave function was not developed.

The router has a data store for buffering messages for later transmission if the 4G mobile data link drops out or is bandwidth restricted. It can also perform averaging of measurements. In our case substation analogue measurements are generally made every minute. These are then averaged over 5 minutes, so that the IoT messages for an analogue measurement are sent every 5 minutes.

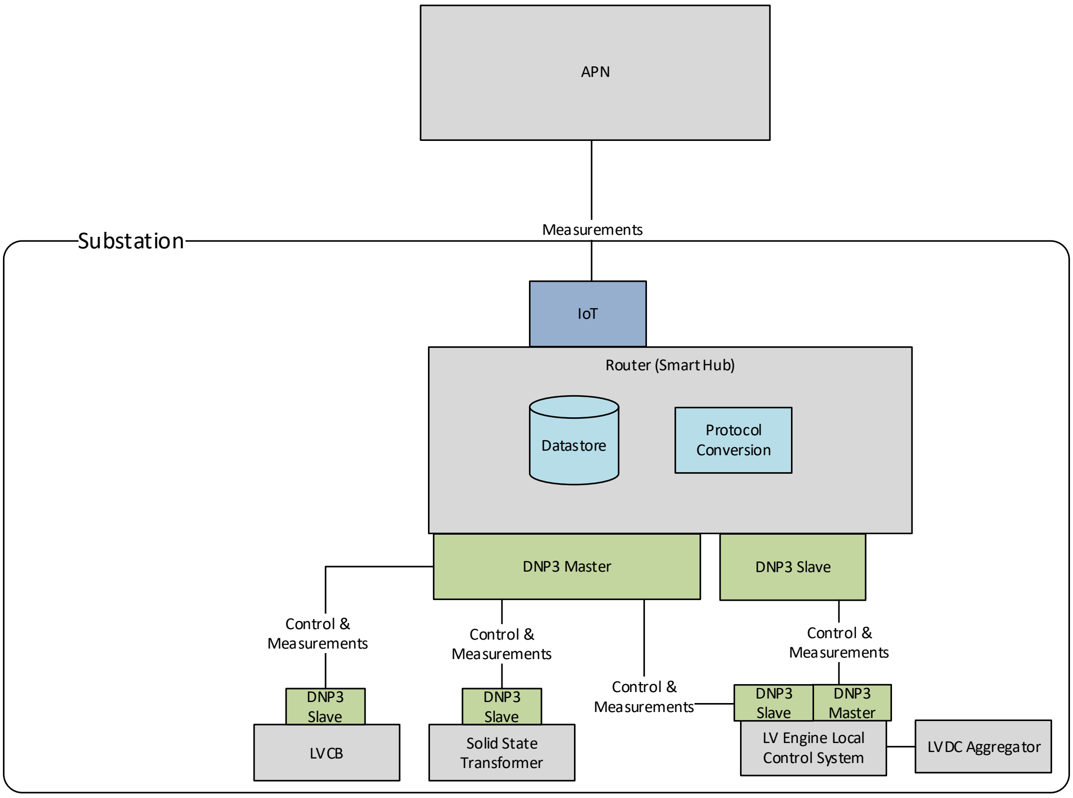

Figure 5 Router (Smart Hub) architecture design

6.2 Monitored data points

In total the following data are monitored and received through the LV Engine system architecture:

- UPFC: 83 parameters
- Local Control system: 11 parameters
- Each AC LV way fitted with LV CBs :45 parameters, LV Engine substation may have up to 5 LV ways

6.2.1 UPFC parameters

Following data points have been included in the design:

10 binary parameters: That includes alarms from various internal faults, status of control modes and switches on the control panel.

73 analogue parameters: That includes control parameter set points, voltage and current monitored for each phases, active and reactive powers for each phase, DC voltage and currents, total power values and losses, device thermal margins, and total harmonic distortions, all parameters for incoming and outgoing terminals.

6.2.2 Local control system parameters

Following data points have been included in the design:

8 binary parameters: status of LVDC circuit breakers, substation battery health system, leakage relay status and warnings, status of 11kV circuit breaker, and customer emergency button status

2 analogue parameters: ambient temperature and humidity

6.2.3 LV CBs parameters

Following data points have been included for each LV ways in the design:

18 binary parameters: change in status of CBs, status of in-line fuses, temperature alarm and warnings.

27 analogue parameters: voltage and currents, active, reactive powers and apparent powers.

6.3 FieldOnline functions

The interface to the FieldOnline system:

- Uses the IoT protocol with an asynchronous publish/subscribe model;
- The link is implemented as an Azure Service Bus topic;
- Messages are encoded in IOT messages;
- The link is encrypted with TLS;
- Authentication is a combination of client certificate and Service Bus Shared Authentication Sercvice (SAS) Tokens.

7 System architecture pre-commissioning testing

One of the challenges was for the team to test the smart hub (router) prior to commissioning on site. LV Engine equipment were supplied by different vendors located in different countries. Therefore, it was physically impossible to give the equipment to the router vendor, Australian based, to run their factory tests and ensure communication with devices and protocol conversions are working as per design.

In order to facilitate the test, we established VPN channels from vendors' offices to the router supplier offices to allow live communication of the devices with the router. In this way, the router supplier could establish the full I/O schedule communication with each device i.e. UPFC, LVCB and LCS. After that confirmation, we had to confirm those IOT messages can receive by SPEN's FieldOnline which uses Azure services.

In order to mimic the SPEN's Azure environment, router supplier created an Azure environment with the same settings as SPEN's Azure to which SPEN's IT team was appointed as Listener via service bus client. In this way SPEN's IT team could see the data points communicated from UPFC, LCS and LVCB vendors to router supplier in IOT messaging format. This data then routed in SPEN IT infrastructure to data historian and LView platform confirming an end-to-end pre-trial test. All these tests were happening while devices where in vendors premisses in their respective countries and in different time zones. Figure 6 show a general set up for pre-trial testing.

Several issues were encountered during these tests that resulted in firmware updates by all the vendors. This exercise was successfully de-risk the issues that could arise during commissioning where vendors were restricted with time and access to the equipment in the substation.

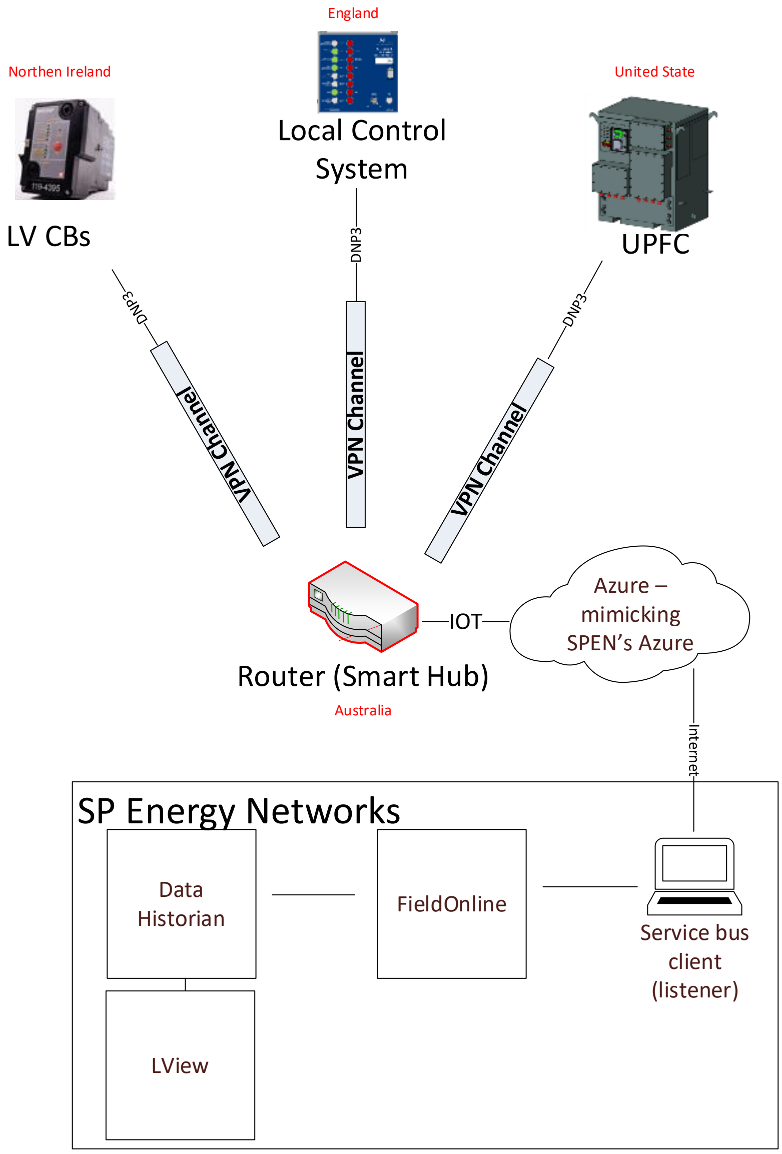

Figure 6 Pre-trial end-to-end tests

8 SCADA PowerON

In order to differentiate between LV Engine substation and the conventional secondary substations, a new symbol was designed and agreed internally which represent the hybrid AC and DC nature of LV Engine substations.

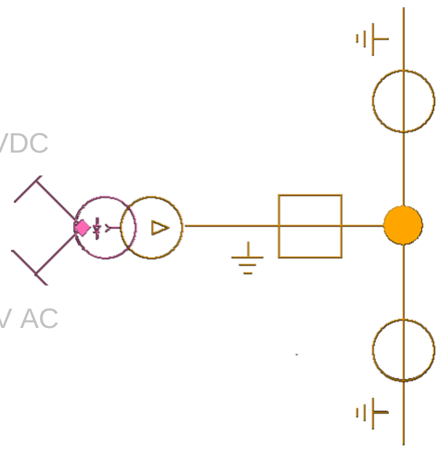

Figure 7 PowerON symbol for LV Engine substation

9 Visualisation platform

We used different visualisation platforms for performance monitoring during the project:

- LView: This platform is for operational purposes and being rolled out across SPEN for to inform day to day LV operation decisions. The historic data only available for the last 24 hours on this platform.
- PowerBI: We created a powerBI dashboard to visualise the historic data for the last 30 days. PowerBI was extracting the information from PI historian and could visualise the data with different filtering options. We could share the link with various stakeholders across the business for internal disseminations and trainings.
- Excel dashboard: As PowerBI reports could not be shared with external stakeholders, and also they can only be used when connected to SPEN's IT network, we created Excel dashboard too which can automatically extract the raw data from PI historian and available for offline analysis.

The ability to monitor the performance of LV Engine substations remotely supported the team to identify any operational issues, collate better learnings and also use the historic data for inputs to LV Engine Deliverable #7 which details the performance analysis of the LV Engine solution.

Solid State Transformer

Description	Legend/Units	Type Code	Status	Chart
System Alarm, 0=NORMAL, 1=FAULT	SYSTEM_ALARM	FSD	OFF (0)	Chart
System Fault, 0=NORMAL, 1=FAULT	SYSTEM_FAULT	FSD	OFF (0)	Chart
Indicator that the Service Panel User Interface AC Service is OFF/ON per the SPUI 0=OFF(Bypass) 1=ON(Active)	AC_IN_SERVICE	FSD	ON (ACTIVE) (1)	Chart
Indicator that the Service Panel User Interface DC Service is OFF/ON per the SPUI	DC_IN_SERVICE	FSD	ON (1)	Chart
Indication of the current state of the AC Service 0=BYPASS, 1=LIMITED, 2=NORMAL, 3=FAULT	AC_SERVICE_STATUS	FDD	LIMITED (1)	Chart
Indication of the current state of the DC Service 0=OFF, 1=LIMITED, 2=NORMAL, 3=FAULT	DC_SERVICE_STATUS	FDD	LIMITED (1)	Chart
Indication of the mesh power control 0=OFF, 1=LIMITED, 2=NORMAL, 3=FAULT	MESH_POWER_CONTROL_STATUS	FDD	BYPASS (0)	Chart
Indicator that the Rectifier is Normal or Fault State 0=OFF, 1=LIMITED, 2=NORMAL, 3=FAULT	RECTIFIER_HARDWARE_CONTROL_STATUS	FDD	FAULT (3)	Chart
Indicator that the Inverter is Normal or Fault State 0=OFF, 1=LIMITED, 2=NORMAL, 3=FAULT	INVERTER_HARDWARE_STATUS	FDD	FAULT (3)	Chart
Indicator the Radial Voltage is Normal or Limited Mode 0=OFF, 1=LIMITED, 2=NORMAL, 3=FAULT	RADIAL_VOLTAGE_CONTROL_STATUS	FDD	LIMITED (1)	Chart
Indicator the Phase Current Unbalance is in Normal or Limited 0=OFF, 1=LIMITED, 2=NORMAL, 3=FAULT	PHASE_CURRENT_UNBALANCE_STATUS	FDD	BYPASS (0)	Chart
Indicator the PFC is in Normal or Limited Mode 0=OFF, 1=LIMITED, 2=NORMAL, 3=FAULT	PFC_STATUS	FDD	BYPASS (0)	Chart
Total source active power	MW	FA5	0.02005	Chart
Total source reactive power	MVAR	FA5	-0.064676	Chart
Total source apparent power	MVA	FA5	0.071012	Chart
Total load active power	MW	FA5	0.000342	Chart
Total load reactive power	MVAR	FA5	0.000605	Chart
Total load apparent power	MVA	FA5	0.001194	Chart

Figure 8 LV Egine dashboard set up on LView platform

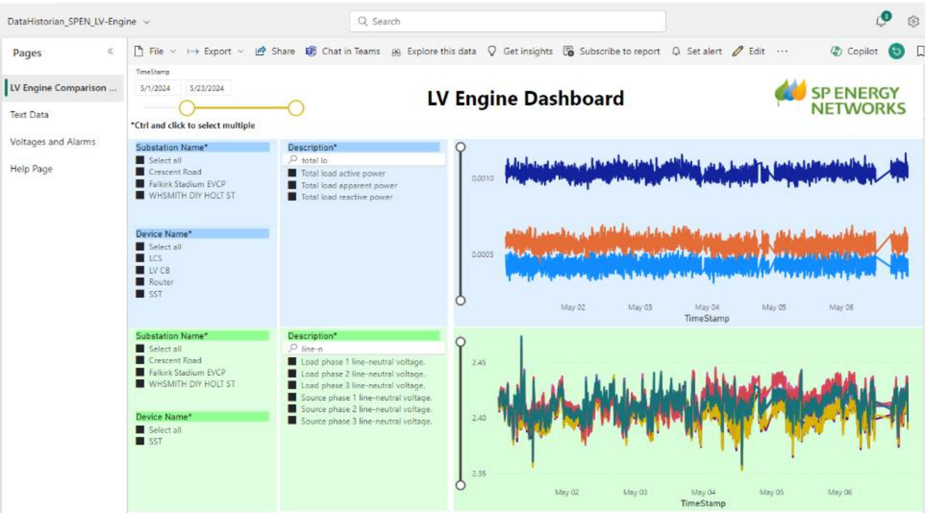

Figure 9 PowerBI LV Engine dashboard used to monitor the LV Engine solution performance

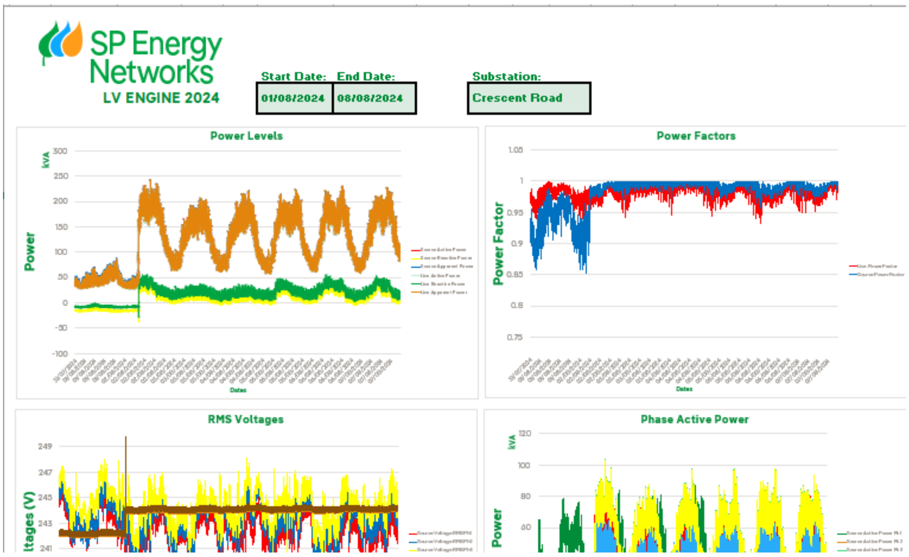

Figure 10 Screenshot from the LV Engine Excel dashboard used for performance monitoring

10 Key lessons learnt

The following key lessons learnt can be shared as part of LV Engine system architecture development:

- Integration of smart solutions in company's IT and OT networks take significant effort and resources. The cyber security, threat intelligence and remote device management requirements are usually the key challenging requirements that should be considered from start of architecture design with adequate resources allocated to these tasks.
- The overall system architecture and implementation in IT or OT networks can be specific to a company's existing infrastructure, strategies, and policies. While the key learnings (at high level) can be shared with stakeholders outside the company, the details of the design remains highly confidential that cannot be published in public reports due to cyber security reasons.
- The safety requirements and procedures for remote control of LV devices, especially remote LV network switching, need further consideration by network operators for more innovation works with focus on safety procedures to mitigate risks of electric shocks.
- LV Engine successfully conducted a pre-installation end-to-end system architecture test with devices located in different countries. The test set up and the arrangement significantly de-risk the issues that we could have encountered otherwise at the time of commissioning.
- LV Engine demonstrated a smart hub solution where multiple devices can communicate with a router using an industry established DNP3 protocol. This solution should be considered for further roll out as we expect more LV monitoring and smart solution to be deployed in secondary substations. Smart hub solution can potentially provide less complexity for device managements, better cyber security monitoring and implementation with minimum dependency on device vendors, and opening market to more competition for devices that can be deployed in secondary substations.
- LV networks data include significantly higher volume data compare to HV and EHV networks. For that reason, LV data usually requires a separate infrastructure for data transmission and also high computational efforts for data analysis. Significant challenge remains on the requirements of an efficient infrastructure that can allow both real time operation of devices and computations required for extracting meaningful analytics. In these designs, the IT and OT networks are likely to require exchange information due to legacy of real time systems being built in OT networks whereas IT networks hold the data analytic practices. This IT – OT bridging design can raise cyber security issues which suggest more room for innovation to capture learning across electricity network companies.

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