FITNESS – GB's Pilot Multi-Vendor Digital Substation - Architecture and Design Philosophy

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Abstract

The FITNESS (Future Intelligent Transmission Network Substation) project will be the first multivendor digital substation and automation system in the UK. This project is funded by Britain's electricity regulator, OFGEM (Office for Gas & Electricity Markets) from RIIO NIC (Network Innovation Competition) and will be deployed at the Wishaw 275kV substation in Scotland. The project is an IEC61850 based multi-vendor solution.

FITNESS proposes a low outage and low risk approach to substation asset replacement and load related investment by replacing hardwired signalling with digital communications using an open platform upon which novel and enhanced monitoring, protection and control functions can be built. This enables faster deployment, greater availability, improved safety and greater controllability with a reduced footprint and lower cost than conventional designs. It will also help to defer new build substations and expansions, deriving benefits for transmission and distribution operators and customers.

In the FITNESS project, the innovation is found in the way the overall system is designed. The project aims to prove IEC61850 interoperability at various levels with the protection and control equipment procured from various suppliers at the process bus, station bus and the substation control system (SCS) levels. To achieve this Scottish Power Energy Networks (SPEN) are working with two main vendors and also with equipment manufactured by a third vendor. The various levels of interoperability the project aims to prove are:

- Between Vendor 1 protection IEDs and Vendor 2 merging units;
- Between Vendor 2 protection IEDs and Vendor 1 merging units;
- Between Vendor 1/Vendor 2 PMUs and Vendor 3 Interrogator;
- Between Vendor 2 protection IEDs and Vendor 1 SAS;
- Between Vendor 1 protection IEDs and Vendor 2 SCUs;
- Between Vendor 2 protection IEDs and Vendor 1 SCUs.

FITNESS will prove not only interoperability at multiple levels but also within a mixture of old and new technologies. In particular, the interoperability of stand-alone merging units and protection IEDs, IEC61850 and IEC61850-9-2LE have been given priority. This is because aspects such as transient response, accuracy and dynamic behaviour will come into play and influence the performance of the overall FITNESS system and other future roll-out schemes.

This paper will address the design philosophies and presents the FITNESS architecture.

1. Introduction

FITNESS, Future Intelligent Transmission Network Substation is GB's first multi-vendor digital substation demonstration project at SP Transmission's (SPT) Wishaw 275kV substation. FITNESS (Future Intelligent Transmission Network Substation) proposes a low outage and low risk approach to substation asset replacement and load related investment by replacing hardwired signalling with digital communication and through provision of an open platform upon which novel and enhanced monitoring, protection and control functions can be built. This enables faster deployment, greater availability, improved safety and greater controllability with a reduced footprint and lower cost than conventional design. It will also help to defer new build substations and expansions, deriving benefits for transmission and distribution operators and customers.

The new technology to be deployed at Wishaw substation, based on modern digital communications with integrated information technology, will help to improve system visibility, diagnostics and operations, resulting in increased reliability and safety. Both vendor 1 and vendor 2 will deploy their optical instrument transformer technology in the selected circuits.

FITNESS is trialling a new substation architecture that significantly reduces the number and length of circuit outages throughout the life cycle of the substation, enables new measurement, monitoring, protection and control applications, and allows integration of low carbon technology into substation design in a standardised and optimum way:

- Measurement using Non-Conventional Instrument Transformers (NCITs) and novel distributed sensor technology, providing increased accuracy, quality, reliability of measurement while reducing safety and environmental impact. As well as conventional transformer measurements digitised at source by a Merging Unit (MU).
- Digital communications using the IEC 61850 9-2 Process Bus standard for publishing digital SV and sent over a fibre optic link, to replace analogue signals over copper wiring from switchyard to control building.
- Monitoring of dynamics, fault recording and PQ functions using the digitised data sources, feeding central information and control systems.
- Protection with digital communications in place of hardwired inputs and outputs, reducing physical size, enabling connection with reduced outage, and adaptable to system conditions.
- Control via flexible logic processes applied to incoming data, enabling grid-sensitive constraint and risk management.
- Substation management and integration to central information systems.

The following standards and literature have been used for designing FITNESS architecture

SPT Standards: -

- PROT-01-008 - Requirements for the protection & control application policy to be applied on the 400kV and 275kV transmission systems within the SP Transmission licence area;
- PROT-01-018 – Protection and Control Design Policy.

IEC Standards: -

- IEC 62439-3 Industrial communication networks – High availability automation networks Part 3: Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR), Edition 3.0 2016-03);
- IEC 61588 / IEC61850-9-3 (POWER PROFILE) - Precision clock synchronization protocol for Networked measurement and control systems IEC 61588:2009(E), IEEE Std. 1588(E): 2008
- IEC61850-9-3 (POWER PROFILE) ™, Edition 2.0 2009-02; IEC61850 Edition 2.

2. FITNESS Architecture

The FITNESS project officially started in 2016 and over the course of the last year through multiple workshops, both main vendors presented their preferred system architectures. Vendor 1 presented a system architecture with a redundant station bus star-connected topology at the bay level and independent dual process bus at the process level. It was agreed both vendors will try their preferred architecture independently on different bays at process bus level and share their findings. There is one integrated architecture at the station bus level. Each vendor agreed to provide the necessary hardware in order to demonstrate both variants and a combination of both. A crucial part of the design of the system architecture to be deployed is to ensure scalability is considered should the need arise to extend the number of bays at the substation.

The FITNESS architecture is a single combined architecture based on the proposals of both vendors demonstrating interoperability among multi-vendor Intelligent Electronic Devices (IEDs) and between conventional and digital substation design. The station level architecture is a common architecture agreed by the FITNESS project team, however, each vendor has assumed responsibility for their designated process level architecture with vendor 1 applying HSR network and vendor 2 applying a PRP network. As described in the IEC61850 standards, there are three main communication categories utilised in a digital substation: Manufacturing Message Specification (MMS), Generic Object Oriented Substation Event (GOOSE) and Sample Values (SV). The MMS is based on a Client-Server communication principle and it covers operational related information such as control, alarms and indications. GOOSE and SV are based on a publishing-subscribing principle and are used for time critical missions such as trip commands and analogue data used by the protection systems.

In the FITNESS architecture at the station bus level, MMS and GOOSE services are utilised whereas, at the process bus level, SV and GOOSE services are utilised. Power system protection elements combined with modern communication technologies enable a robust system architecture organised on three vertical levels from the process level to the station/control room level.

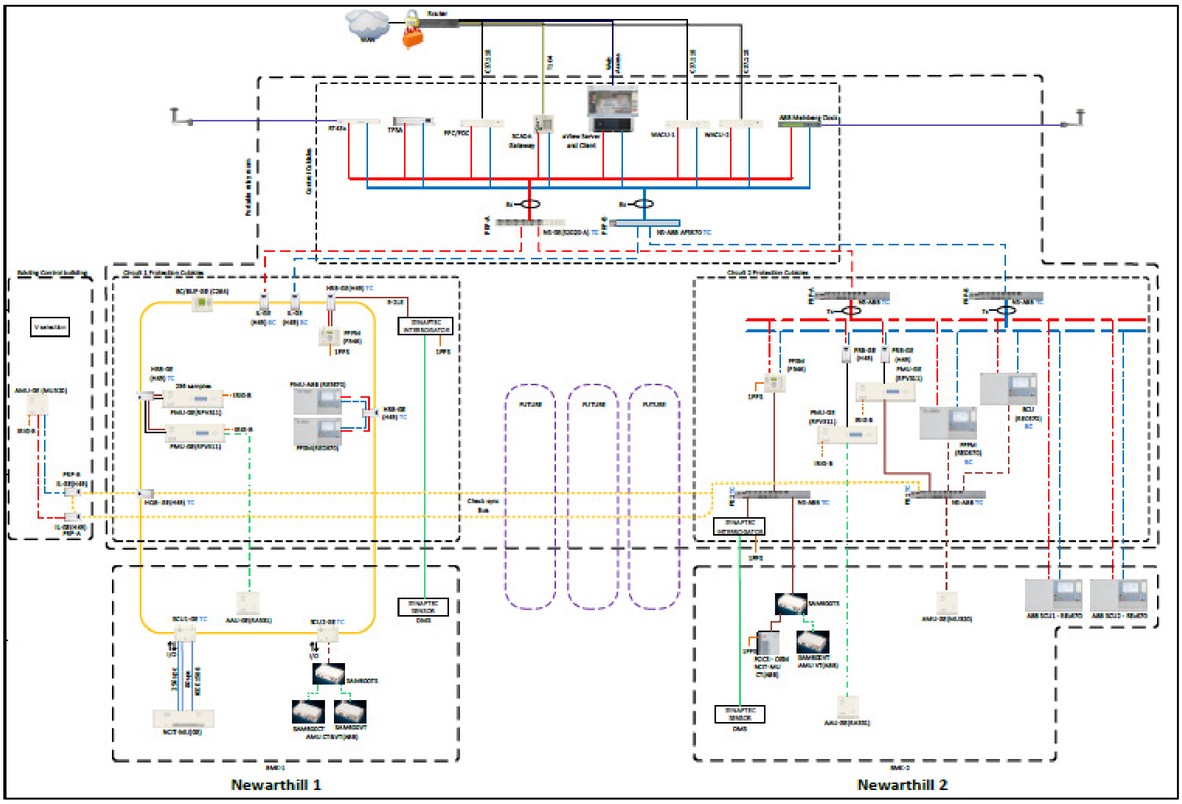

Figure 1: FITNESS architecture

2.1 Station Level Architecture

The station level devices comprise of:

- A gateway
- Wide Area Control Units (WACUs)
- HMI
- Time synchronisation units
- Phasor data concentrator
- Routers
- Station level switches
- Tele-protection standalone units

The architecture at the station level is based on PRP.

Bay level switches are configured to operate as boundary clocks which mean they can become master clocks if no better clocks are detected on the network. By doing so, this will keep the station bus synchronised.

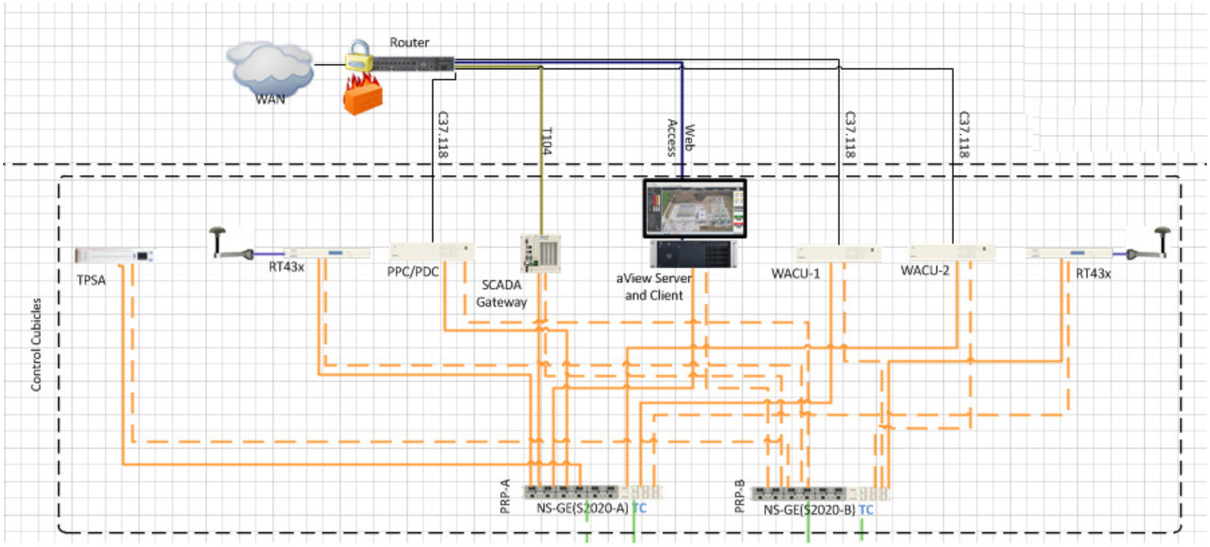

Figure 2: Station level architecture

2.2 Process Level Architecture

The bay and process levels consists of protection IEDs supplied by two vendors, a centralised measurement recorder, network switches and bay control units (BCU) manufactured by vendor 1. The BCU includes integrated backup protection; delayed auto-reclose (DAR) and breaker fail (CBF).

2.2.1 Bay 1 Architecture

The architecture proposed by vendor 1 uses Ethernet as the backbone. It implements IEC61850 Edition 2 unifying communication standard to facilitate information sharing and interoperability. IEC61850-8-1 is used for exchanging digital and analogue information over the station bus and process bus. Analogue information is transmitted from field devices at the process level to the respective IEDs using IEC61850-9-2 sampled values. The protection IEDs use 80 samples per cycle whereas the measurement processes will be based on both 80 and 256 samples per cycle for the benefits of comparison.

Redundancy in Bay 1 (Wishaw – Newarthill 1) is achieved by means of a high availability seamless redundancy protocol (HSR) ring. HSR was selected due to its simplicity for the relatively small number of IEDs at the process level and because use of a one gigabyte network ensures message latency and bandwidth are not constraints for the application. Redboxes are used to connect IEDs that do not support HSR. Interlinks are used to interconnect HSR and parallel redundancy protocol (PRP) networks where the process level and station level meet and to optimise the data traffic of the whole system.

Bay level IEDs send command or trip signals to the switchgear control units (SCUs) to operate primary plant. Having a shared network allows redundant tripping devices (SCU 1 and 2). In the same way, information/alarms can be acquired by both SCU's to provide redundant information at the bay level IEDs.

On a separate stream of work to compare different data streams and accuracy of each stream a Phasor Measurement Unit (PMU) from vendor 1 is used to acquire analogue information from measurement class CTs. This data will be compared with the digitised data coming from the non-conventional CTs using a PMU from vendor 2. One dedicated PMU will be used to compare SV data received using 256 samples/ cycle from the MU's. This process will analyse interoperability, quality and accuracy from each stream. The outcome of this comparison will provide valuable insight into both suitability and benefits of digital substations for wide area monitoring and protection (WAMPAC) applications.

Bay levels IEDs report status and alarms as well as disturbance records to the station level through the H49 switch configured as a PRP-to-HSR (interlink). This topology allows two redundant connections per bay whatever the number of IEDs included at bay level. Redundancy is achieved by means of HSR. Interlinks are used to interconnect HSR and PRP architectures. Inter-bay information will be exchanged using a separate network connected to each bay. The interconnection can be done through a single star topology or redundant topology (HSR) depending of the level of criticality of necessary information.

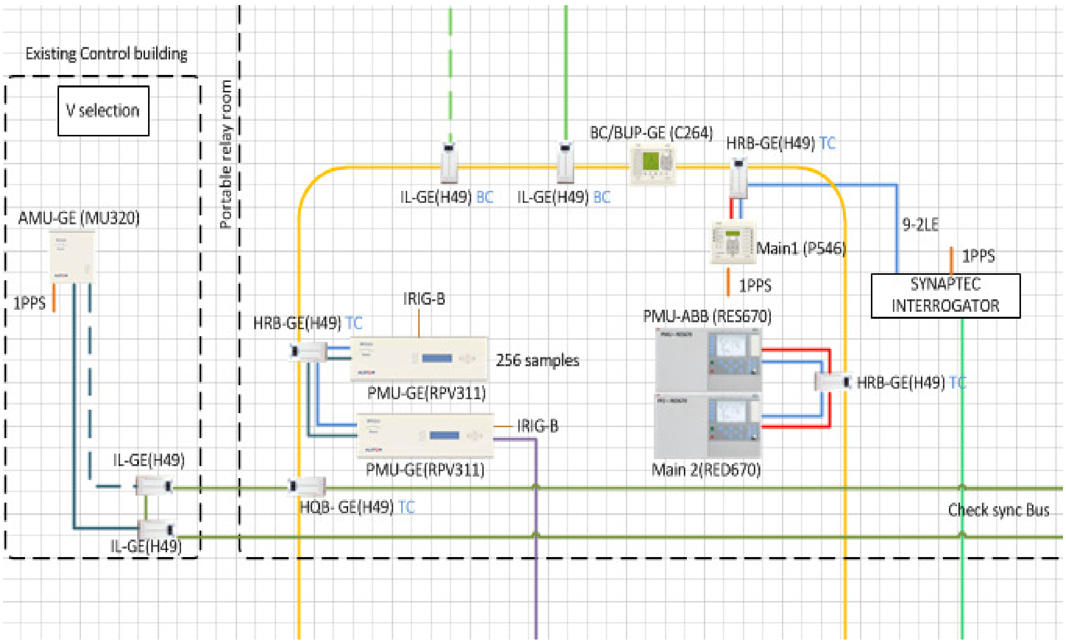

Figure 3: Bay 1 system architecture at bay level

The process level architecture consists of one gigabyte HSR network in Bay 1 where information is shared within the same network. Both standalone merging units and conventional merging units are connected to the process bus via the switchgear control unit (SCU) acting as a redbox as well as a command and tripping device. Information is then subscribed by bay level IEDs. Bay level IEDs are connected directly to the gigabyte networks or through a redbox depending on their capabilities. The process level includes equipment provided from the three vendors involved in the FITNESS project:

- Vendor 1 SCU
- Vendor 1 standalone merging units (SAMU) for the deployed NCITs on one bay and conventional merging units for interfacing with the CTs and VTs on the other bay
- Distributed measurement sensors supplied by Vendor 3

- Vendor 2 merging units.

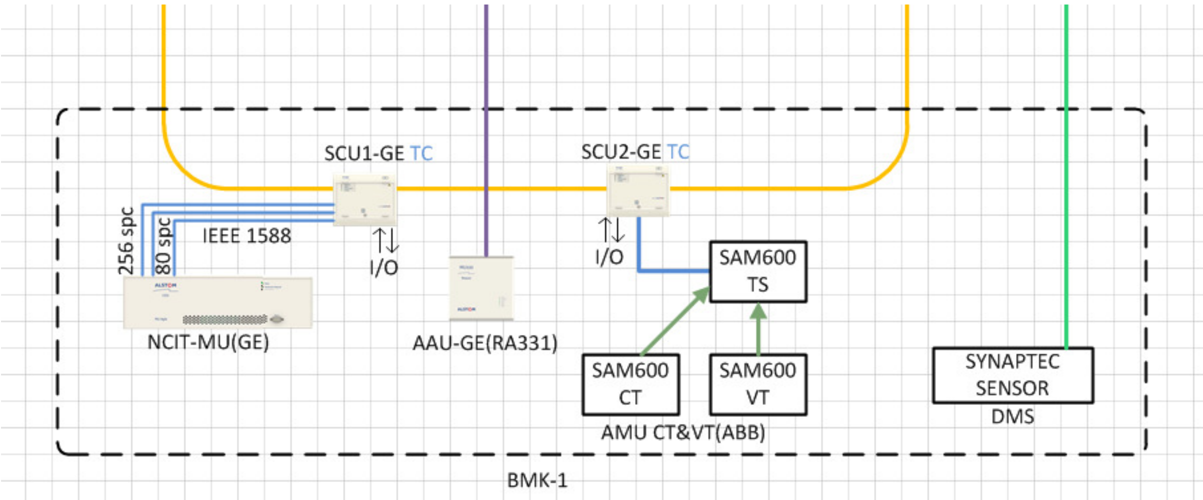

Figure 4: Bay 1 system architecture at process level

2.2.2 Description of Data Streams

This section will briefly outline data streams passed around the architecture.

IEC61850-8-1:

GOOSE messages are used to exchange status information in addition to protection trips and control signals to plant equipment. Field devices will perform the acquisition and send fast information; typically single point status and double point status to bay level IEDs. Bay level IEDs will send trip GOOSE and command GOOSE messages to field IEDs. Bay IEDs can also exchange GOOSE messages for any automation purpose such as breaker fail initiation or auto-reclose blocking.

IEC61850-9-2 LE:

The bay level IEDs receive the voltage and current information from the conventional and non-conventional CTs and VTs by sample values from the merging units at 80 and 256 samples per cycle. Protection relays use 80 samples per cycle while 256 samples per cycle are used for power quality measurements.

IEEE C37.118:

These messages are used for wide area monitoring and control applications located at the station level or above. The RPV311 device will read sample values from either MUs or SAMUs and convert to IEEE C37.118 to facilitate the exchange of phasor information between the station level and bay level measurement IEDs.

IEC61850-9-3:

Both station level clocks are connected to GPS antennas. GPS converts the timing information into IEC61850-9-3 (Power Profile) format and transmits this over Ethernet on station bus and process bus respectively. This information is used by protection IEDs for sampled values and event time synchronisation.

1PPS:

A 1 pulse per second signal is available for the sampled value synchronisation and line differential protection function.

IRIG-B:

The IRIG-B signal is available for synchronisation of the phasor measurement units.

2.2.3 Bay 2 Architecture

vendor 2 presented a single ring/dual ring architecture connecting all components into one single/dual ring. A redundant station bus star-connected topology at the bay level and independent dual process bus topologies at process bus level is the preferred system architecture from vendor 2's perspective. This architecture features a series of advantages, among them: -

1. It follows the engineering concept of complete segregation between process and station bus, as opposed to single / dual ring where both station and process buses are merged into just one;
2. It is in line with the conventional protection system approach, as dual process bus mimics very well the concept of main 1 / main 2, tripping system 1/ tripping system 2. It should be noted these process buses are not communicated outside the bay. If required, a third Ethernet switch can be added within each bay – this could act as an inter-bay process bus. This Ethernet switch is to be provided by vendor 1 and probably housed in the control room;
3. It offers a maximum level of independence during equipment replacement or trouble-shooting (the redundancy of the scheme is not compromised whilst taking out of service one device).
4. It's very much in line with the AS3 concept promoted by National Grid, UK and the University of Manchester.

The proposed solution from vendor 2 encompasses dual LANs organised in a PRP mode on station bus and independent dual process buses within each bay. For redundancy, there will be two station clocks and two station LAN switches from different vendors which fully supports the power profile with boundary clock and transparent clock functionalities. NCITs will be digitally connected to IEDs via merging units. Each vendor will deploy their optical instrument transformer technologies on different circuits. The three single-phase NCITs will be connected via fibre optic to the optoelectronic module (OEM), housed in the bay marshalling kiosk (BMK). It is here where the final IEC61850-9-2 LE stream is generated by merging units provided by the OEM unit for current and a separate unit for voltage. The unit to be utilised for voltage is also responsible for time synchronising the whole chain of merging units and providing, where necessary, the 1 PPS signal. The BMK will be located near the primary plant in the substation and shall be designed to provide the necessary protection class to all sensitive equipment housed inside.

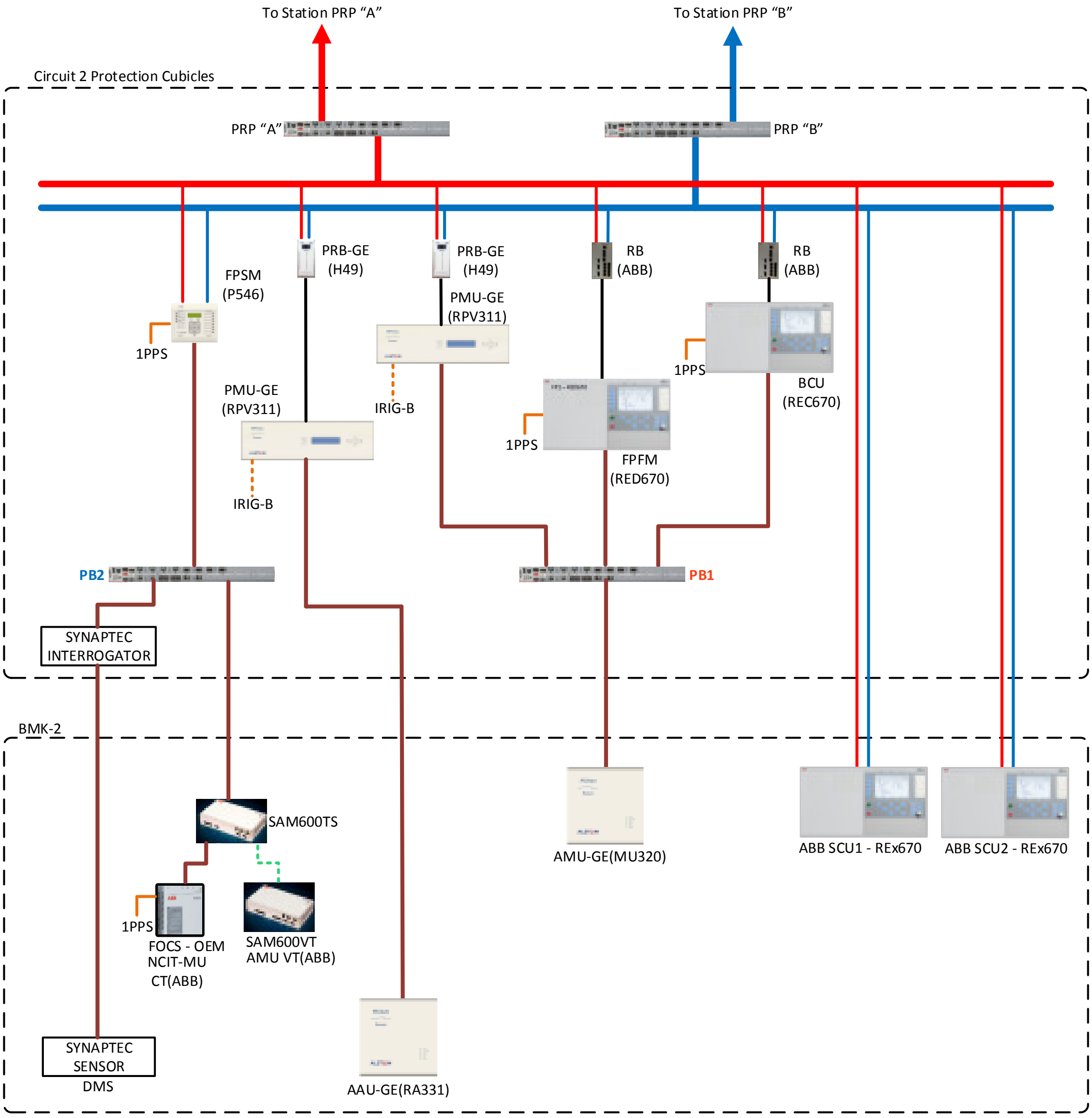

Figure 5: Bay 2 system architecture at bay and process level

2.2.4 Description of Data Streams

On bay 2, Wishaw - Coatbridge - Newarthill 2 circuit, the following data streams are passed around the network:

Process Bus Data (IEC61850-9-2LE):

The merging units derive their analogue quantities from non-conventional CTs and conventional VTs. Both streams of data (sample values containing both voltage and current) are then merged by the SAM600TS unit and published on the corresponding process bus switch at the station level. The vendor 1 supplied merging unit derives its analogue quantities from conventional CTs and VTs and publishes the merged SVs to the corresponding PB switch at the station level.

At the bay level the relevant IEDs are configured in such a way that the vendor 2 IEDs will utilise the sampled values provided by the vendor 1 merging unit and vice-versa.

Station Bus Data (IEC61850-8-1):

GOOSE messages are widely used to exchange status information in addition to protection trips and controls to plant equipment. SCUs 1 & 2 will perform the acquisition and send fast information to the bay level IEDs. Bay level IEDs will send trip goose and command GOOSE messages to the SCUs. Bay IEDs can also exchange GOOSE messages for any automation purpose such as CBF initiation or auto-reclose blocking.

3. Time Synchronisation

For the FITNESS project, the time synchronisation architecture comprises two GPS based master clocks – one supplied from each vendor – acting as grand master clocks, directly connected to the two station LAN switches, configured to act as transparent clocks. From the station level, the clock signal is transferred to the bay level switches, configured as boundary clocks. These devices participate in selecting the best master clock and can act as the master clock if no better clocks are detected. The boundary clock mitigates the number of network hops and packet delay variations in the packet network between the grand master and slave.

As none of the IEDs involved in the architecture can act as a boundary clock, in order to synchronise the process bus switches (PB1 and PB2), the CLK1-2 PTP output will be connected directly to the PB1 switch and CLK2-2 PTP output will be connected directly to the PB2 switch.

This will enable the synchronisation of vendor 1 and vendor 2 merging units. Once synchronised, the vendor 2 merging units can provide multiple outputs of the time synchronisation signal in 1 PPS format, as this may be required by some devices that are not yet compatible with IEC61850-9-3 (Power Profile) PTP time synchronisation protocol.

If the PTP signals are down, for instance the loss of GPS for both clocks, the system will react as follows:

Station Bus:

Bay level switches are configured to operate as boundary clocks which mean they can become master clocks if no better clocks are detected on the network. By doing so, this will keep the station bus synchronised.

Process Bus:

For the process bus there are two options:

- The aforementioned merging unit can act as a master clock and provide time synchronisation to IEDs connected on the same process bus as well as the merging units under no PTP condition. This is known as "free running mode" and may require the reconfiguration of the merging unit.
- Configure PB1 and PB2 as a boundary clock to act as master clocks when the PTP source fails. This is the preferred option.

The above methods will keep the process bus synchronised. There are two station clocks, one being synchronised to GPS/GLONASS. This clock converts the timing information into the IEC61850-9-3 (POWER PROFILE) format. During normal operation, the system is synchronized by the best Grand Master Clock. At the station level and bay level switches, PTP time synch format is used. For vendor 2 IEDs at the station level, the synchronisation is done via SNTP; the same applies for both SCU 1 & 2 located in the bay marshalling kiosk (BMK). The P546 is synchronised at station level via PTP (slave only). Both vendor 2 and vendor 1 protection IEDs will need 1PPS (one pulse per second) signal for the sampled value synchronisation and line differential protection. The merging unit gets its time synch from its associated process bus switch synchronised via PTP. The synch signal is then provided to the standalone merging unit.

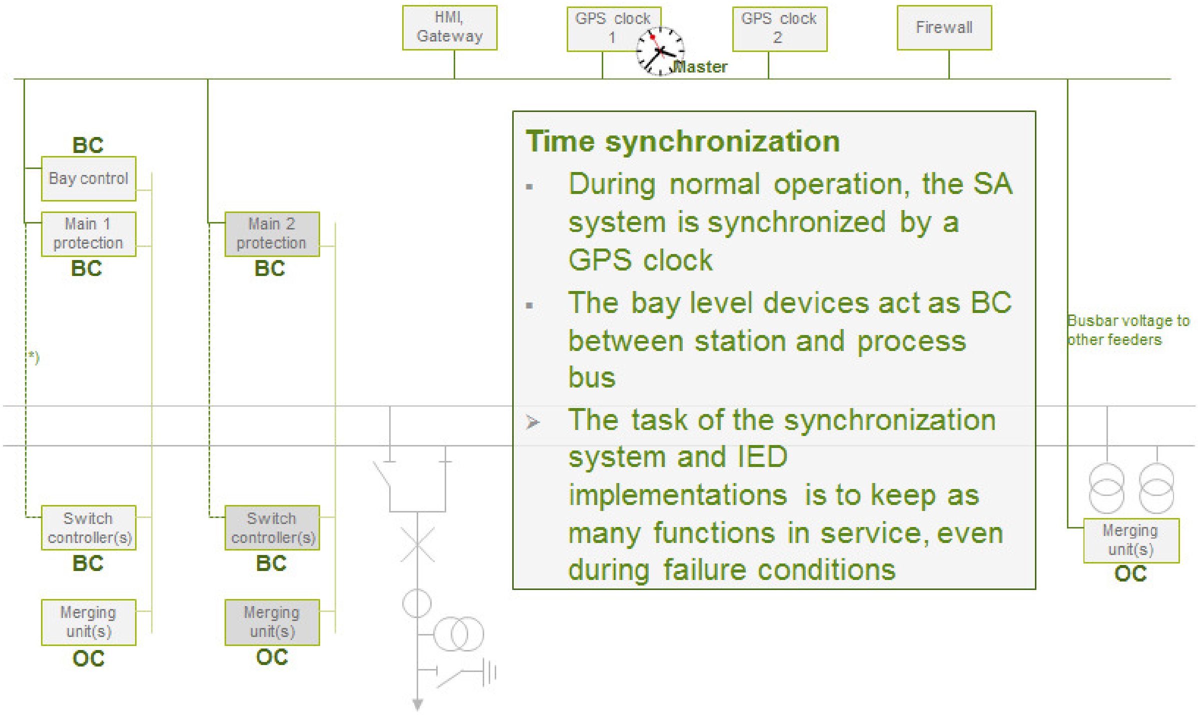

Figure 6: Time synchronisation diagram

4. Wide Area Signals and their Applications

The measurement data is used to calculate several useful wide area information streams, as follows:

- Classical 50 Hz PMU data
- Fast 200 Hz phasors
- Waveforms at 200Hz
- Harmonics

("Slow") 50 Hz PMU data is a classical form of synchrophasor data used for different monitoring and control applications. Fast 200Hz phasors are computed using a shorter data window which makes them applicable for monitoring of fault currents in contrast to the classical synchrophasor data. Waveform data are reported with a 200 Hz reporting rate. This data can be used for monitoring of sub-synchronous oscillations. This application has been demonstrated in a previous innovation project (VISOR) and it is considered to be a proven technology. These streams will be included in FITNESS only if the communication network capacity and computational power of the PMUs allows. Waveform data is also available on triggered events as standard COMTRADE high resolution signals, following conventional practice.

A need for monitoring of harmonics in the grid is widely recognized and consequently FITNESS will provide an architecture for real time harmonic information streaming. Collecting information as streamed data enables continuous data capture and longer term comparisons between data sources, as well as proving that the information can be made available in a suitable form for future monitoring and control applications.

5. Wide Area Monitoring and Control Infrastructure

The data streams presented in the previous section will be used for the development of wide area monitoring and control applications. The overall logical wide area monitoring and control infrastructure is given in the following figure:

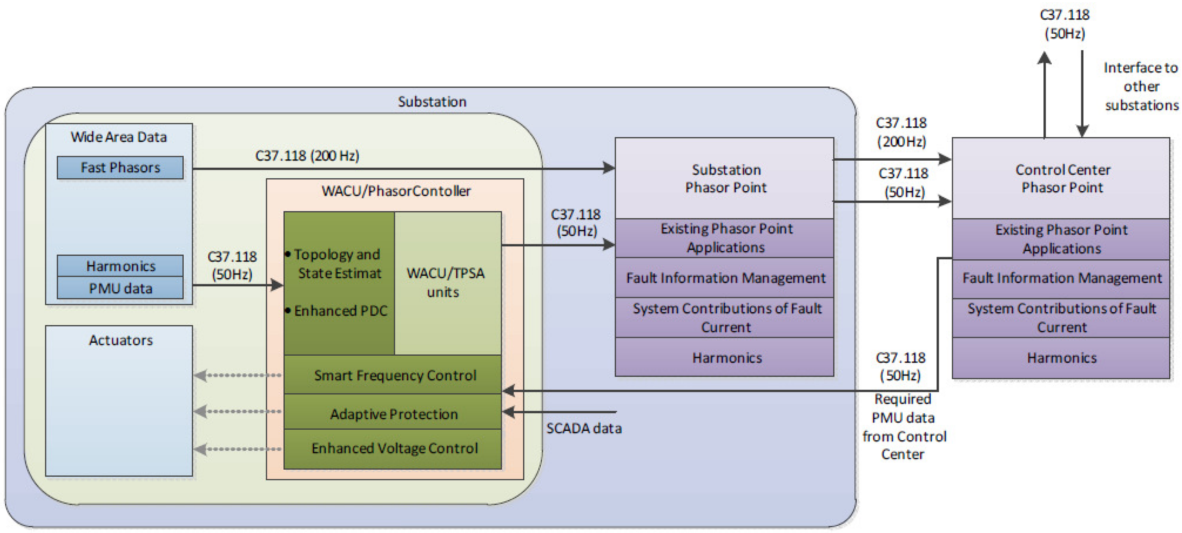

Figure 7: Wide Area Data Flow

The WACU/Phasor Controller platform is the core element of a future substation with regards to monitoring and control architecture. From the hardware perspective, this platform consists of 1 or 2 WACU(s) and 1 TPSA unit. It will receive all the PMU 50 Hz data and will be able to provide substation applications (Topology and Local State Estimation, Enhanced PDC, Smart Frequency Control, Enhanced Voltage Control and Adaptive protection). The TPSA will be able to provide test data streams and GOOSE into the WACU and to the outside world (Central PP).

The topology and local state estimation will communicate with the SCADA system at a slower rate, but these communications are not shown since they are not part of the wide area monitoring and control architecture.

Harmonics are calculated in the PMUs every 3 seconds according to the IEC 61000-4-7 standard. This information will be transmitted as analogue data through the existing classical 50 Hz data stream or potentially using a separate C37.118 data stream at a slow data rate (1Hz), which in that case will not be processed in the enhanced PDC.

PhasorPoint servers will be placed in the substation and in a control centre. These two servers will communicate over TCP protocol. This architecture provides data storage redundancy and solves potential issues with limited telecommunication bandwidth. PhasorPoint will provide functionalities needed for data analysis.

6. Testing the System Architecture

A detailed testing procedure for project FITNESS is currently under development. The testing methods and results will be presented in future papers.

Edition 2 of IEC 61850 clearly defines the mechanism for isolating and testing IEDs that use GOOSE and sampled values in an IEC 61850 system environment. IEC 61850 Edition 2 IEDs provide support for both test and simulation modes. The IEC 61850 test mode defines the output behaviour of an IED in response to test signals. It allows for one or more IEDs to be tested, without affecting other IEDs on the same network in the substation.

When a device is in test or test-blocked mode it will accept 8-1 GOOSE messages from other IEDs that are also in set in test mode. Test-blocked mode is a variant where in addition to the above, the IED’s output contacts are blocked.

The IEC 61850 simulation mode defines whether the IED will accept signals generated by simulation equipment such as (8-1) GOOSE and (9-2LE) sampled values. When an IED is in simulation mode, it will accept any available simulated messages. The other IEDs that are not in simulation mode, cannot accept simulated messages.

These new features open up the possibility for on-line testing, with simplified operational procedures on the secondary system. For FITNESS, computer-controlled plant simulators in order to simulate substation plant, such as circuit breakers/disconnections, both analogue and digital signals will be applied via a PC controlled injection test set. All test conditions will be simulated via automated, self-monitoring test sequences. Tests reports will be produced automatically and will be 100% repeatable and traceable.

Advantages of proposed philosophy

Controlled factory conditions:

The majority of work to configure and commission substation automation equipment is carried under controlled factory conditions, thus providing the highest possible level of quality control.

Early interaction with Commissioning Engineers:

Commissioning engineers will be on hand in the factory to help with testing and facilitate planning for the on-site installation. There is still work to be done on site, but the risks of unexpected situations are significantly reduced.

No wires disturbed:

The P&C enclosure brings together all protection and control systems within a containerized, transportable unit. This enables a complete system to be built at the factory, configured, tested and largely commissioned at the FAT stage and then despatched to site as effectively a 'plug and play' solution, with no need to disturb any wiring.

Minimizes the need for outages:

Using a P&C enclosure can help to reduce the level of disruption during delivery and installation and minimize the need for outages. A P&C enclosure is a substantial unit, weighing up a couple of tonnes, so pre-delivery planning is a key safety aspect of the project to enable the site manager to prepare how it will be delivered and offloaded safely and efficiently.

7. Conclusion

The FITNESS project will be the first multivendor digital substation and automation system in the UK. FITNESS will demonstrate complete multi-vendor interoperability for digital substations and demonstrate interoperability between conventional and digital components proving digital substations are also suitable for brownfield substation replacement/refurbishment programs.

FITNESS is trialling a new substation architecture that significantly reduces the number and length of circuit outages throughout the life cycle of the substation, enables new measurement, monitoring, protection and control applications, and allows integration of low carbon technology into substation design in a standardised and optimum way. The P&C enclosure design brings together all protection and control systems within a containerized, transportable unit. This enables a complete system to be built at the factory, configured, tested and largely commissioned at the FAT stage and then despatched to site as effectively a 'plug and play' solution, with no need to disturb any wiring.

This substation design approach enables faster deployment, greater availability, improved safety and greater controllability with a reduced footprint and lower cost than conventional designs. It will also help to defer new build substations and expansions, deriving benefits for transmission and distribution operators and customers.