DEMONSTRATION OF A WHOLE ENERGY SYSTEMS ACCELERATOR

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ABSTRACT

This paper presents a novel testing and demonstration platform, named the Whole Energy System Accelerator (WESA), developed by PNDC and Energy Systems Catapult (ESC). This platform enables real households to interact in real time with network hardware in a closed feedback loop.

At the distribution level, rapid decarbonisation of heating and transport and the growing penetration of distributed energy resources can result in new patterns of generation and demand. Consumers on a local network will collectively influence the network state, however the prevailing market arrangements and consumer preferences will determine individual reactions to this state. The WESA testing and demonstration platform enables a holistic exploration of interaction between networks and domestic consumers, i.e. impact of domestic loads on a network under different scenarios and the level of demand side flexibility achieved by different market structures. This paper presents the architecture of the WESA platform. A test scenario where a physical EV charger is integrated and controlled within the core WESA data flow and the results of the first real life demonstration of the feedback loop are also presented. The WESA platform can be used to simulate future scenarios with consumers switching to LCTs and the impact on the network assets, and to test and demonstrate different possible management/incentive approaches including market options for achieving demand flexibility.

INTRODUCTION

Decarbonisation will pose a major challenge to existing electricity distribution infrastructure as the timing of peak loads change and their maximum levels increase from the historic values. Although computer simulation is a well-established tool to predict how a given distribution network may be impacted in future decarbonisation scenarios, the key unknown factor required for a well-understood and controllable network is the human consumer of electrical energy, their usage preferences, and their priorities which shape those preferences. The Whole Energy System Accelerator (WESA) being developed by PNDC and Energy Systems Catapult (ESC) is aimed at filling this gap by understanding how real people will react to network constraints, market-driven pricing incentives and also network-imposed limitations to energy usage in future network net-zero scenarios.

In setting up this capability, the high-level objective was to achieve real-time bi-directional communication between the Living Lab and PNDC's network. The fundamental concept of WESA is shown below in Figure 1, and it leverages two main capabilities which have evolved separately to meet distinct use cases.

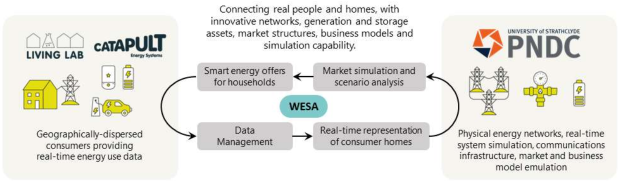

Figure 1: WESA concept high-level view

ESC has developed a Living Lab of over 1600 UK households. The Living Lab collects static information such as high-level household demographic information, home type information, home appliance types etc. while also giving participants the option to consent to provide smart meter data on electrical demand and gas consumption, EV charging, Heating usage behavior etc. Some houses are also fitted with consumer access devices (CAD) that allow more real-time collection of gas and electricity usage.

PNDC has a comprehensive distribution network including an 11 kV primary substation and a replica of all the network and load components set up for emulating distribution networks and accelerating the development, commercialisation and adoption of innovative products and systems for distribution networks.

The combination of these capabilities, with suitable exchange of data between the facilities, allows the creation of a feedback loop where real consumers affect the PNDC distribution network, and the network state and connected assets influence the behaviour and range of options available to consumers (in real time). This capability is unique and adds to the existing simulation efforts by giving insight into the human interaction with future energy networks. The novel capabilities of the WESA include:

- Integrating real network assets such as transformers, cables, and connection infrastructure including link boxes and fuse pillars
- Stress-testing third-party control systems by the addition of volatility from real user behaviour
- Testing the end-to-end integration of monitoring and control systems
- Long-term testing to prove whole energy system reliability, security, robustness and capability to deal with extreme network and external events
- Studying specific scenarios and classifying consumer reactions through appropriate consumer insight trials

SYSTEM ARCHITECTURE

Objectives and overall architecture

In setting up this capability, the high-level objective was

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to create a real time closed loop by establishing a bi-directional communication between the Living Lab and PNDC's network. The data link was required to be capable of accepting real-time measurement data recorded at PNDC's network and feeding the data back to a simulation of markets and the wider energy system, which in turn would create the tariff/control signals that would influence the actions of trial participants and their appliances within the Living Lab. Figure 2 shows the general principle and scope of the communication architecture.

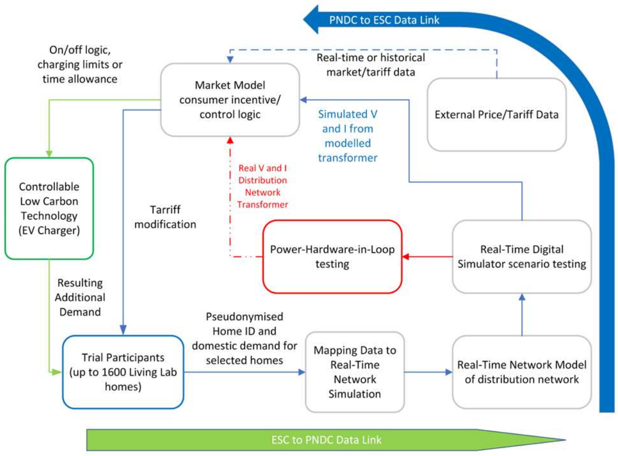

Figure 2: Concept of Demonstration (lines indicate the communication links and the arrows indicate the direction of communication)

Network simulation and power hardware

PNDC uses a Real-Time Digital Simulator (RTDS) system [1] to create network models that can be used in combination with Power Electronics converters [2] to enable Power-Hardware-in-Loop (PHIL) [3] and create power flows in real-time, normally used to test physical hardware response, and for testing with WESA, to provide highly controllable loads which can be used to study network impacts on distribution network transformers and cables [4,5]. To achieve this, a fully-programmable bidirectional 540 kVA Power Supply Unit has been used in combination with the RTDS. The PSU has been used in a control mode where the magnitudes and phase shifts of voltage and current waveforms are directly set using analogue control signals from a real-time power system model, where simulated control response and analogue measurement waveforms correspond closely with real physical systems and hardware. The overall concept of operation is shown in Figure 3, where a bi-directional power electronics converter operating in current-source control mode, applies control set points sent by an RTDS distribution network model. The resulting load on a real transformer can be read back in real-time to ESC's market model, WESA Market Emulator (WESAME).

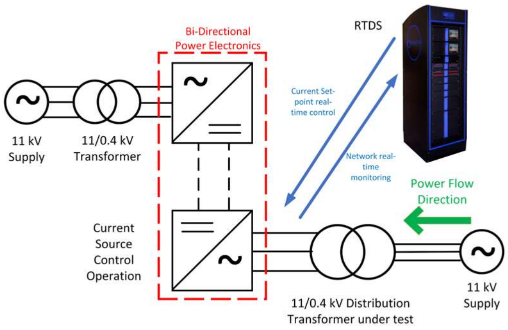

Figure 3: Power-Hardware-in-Loop concept for WESA

Bidirectional inter-facility communication

A communications solution was developed to feed the RTDS model with dynamic load set-points derived from Living Lab participant data, and to return live measurement data from PNDC's systems. Specifically, the interface between the ESC Living Lab and the PNDC systems takes the form of a shared-access PostgreSQL database hosted in a cloud environment. This database is updated with real-time home data from the Living Lab's digital systems, in a schema containing data creation timestamps, pseudonymised home identifier numbers and electrical load provided as the change in electrical meter reading in Wh/min. The electricity consumption data originates from standard UK domestic smart meters in participants' homes, relayed in real time at 1-minute granularity using in-home Consumer Access Devices (CADs), and ingested into the Living Lab cloud systems from the CAD vendor's systems before loading to the WESA database.

Using a set of open-source Python software tools, this data is securely copied to a PNDC-operated cloud server and filtered in readiness for a local data network connection to the PNDC RTDS system, which applies incoming power set-point values to the active real-time model.

ESC's Living Lab systems include the capability to modify electricity consumption data to simulate the effects of additional Low Carbon Technologies, therefore the data contains both the original measured consumption of the home, and the modified home consumption including the effect of the simulated appliances.

PNDC's information transfer back to ESC consists of measured voltages and currents at points within the network configuration under test, which is either real-world data provided by the power electronics converter to the RTDS model or else the simulated value within the RTDS if PHIL is not used. These values are timestamped and loaded into the shared-access database, to be read by ESC's WESAME Market Emulator.

Market model control logic

The market model logic is developed as a black box such that it can have complex models representing the decision-making and control by organisations and actors within the electricity sector or simple control logic such as on/off triggers. These models are built using MATLAB and

Simulink, and deployed to a cloud environment using MATLAB Production Server. During execution these models can access both static/preconfigured data and dynamic data received from homes and from PNDC's network models.

Test network configurations

To demonstrate the WESA feedback loop functionality, a number of test network configurations have been trialled by ESC and PNDC. These were based on a RTDS distribution network model (scenario details described in Table 1 and shown graphically in Figure 4). This model would control PNDC's power electronics, with the electrical demand at up to 30 dynamic controllable loads being updated in the RTDS model in real-time at 1-minute resolution by the data link developed jointly by ESC and PNDC.

Table 1: RTDS model parameters

Component	Value	Comment
Supply Distribution transformer	315 kVA	Matches PNDC hardware so results can be compared with future PHIL test
Feeders/Phases	1 feeder per phase	3 feeders (1 per phase) with up to 7 homes mapped to each phase
Background Load	Base value of 150 kVA, peak sinusoid profile of 200 kVA	Sinusoid load profile generated by RTDS and superimposed on flat base line
EV chargers	7 kW	Installed at each home and active when permitted by market model
Control thresholds	Switch-off: 330 kVA Switch-on: 220 kVA	The control model used hysteresis – thus once the upper threshold was breached, EV charging was disabled until the power demand had dropped below the lower threshold

For this demonstration, the bi-directional power supply shown in Figure 3 acted as grid-connected current source which applied programmable three-phase loadings to a 315 kVA ground-mounted ONAN transformer onsite at PNDC's test facility.

A similar test, using simulated network response without the PHIL capability, demonstrated the operation of the full feedback loop. An additional controllable load was included to showcase feedback loop control. This is an EV charger located at ESC's test facilities, which responds to logic signals from ESC's market model. The EV charger behaviour was overlaid on the real homes' demand profiles as a simulated appliance, as described above. Stress on the simulated distribution network was achieved by modelling a simple half-sine oscillation above a flat background load, which allowed the transformer load limit to be approached. This was combined with the real data from homes when determining the transformer loading value and thus the required control for the EV charger.

The control approach involved scheduling charger switch-on and switch-off points based on transformer load compared with fixed thresholds. A hysteresis controller was used to reduce oscillation, employing separate thresholds for switch-off and switch-on. In a more realistic scenario, control of in-home loads in response to LV loading conditions could be achieved either through time-of-use tariffs or through direct control by the network operator in exchange for a recompense (e.g. reduced connection cost/time in the case of a flexible connection, or operational payments in the case of provision of flexibility services to the network operator [6,7]).

In this configuration, it was expected that the EV charger portion of the consumption data passed through the communications link would react dynamically as the load on the RTDS-simulated transformer reached undesirable levels. This combination provides an imitation of the behaviour of a real home with an EV charger installed, responding to a market control signal, with the principle of ensuring that the modelled distribution network would not be overloaded by EV charger activity as the background load on the network neared a typical peak.

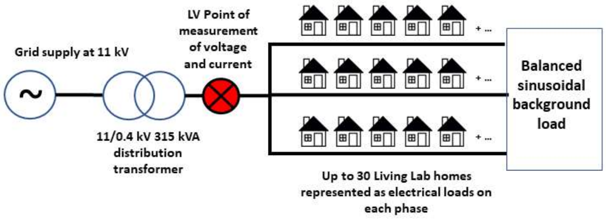

Figure 4: Schematic of RTDS model setup

RESULTS AND DISCUSSION

An initial test of the data flow from ESC to PNDC for 10 homes was carried out to show the typical values returned by a PHIL-enabled RTDS model, controlling PNDC's PSU to apply variable levels of current to a standard 315 kVA 11/0.4 kV three-phase ground-mounted distribution transformer. The currents and voltages seen at the LV point of measurement are shown in Figure 5. From the measurements it can be seen that when the transformer is loaded with the load currents from the Living Lab data reflecting real life consumption, there are unbalances in the network resulting in significant neutral current on the transformer neutral connection. The measured voltage dip on the LV side of the transformer correlated with the applied load current as expected, as shown in Figure 5.

After this open loop test demonstrating the effect of a simulated network load on a real transformer, the data link was upgraded to be bidirectional and accept measurements from PNDC in real-time, which were ingested by the market model to provide a control signal to the test EV charger. Control of the EV charger activity was based on the total transformer load modelled by PNDC's RTDS system. The total load included the Living Lab data shown in Figure 6, and a base load described in Table 1.

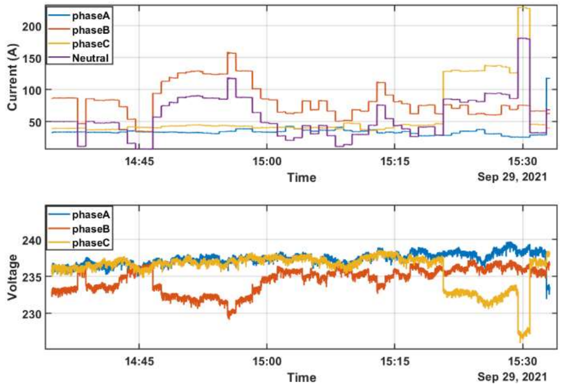

Figure 5: PHIL test data using live Living Lab data for 10 homes mapped through a basic RTDS network.

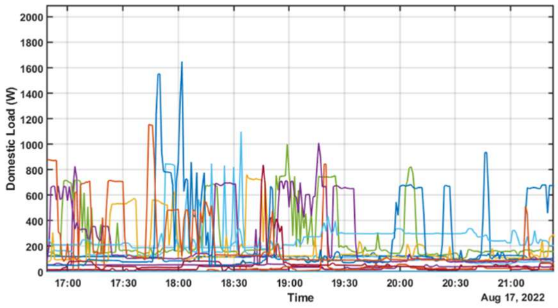

Figure 6: Live consumption data from 10 Living Lab homes during test

Figure 7 shows the controlled response for each home modelled in the RTDS model in more detail. The step changes in load come from the EV charger, and this signal is applied to each home. The individual variation in each home is from the Living Lab data provided by ESC. 10 homes were used in the network model that generated the results in this paper, therefore the effect of charger curtailment is a drop in demand of 70 kW in total. The data link has been trialled more recently using up to 30 homes as the system is continuously upgraded and more trial participants become available.

Figure 8 shows the overall effect of control on the total simulated network demand, including the half-sinusoidal simulated peaks. As described in the previous section, in this test configuration the EV charger is assumed to be controlled by network loading thresholds, with the control signal generated by the market model: once the load exceeds 330 kVA, EV charging is disabled until the network load falls below 220 kVA. The lag in response to the threshold is due to data propagation delays around the feedback loop, including the data collection lag from the smart meters/CADs, and was observed to be around 2-3 minutes during tests. As a result of the delay, the peak demand on the transformer occurs before the control logic acts to curtail charging, but nonetheless the controller prevents additional stress on the transformer at the time of the peak in background demand. The simulated effect on transformer voltage and current are shown in Figure 9 and Figure 10 respectively. Note this is a simulated response and these results will be augmented by a full PHIL study in future.

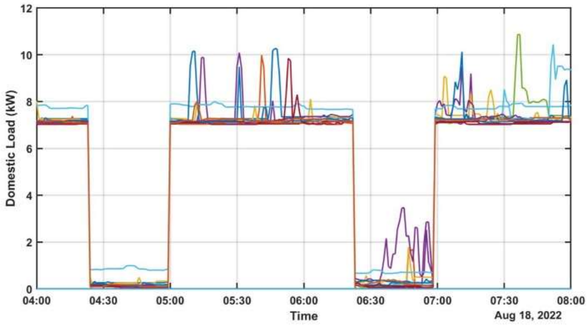

Figure 7: Simulated impact of EV charging load on individual consumer loads

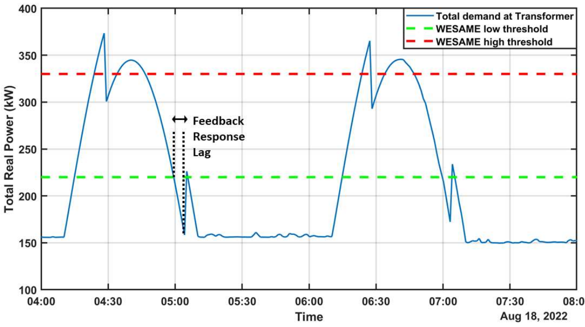

Figure 8: WESA feedback loop results showing feedback response as total power levels at modelled transformer cross control threshold levels.

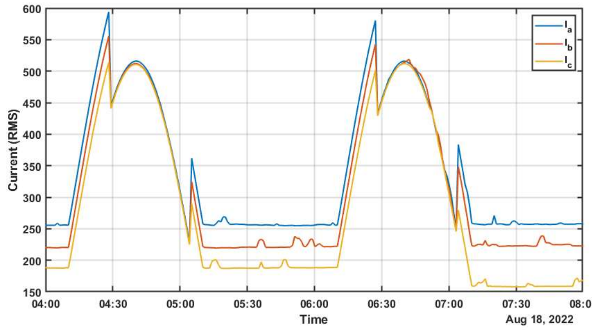

Figure 9: WESA feedback loop results showing simulated current at Transformer.

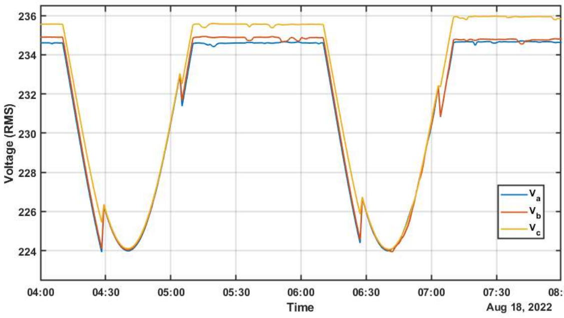

Figure 10: WESA feedback loop results showing simulated voltage at Transformer.

CONCLUSION

The Whole Energy System Accelerator (WESA) feedback loop concept, developed in collaboration between PNDC and ESC, involves the real-time simultaneous interconnection of real domestic consumers in ESC's Living Lab; a model of the distribution network hosted by PNDC; and an emulation of the response of markets and energy system actors to the distribution network status, both running simultaneously. The WESA concept has been implemented and tested using real-time data obtained from a subset of Living Lab trial participants.

The main scenario tested was focussed on a deliberately simple approach for curtailment of EV charging based on real-time transformer loading. Electricity consumption values from Living Lab homes were passed from ESC to PNDC, and used as inputs to a simplified electrical distribution network model running in real-time in RTDS. The resulting voltage and current values were then transmitted via the bidirectional data link to the market model, which determined whether EV charging could be allowed at that instant. This control signal then determined the status of a test EV charger in ESC's lab facilities, which in turn was used to overlay a simulation of EV charger demand on the data feeds from the Living Lab homes. Modified home data then travelled through the data link to influence PNDC's network model in real-time, thus successfully demonstrating the operation of the WESA feedback loop concept. This scenario-based trial used a virtual network model. Therefore, PNDC and ESC look forward to further testing in the future using PHIL on real network assets as a fundamental part of the controlled feedback loop dynamics.

WESA has a demonstrable capability to accelerate innovation in electrification of heat, adoption of electrified mobility, and other low-carbon technologies. It has been designed as a facility to support both innovators and energy system stakeholders (such as electricity network operators), by providing a low-risk environment to trial novel products and services and to understand their interaction with real network hardware and real households. With the addition of physical PHIL-induced network feedback to a control system demonstrated in the discussion section above, the addition of more complexity to the network models, increases in the number of homes available, and inclusion of other network assets and low carbon technologies, WESA has the potential to achieve a tangible impact on decarbonisation of the energy system.

MISCELLANEOUS

Acknowledgments

The authors would like to acknowledge the work of the teams at ESC and PNDC who have been involved in the developments described in this paper. This work has been supported by the Scottish Government Green Jobs Fund.

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