RDD353

Real-time State Estimation Demonstration on Irish Distribution Network

Final Report

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NOVOGRID

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Executive Summary

As more electrification is required to shift the heating and transport sectors away from carbon-based sources, the distribution system will be relied upon to facilitate the demand sought. This surge in electricity use will alter planning assumptions and drive reinforcement projects sooner than anticipated, as well as affect the day-to-day operation of assets throughout the power system. Furthermore, the increase in embedded renewable generation will undoubtedly broaden the expected range of operation of the distribution system asset base, causing reverse flows and voltage rise in areas of high concentration. A real-time picture of the network is essential to the secure integration of renewable distributed resources and demand flexibility.

This project involved research and innovation targeted at the development of a software platform to provide real-time insight into distribution network power flows and voltages. Over the course of the project the estimation capability expanded to accommodate the entirety of the Irish MV distribution network. The project platform presents estimates of network states in real-time, where measurements have been made available to the platform.

The project developed hardware solutions to communicate to the cloud platform, and having proven assumptions on desktop studies, took in measurements in the field in order to pilot the real-time estimation capability. Validation of the platform was achieved in collaboration with ESB Networks where pilot measurement locations were established and estimations by the platform were verified.

Glossary

KEY WORD	INTERPRETATION FOR THIS REPORT
DER	Distributed energy resource for example, batteries, solar, wind generation
DSO	Distribution System Operator
Endpoint	a device in the field transmitting measurments to the estimation platform
GridVis	The name of the real-time estimation platform
HV	High Voltage refers to portions of the Irish distribution system operated at 110kV or 38kV
IFT	A transformer within the MV network that links 20kV and 10kV network
kV	The unit of voltage - electrical potential difference
kVA	The unit of complex power, used for analysing alternating current circtuits equal to the product of root mean square of current and voltage.
kVAr	The unit of reactive power, a bi-product of ac power flow used to regulate voltage
kW	The unit of active power, the product of electrical current flow through a device with an electrical potential difference
kWh	The unit of electrical energy, the active power delivered over time
LV	Low Voltage refers to portions of the distribution system operated at 400V or 230V
Modbus	A standardised communication protocol operating over Serial or TCP/IP ethernet connections
MV	Medium Voltage refers to portions of the distribution system operated at 20kV or 10kV
PLC	Programmable Logic Controller – a programmable device capable of rudimentary calculation that typically communicates over Modbus or other standardised communication protocols. See Figure 6
RTU	Remote Terminal Unit – a device to monitor analogue parameters and transmit data to a repository and execute routine logic statements.
SCADA	Supervisory control and data acquisition – the interface which enables monitoring and issuing of set point changes in the distribution system
SQL	SQL is a standardised programming language that is used to manage relational databases and perform various mathematical operations
Station	A compound where the voltage is stepped down from HV to MV by large transformers and power is distributed from the HV network to multiple MV feeders
Substation	A smaller transformer found on electricity poles, in buildings or enclosed in metal units, see Figure 9
UUID	Universal Unique Identifier – a 128-bit value used to uniquely identify an object or entity on the internet
WP	Work package of the SEAI RDD&D funding program

Introduction

Real-time visibility of electrical distribution networks is a key challenge for DSOs in the coming years. Increasingly active distribution networks are now hosting infrastructure for renewable generation and demand side aggregators. This, when accompanied by new dynamic pricing regimes, poses challenges to many of the assumptions which have driven network planning and operation.

The challenge of network visibility is fundamentally about having a real-time, live picture of network states of sufficient granularity such that control actions can be taken. This requires minimising errors in the measurements, time stamps and any required communications. A real-time picture of the network status is essential to the secure integration of renewable distributed resources and demand flexibility.

Presently, research in state estimation is generally concerned with adjustments to the numerical method used, new techniques for bad data detection or consideration of the optimal placement of new measurements. The research here is distinct. Classic state estimation is concerned with solving a reduced Jacobian matrix, often called the measurement Jacobian, generally using a weighted least squares approach, minimising the weighted sum of the squares of the errors in the results of every bus considered.

This project involved research and innovation targeted at the development of software platform to provide a real-time view of network status for network operators. It represents a collaboration with ESB Networks (Irish DSO) who together with NovoGrid undertake a pilot of the software platform of the system to be developed in this project. The project provided a necessary and valuable validation of the platform and has enabled demonstration of the benefits of such systems to network operators and low carbon energy networks can be supported.

In Work Package 1 the modelling capability to perform accurate power flow analysis is developed, benchmarked against ESB Networks solutions. The test feeders identified for demonstration were chosen to match the circuits with existing measurement instrumentation. With the modelling capability achieved, the estimation procedure, formulating remote network conditions, was completed in Work Package 2. The capability for real-time visibility is developed in Work Package 3 where numerous endpoints were investigated in the Irish distribution network. A dedicated section on the final platform, named GridVis, reveals the services developed to produce real-time estimates.

WP1 Network Analysis and Test Feeder Identification

The objective of WP1 was to establish the test network in which to install NovoGrid RTUs and to execute offline power flow analysis on the network model in preparation for a field trial. This WP initiated the development of the power flow modelling capability in the OpenDSS[1] simulation environment to the same standard as ESB Network models.

The deliverables completed as part of this work package are listed in Table 1.

TABLE 1. WORK PACKAGE 1 DELIVERABLES

WP1-D1	WP1-D1: Optimal RTU installation points and required measurement sets.
WP1-D2	WP1-D2: Test network model.

The Irish Distribution System

A distribution system refers to the portion of a power system at the final stages of power delivery, it is the collection of infrastructure that connects electricity users with the electrical grid. In Ireland, the distribution system consists of multiple voltage levels: low voltage (**LV**: 400|230 V) associated with residential settings, medium voltage (**MV**: 10 kV and 20 kV) used distribute power across townlands, cities and connect large customers, and high voltage (**HV**: 38 kV and 110 kV in the Dublin Areas) the sub-transmission network spanning greater distances with greater load reach, supplied from the transmission system (110 kV, 220 kV and 400 kV level).

The network is planned to adhere to the distribution system planning standards[2] wherein voltage profiles are maintained within defined ranges under normal and contingency operation. Figure 1 illustrates the voltage levels and the interface points on the Irish distribution system. The modelling effort of this project focused on circuits fed at the MV level, accounting for ~94,000 km of network, where it is anticipated that the electrification of heat and transport sectors will necessitate real-time estimation capability.

Undertaking the task of real-time estimation of power flow through the system required accurate simulations. The creation of an electrical model was made possible through a shared asset database provided by ESB Networks. The distribution system consists of a multitude of assets; conductors found overhead and underground, fuses rated to protect current flow limits of conductors, equipment to detect and manage faults, insulators that uphold the separation of the electricity grid from land and property, transformers to interface voltage levels, switchgear to direct the flow of electricity through the network, and many more assets.

[1] OpenDSS: Link to Web Page
[2] Distribution System Security and Planning Standards - ESB Networks [2021]

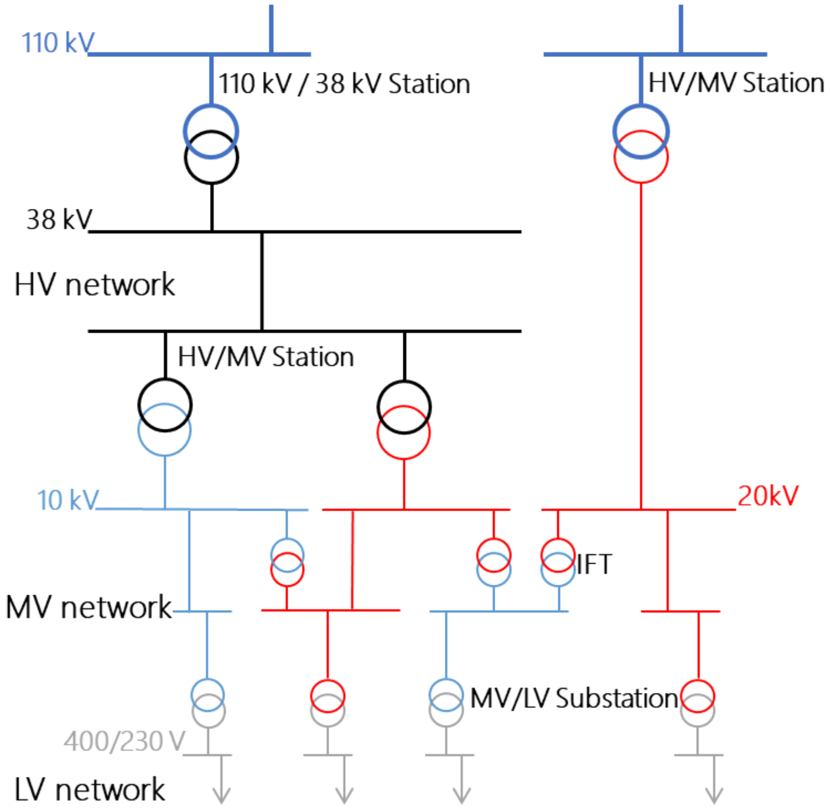

FIGURE 1. DISTRIBUTION SYSTEM VOLTAGE LEVELS OF ESB NETWORKS

Modelling Environment and Assumptions

The electrical properties of each component of the Irish distribution system were shared for the purposes of accurate modelling throughout this project. Network maps, documenting the geographic information of circuits, were also provided. Historical logs of HV/MV Station data at feeder level and customer numbers at each MV/LV Substation were supplied. In addition, planning assumptions used within ESB Networks were communicated so that they could be included in the simulations undertaken throughout the project.

OpenDSS is an electric power distribution system simulator designed to support distributed energy resource (DER) grid integration and grid modernisation. It enables complex electrical analyses through a platform designed to meet present and future distribution system challenges. On this project OpenDSS was incorporated within python programming routines to develop accurate power flow results of actual distribution network to validate real-time estimates against field data.

Owing to the scale of the Irish distribution network model, it cannot be simulated in one power flow model. In practice, sections of network are apportioned to their HV/MV Station where interactions between HV and MV network can be captured and detailed modelling of MV circuits is performed.

All network models simulated in this project replicate the actual distribution network. The models contain details of the electrical impedance of conductors and transformer substations (HV/MV, IFT, and MV/LV) the location and power demand and generation at each MV/LV Substation, voltage regulators if installed, and the network open points between adjacent circuits.

The maximum and minimum load modelling assumptions adopted by ESB Networks team were replicated to allocate demand use at an MV/LV Substation in a given instant as a relative portion of energy drawn in a calendar year by the entire circuit.

OpenDSS models were validated against benchmark ESB Network power flow models simulated in their in-house modelling environment. This important milestone meant that the offline studies performed through the project were as accurate as the assumptions made in planning the actual network.

Test Feeder Identification

The capability to determine optimal placement of measurement sites was produced as part of this WP. The original intention to install measurement instrumentation at precise locations and selecting the test feeder on which to demonstrate the project was not possible to deliver, in the context of COVID-19 pandemic restrictions that came into effect in 2019-2021.

As an alternative, ESB Networks shared the electrical properties of the entire distribution network model and the location of existing field-measurement instrumentation. Ground conditions as well as public consent are often over-riding factors that determine where instrumentation is installed. This shift in approach resulted in a pragmatic real-world field-test of measurement placement for the platform.

The outcome of this WP has exceeded the objective of the deliverables where NovoGrid was tasked with site selection in a location determined as optimal. The WP has delivered the capability to model the entire Irish distribution system. This shift in modelling capability was an important development for the success of the project. It allowed the flexibility to demonstrate the real-time estimation technique at existing locations of measurement instrumentation and prompted to scale both the modelling approach and the estimation platform to cater for an entire distribution network and not just sample test feeders.

WP2 Network Simulation of Platform Performance

The objective of WP2 was to enhance the NovoGrid estimation technique to produce accurate results in a simulation environment for validation against monitored locations on the distribution system. The real-time state estimation platform developed is referred to as **GridVis**.

The deliverables completed as part of this work package are listed in Table 2.

TABLE 2. WORK PACKAGE 2 DELIVERABLES

WP2-D1	WP2-D1: Remote network conditions estimation in a simulation environment.
WP2-D2	WP2-D2: State estimation validation and monitoring parameters adjustment.

Figure 2 shows a flow chart of the estimation technique. Preformed offline, representative demand and generation profiles are assigned to every location of MV/LV substations. Simulated on an actual network model, enhanced by field-data and overlayed with ESB Networks planning assumptions, equations are formed in this offline analysis to be solved in real-time using measurements present on the network in each instant.

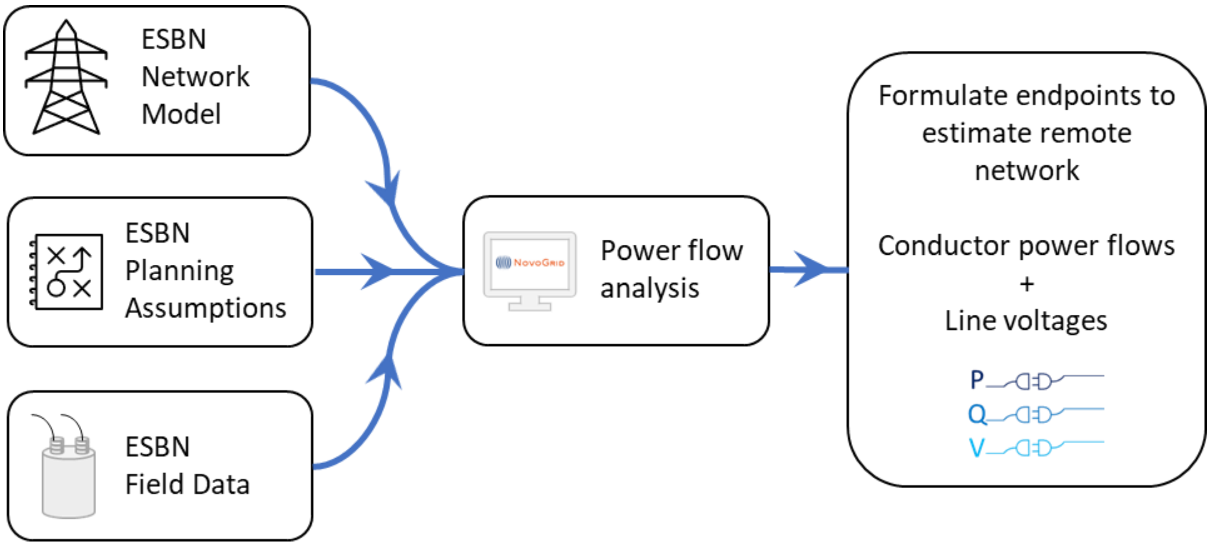

FIGURE 2. OFFLINE ANALYSIS REQUIRED FOR GRIDVIS ESTIMATION TECHNIQUE

Estimation Technique

The core methodology of the estimation technique uses nonlinear regression, where observational data is modelled by a mathematical function containing a nonlinear combination of multiple independent variables. Combining the data captured in time series power flow and those found from a sensitivity analysis power flow, an equation is formed using the local measurements as the independent variables and the results of the power flow as the observable data.

Least squares estimation minimises the sum of square of residuals between the observed data and the evaluation of the fitted equations at respective points. An algorithm, for example the Gauss-Newton method, determines the coefficients of the fitted polynomial; beginning from an initial guess and converging toward a specified tolerance between the estimates and observed data. From one iteration to the next the coefficients change in a direction that minimises the sum of squares of residuals[3].

The outcome of this offline analysis is the creation of two-variable second-order equations, as per (1), that link local measurements (x and y) embedded at a point in the distribution system to desired observations, or estimates, in the network (z).

$$z = a_1x^2 + a_2y^2 + a_3x + a_4y + a_5xy + a_6 \tag{1}$$

In an online setting local measurments can then be used to compute the estimates in a non-iterative direct calculation. The estimate data can be voltage, current flow, reactive power or active power flow, and can even determine derivatives of the power flow problem for example voltage sensitivity to a change in active power.

One application of these estimates form part of an existing commercialised product GridBoost[4]. This determines control set points of a DER at a sub-second level; in order to maximise the energy delivered from the asset by minimising the network losses the generator itself can influence. This method relies on a sensitivity analysis by changing paramaters of the DER and navigating the solution space determined from power flows. For this demonstration project further enhancement was achieved with the inclusion of time-series analysis, SCADA measurements and ESB Networks distiribution planning assumptions.

Sensitivity Analysis

For any location in the network where live measurements are to be used for the GridVis technique, an analysis is required to determine the sensitivity of the site to affect and be affected by remote network conditions, for a single instant in time.

At the measurement node, active power is set to the lower bound of operation, and reactive power is set to the lower inductive bound. The power flow is solved and the variables of interest are stored; these can include branch flows, node voltages, and entries of the Jacobian matrix. Next, a step change increase in reactive power occurs at the measurement node, by a third of the upper capacitive limit. Individual power flows are solved until the measurement node reach the upper capacitive bound.

When all permutations of reactive power combinations have been captured, the active power at the measurement node is increased by 1%, and the procedure begins again, resetting the reactive power to the inductive bound, running a power flow at each reactive power set point and storing the results of interest from the converged power flow solutions.

This collection of observed local and remote operating points, found from all permutations of power injections at the measurement node and the results of time-series power flow, are combined for analysis in the nonlinear regression.

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[3] S. C. Chapra and R. P. Canale, Numerical Methods for Engineers, 2nd ed. New York, NY, USA: McGraw-Hill, 1988.
[4] GridBoost service for distribution connected wind farms. LINK TO WEBPAGE

Time Series Power Flow

Numerous inputs are required to accurately reflect the state of an outlet on the distribution system using power flow analyses, these include:

a) System topology and network open points
b) Accurate phase information
c) Conductor type and length of each section
d) Customer location
e) Customer loading

Best practice, of ESB Networks, is to use extracts of every MV outlet supplied from 110 kV and 38 kV Stations. These models, taken from the central GIS system and contain geographical representative models, match the instructed topology of each distribution feeder.

The conductor types of each section of a feeder are also extracted and represented in the software model assigned from the conductor library. Furthermore, the location and number of customers recorded on each section and MV/LV Substation is known.

Criteria a) – d) are met and the only remaining input required to perform time-series analysis is an accurate representation of generation and demand customer loading, added to every MV/LV Substation.

To implement a time series analysis, several further inputs were provided by ESB Networks to create representations of customer loading:

- Half hourly SCADA measurements taken at the HV/MV Station,
- Annual energy use and peak power drawn[5] at 3-phase MV/LV Substations,
- Half hourly measurements from MV/LV Substations, where possible, and
- In-house modelling assumptions of the network planning department.

Profile of Customer Loading

Measurements from the SCADA system were extracted for identified MV circuits. Measurements type (current [amp], power [MVA], voltage [kV]) and availability (some missing data) vary depending on the telemetry in use at each HV/MV Station. Prior to use in the regression analysis study, the data is filtered to remove erroneous recordings and measurements that did not represent the normal topology of the circuit. Figure 3 shows a spread of current readings typical for a circuit that has not been used in standby operation[6], nor has this circuit been supplied from another source. As is commonplace in these recordings missing data features in the dataset as zero-amp readings and these too are removed from the dataset.

[5] Heat Map of available network capacity: Link to Web Page

[6] *circuits should have standby cover, by way of normally open interconnection(s) to neighbouring feeders. They should provide standby cover for their load in the event of a fault, within the standby volt drop allocation*. - Extract from source [2].

As well as showing zero-amp readings, Figure 4 also displays a step change appearing in the current readings typical for a circuit that has been switched to receive a supply from another HV/MV source; either another circuit in the same station or a another HV/MV Station entirely. While this data is removed to determine the estimate formulations for the normal condition of the network, estimate formulations can be calculated and associated to this standby feeding arrangement. It is typical that a feeder would have a known back-feeding arrangement[6] needed in the case of a loss of supply from the feeding HV/MV Station.

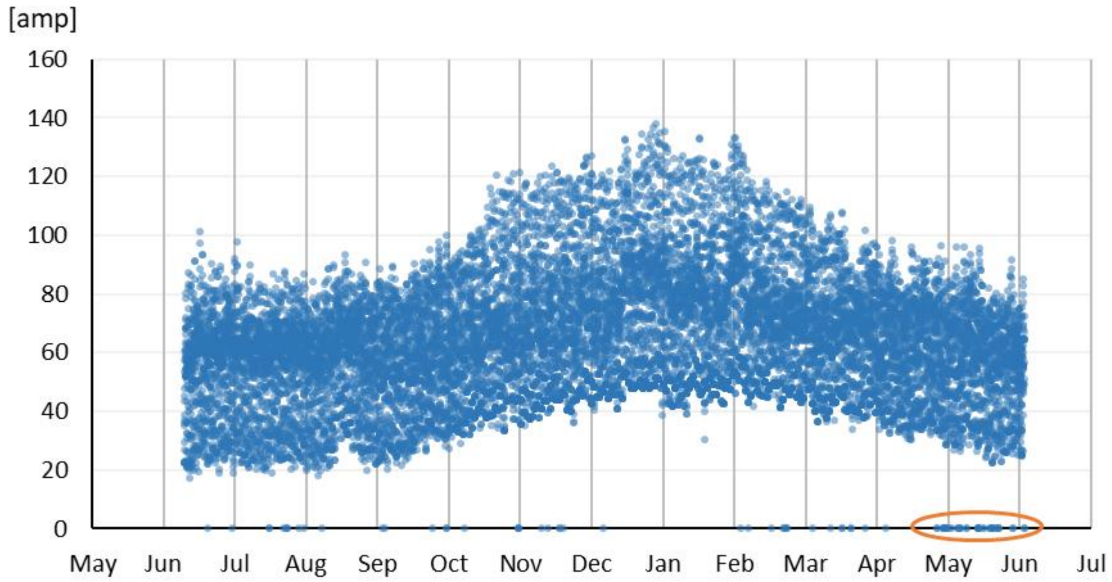

FIGURE 3. SCADA HALF HOUR CURRENT MEASUREMENTS FOR AN MV CIRCUIT- SHOWING SOME MISSING DATA

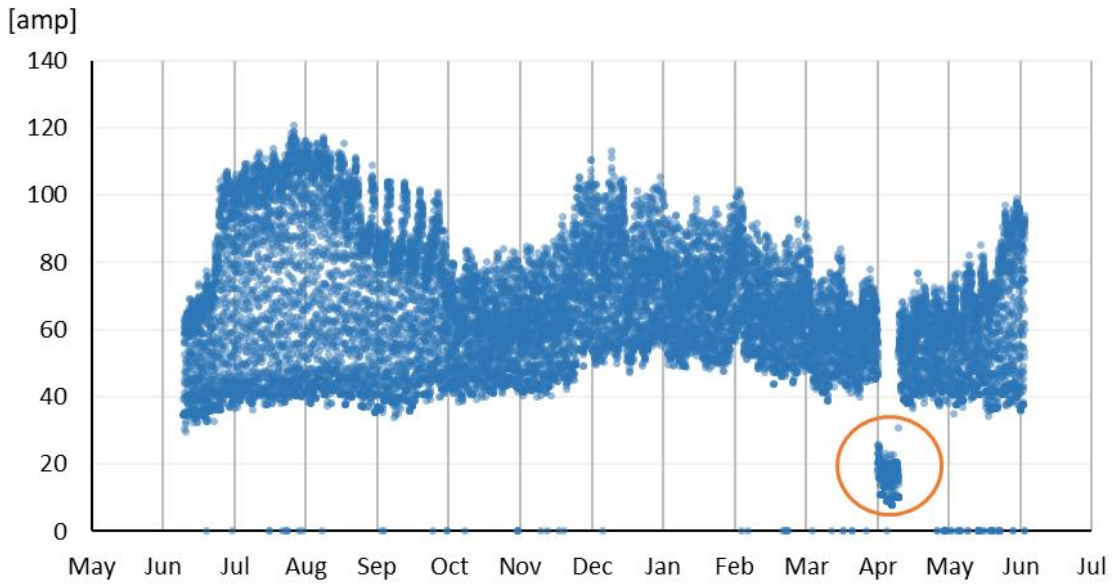

FIGURE 4. SCADA HALF HOUR CURRENT MEASUREMENTS FOR AND MV CIRCUIT - STANDBY FEEDING IDENTIFIED

The power required by an entire MV circuit is known from the current flow recordings of the HV/MV Station SCADA. Power requirements at each MV/LV substation, if known, would then form a complete picture of power demand with losses incurred on the network. Time series data was provided for a limited number of sites, further details are provided in WP3. In the absence of time series data for any MV/LV station, a load allocation procedure was undertaken through the model for each timestep. This procedure replicates the peak load allocation assumptions of industry practice.

Note, the scripting routine was modularised in such a way as to accept the assignment of customer meter readings to their MV/LV Substation. As the Smart Meter roll-out is complete and these measurements become available, and meter readings are summated to each MV/LV Substation, they can be included in the load allocation process and further enhance the accuracy of power flows.

WP3 Real-Time Visibility Demonstration

The platform for real-time visibility is developed in WP3. This WP demonstrated three endpoints: hardware endpoints, simulated endpoints and cloud stored catchment network endpoints. The work package advanced and developed upon NovoGrid's existing hardware solutions and enhanced simulation routines to include the power simulation of thousands of MV/LV substations for real-time estimation. The work package deliverables in WP3 are provided in Table 3.

TABLE 3. WORK PACKAGE 3 DELIVERABLES

WP3-D1	WP3-D1: Test network and estimation validation setup.
WP3-D2	WP3-D2: Network visibility results and performance assessment of NovoGrid platform.

End-to-end Data Flow

An endpoint is a device that transmits information through a network to which it is connected. The demonstration of numerous endpoints was tested throughout the WP from end-to-end.

Figure 5 summarises the data flow from endpoints through to the GridVis dashboard interface. As seen, the endpoint locations envisioned for the GridVis platform are either the SCADA systems or field data from MV/LV transformers. These endpoints were embodied as hardware readings, simulation results, and as historical logs on a local prototype implementation of the platform and then executed on a live web application, presented in The GridVis Platform section.

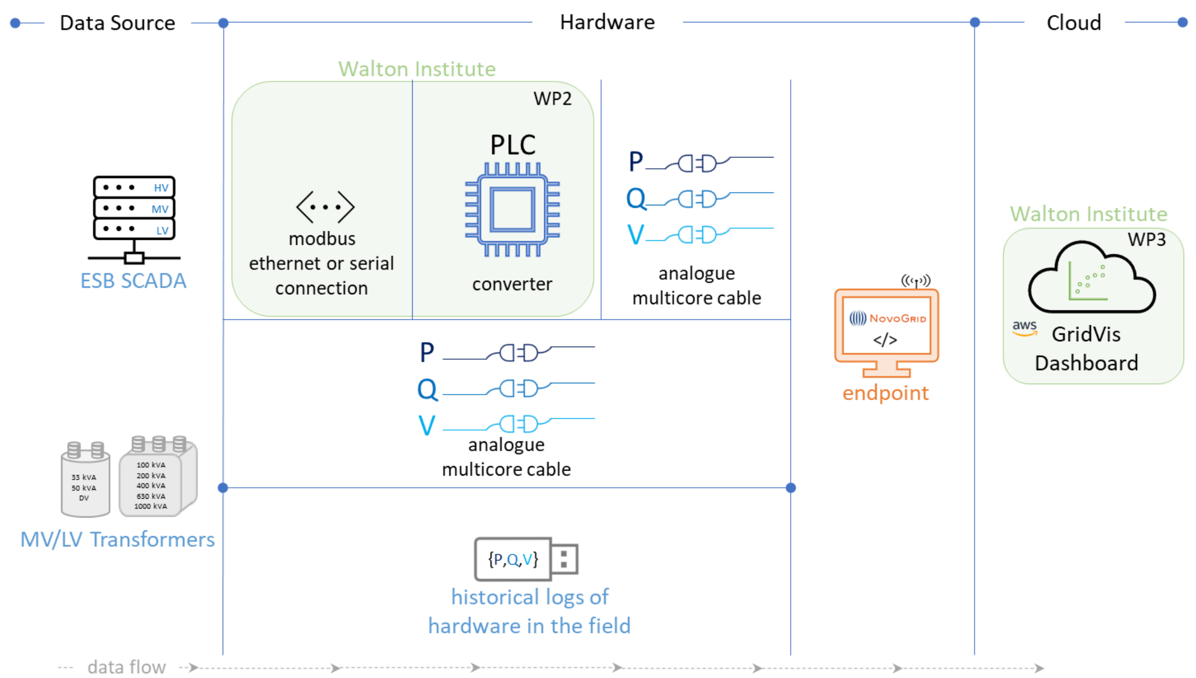

FIGURE 5. DATA FLOW THROUGH THE DEMONSTRATION PLATFORM

Demonstration of a Hardware Endpoint

The NovoGrid RTU, designed to measure analogue signal inputs, was utilised in this work to adhere to Modbus[7] communication protocol. This capability ensures a more streamlined installation on network assets where the protocol has been invested in and where analogue signals are unavailable. It provides a further option to install in HV Station environments without the need to retrofit with analogue cards. Development of Modbus protocol on NovoGrid hardware was achieved in collaboration with The Walton Institute[8].

Demonstration of the Modbus facility was achieved in a lab environment, where a host server (SCADA system) was emulated on a Raspberry Pi and communicated over Modbus protocol to the client (the NovoGrid RTU).

The server and client were based on an existing open-source package *pyModbusTCP*[9] that publishes the Modbus readings to the server based on a configuration file containing the IP address and register location. It is hosted in Docker[10] and both the server and client services are linked in a docker network.

Figure 6 shows the components of the hardware that could be installed on network assets.

Figure 6. a) Rasberry Pi emulating SCADA system Modbus stream, b) Schneider Electric – Programmable Logic Controller, c) Remote Terminal Unit interpreting measurements, d) EwonCosy 131 – communication to cloud platform from RTU.

The Raspberry Pi (a) was coded to replicate the SCADA readings of a HV Station and a MV/LV Substation. These readings were passed through a Schneider Electric

[7] MODBUS Protocol messaging structure: Link to Site
[8] Walton Institute for Information and Communication Systems Science: Link to Site
[9] A Modbus/TCP client library for Python: Link to Site
[10] Docker container platform: Link to Site

Modicon (b) M221 PLC[11] via Modbus using an ethernet cable, converted to an analogue range, and read by the NovoGrid RTU (c). On the RTU the raw data feed could be uploaded to the cloud, or the estimation calculation could be performed locally and then broadcast to the cloud platform, through the GSM modem (d).

FIGURE 7. ANALOGUE SOURCE REPRESENTING ACTIVE POWER, REACTIVE POWER AND VOLTAGE

The test facility was also developed to bypass components (a) and (b), and these could be replaced with any logical value through a direct analogue source, seen in Figure 7. These analogue sources can be manually changed via a dial to emulate the condition of any point on the distribution system.

Simulated Endpoints

A simulated endpoint refers to point in the network where power flow results are produced continuously and used for the estimation of flows and voltages in the surrounding network. Formulations such as in (1), once determined for a network point, are solved using these simulated time-series measurements from that node. Active power, reactive power, current drawn and resulting voltage are measured and used by the platform as though they are a real installation point receiving measurements live from the network.

With the development of the Simulator service, expanded upon in the GridVis Back-End section, the means to broadcast measurements from a single point or multiple points on the distribution system was achieved. This provided the capability to demonstrate that estimates generated matched observed values in a simulation environment.

Historical Endpoints

The GridVis platform was provided with access to historical logs of 101 measurement devices located around Ireland. The sensors were placed on MV/LV substations, illustrated in Figure 8 as green circles.

[11] M221 PLC Product Overview: [Link to Site]

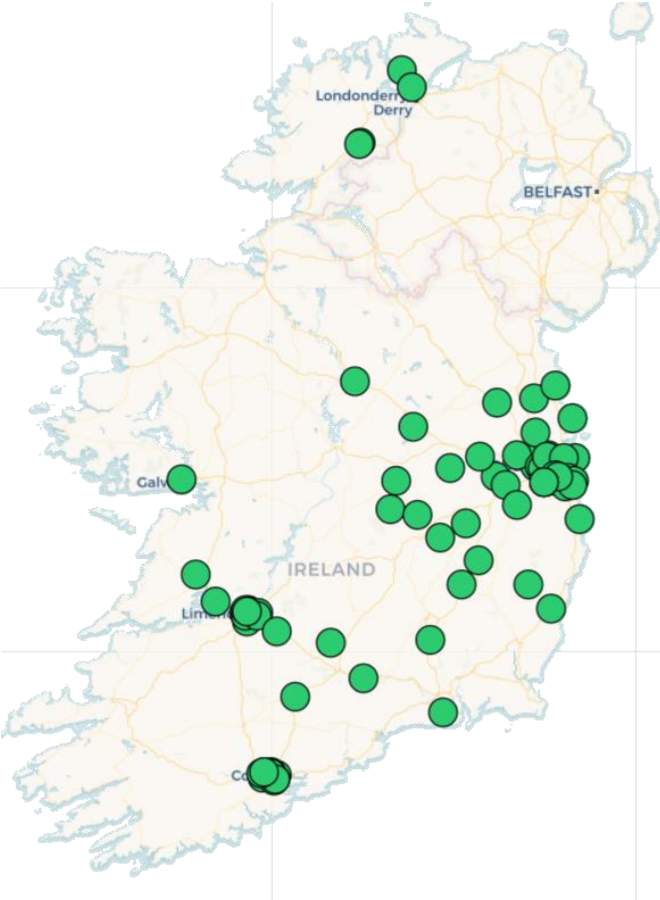

FIGURE 8. OVERVIEW OF MEASUREMENT LOCATIONS INCORPORATED INTO THE GRIDVIS MODELLING PLATFORM

These historical logs provided the opportunity to test the platform capability in estimating remote power flow and voltages in the presence of the two voltage levels found within the Irish MV distribution system.

The 101 MV/LV sensors were situated on 88 different MV circuits, representing a variety of circuits supplying urban load centres, sub urban housing and rural population. A breakdown in the summation of substation by type is provided in the table below, shown with the voltage divide on the MV busbar of each circuit.

TABLE 4. MV/LV SUBSTATION TYPE

	Count
Pole mounted 1ph	17
Pole mounted 3ph	20
3ph Unit substation	64
10:20 kV divide	86:15

As detailed in Table 4, measurements were received from three different categories of MV/LV substation. These were pole mounted 1-phase (a), and pole mounted (b) and ground mounted (c) 3-phase transformers and are illustrated in Figure 9.

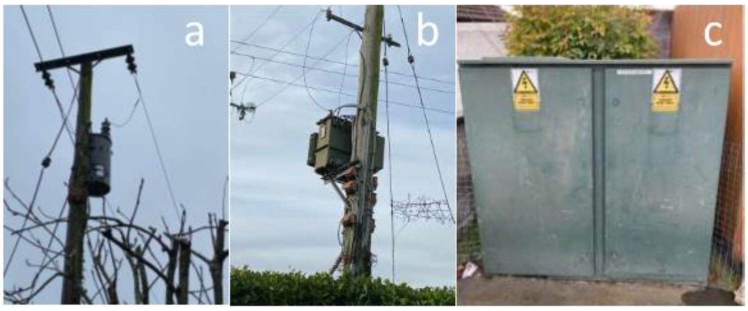

FIGURE 9. MV/LV SUBSTATION TYPES ON THE IRISH DISTRIBUTION NETWORK

Timestamped SCADA information was obtained for the 88 MV circuits and the supplying transformer of the HV Station. This enabled timestamp matching between the head of the circuit and the field measurements, for current and voltage readings. As per Figure 2, combing this data in a power flow simulation environment that drew upon network planning assumptions and peak measurement information of every 3ph MV/LV substation of the circuit, found in ESB heatmap data[5], created a representation of the flows through the circuit and voltage behaviour of each node. NovoGrid's parameterisation of remote network states[12] was then applied to the measurement set of the sensors to enable the real-time estimation of the each of these circuits.

[12] "Method for Controlling Power Distribution, Patent Application Number WO 2015/193199, University College Dublin," 2015.

The GridVis Platform

This section details the GridVis platform developed over the course of the project, produced from the work package deliverables. Throughout WP 2 and WP 3 NovoGrid engaged with The Walton Institute[8] to develop the means to demonstrate our real-time electricity network visibility capability. This put a focus on the end-user navigation to create a click-through dashboard using live application data. The capability to host multiple endpoints was also achieved.

Figure 10 shows the applications used to develop the GridVis Platform and the location where each application performs their task. As shown, the implementation involved two aspects: a set of calculations, power flow analysis and regression analyses, performed on local desktop computers: and deployment on Amazon Web Services (AWS) where a range of services securely interact. The output from the local calculations is condensed to a set of .csv files which are interpreted on AWS for use in real-time estimation.

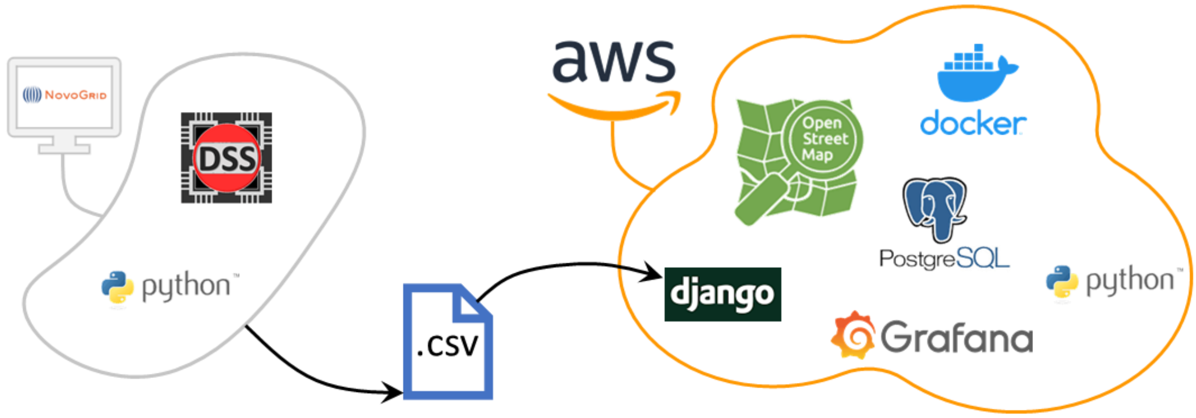

FIGURE 10. APPLICATIONS USED TO DEVELOP GRIDVIS

GridVis Architecture

The deployment architecture diagram, detailed in Figure 11, summarises the services necessary to demonstrate a live platform of estimates calculated from the real-time state estimation technique, GridVis. The role and interaction between the services is defined and the applications are identified. These services are the Map, Dashboard, Application, Datastore and Simulator.

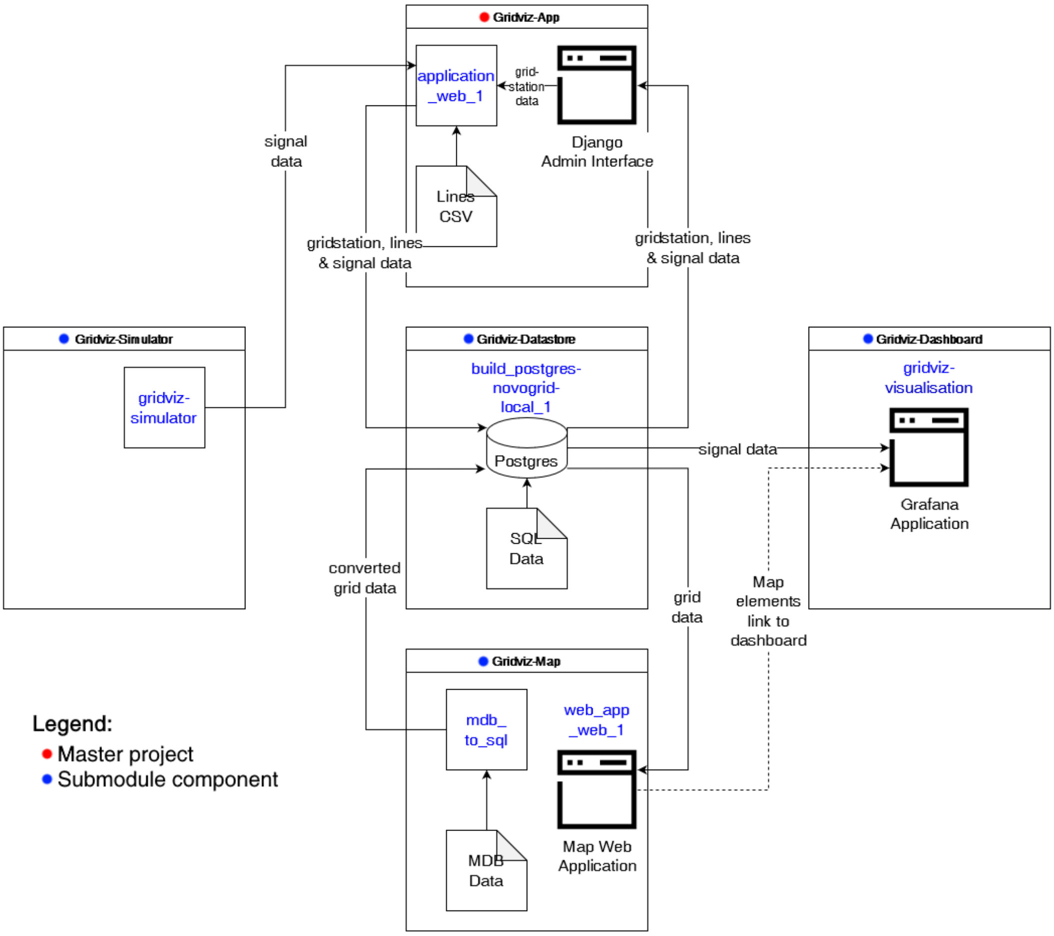

FIGURE 11. DEPLOYMENT ARCHITECTURE OF THE GRIDVIS PLATFORM

GridVis Map

The GridVis map is the main user interface for navigating the sections of network estimated by the platform. The site is hosted at https://gridvismap.novogrid.com. To arrange a demonstration and request log in details contact info@novogrid.com.

ESB networks asset library contained coordinates of all sections of the MV distribution system, which made it possible to view the geographic expanse of the network. Built on OpenStreetMap[13], details of interest are colour coded on a backdrop of the country showing road infrastructure, building structure outlines and placenames. It is possible to display all assets, fuses, relays, regulators, substations etc, for this project demonstration the electrical features on display are limited to conductors, HV/MV Stations and network open points. MV 3-phase network is shown as dark blue, MV 1-phase network is coloured a lighter blue, network open points are marked as white circles and HV Stations marked as yellow circles. Endpoint locations, where measurements are received, are marked as larger green circles. A screenshot of the map is shown in Figure 12, displaying a portion of Co. Wicklow, from Roundwood to Kilcoole.

[13] OpenStreetMap Project: Link to Site

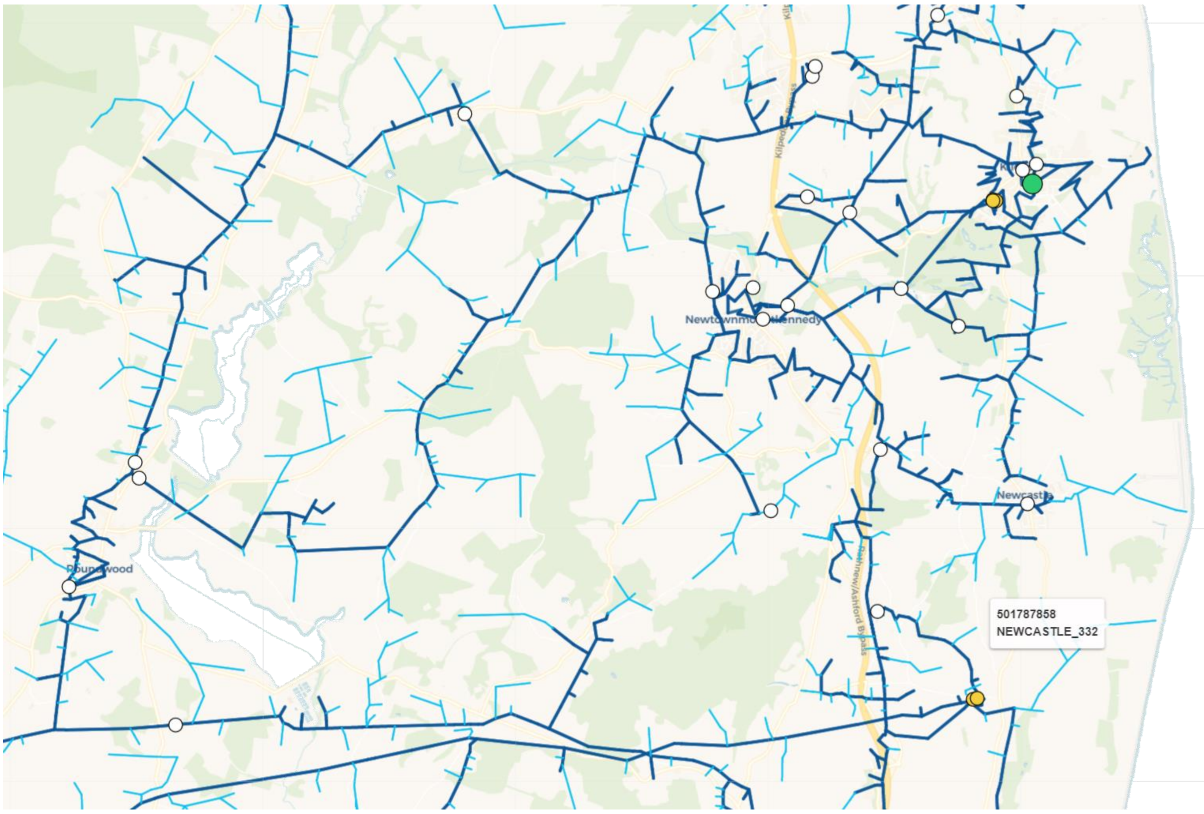

FIGURE 12. SCREENGRAB OF THE GRIDVIS MAP USER INTERFACE

Navigating the cursor around the map prompts a pop-up bubble that displays information on a network feature: namely the Section ID and the MV circuit identifier. An example of this is seen in Figure 12, in which a pop-up bubble lists the details of a section of 1-phase network. Other meta-data associated with the section of network could be included in this bubble for example section length, customer numbers, voltage level, conductor type, year of installation.

Displaying live estimates on the map platform involves a dedicated service running continuously to link the calculation database with the map display. This would make it possible to colour code sections by available ampacity or show regions of high voltage drop or regions nearing an upper voltage limit.

While costed and scoped, this was not completed as part of this project due to the high-cost implications of cloud storage and processing. Instead, users can click on a network feature whereupon they are navigated to the GridVis Dashboard that reads-while-queried from the calculation database.

GridVis Dashboard

The GridVis dashboard displays the measurement information of endpoints hosted on the GridVis platform, and the estimations produced of real-time condition of remote asset flows and voltages. The site is hosted at https://gridvis.novogrid.com/. To arrange a demonstration and request log in details contact info@novogrid.com.

The dashboard for endpoints, represented as green circles on the GridVis Map, shows live active power, reactive power and voltage information as well as time-series plots of these measurements. A PQ capability plot is also provided, which has applicability for distributed generators restricted to operating within certain power factor regions. An example endpoint dashboard is provided in Figure 13.

FIGURE 13. ENDPOINT DASHBOARD DISPLAYING LIVE MEASUREMENTS

Measurements can be received with a resolution of 1 second or greater. The calculation which estimates remote network conditions is a sub second calculation. Simulated Endpoints and Demonstration of a Hardware which read analogue signals, were assigned 10 second resolutions. The readings from Historical Endpoints were captured every 30 minutes. The resolution seen on estimation dashboard is generated at the same rate as incoming measurement signals.

The core of GridVis is to estimate remote conditions on the distribution network. Sections with estimates available are displayed on the Estimation Dashboard, an example dashboard is shown in Figure 14.

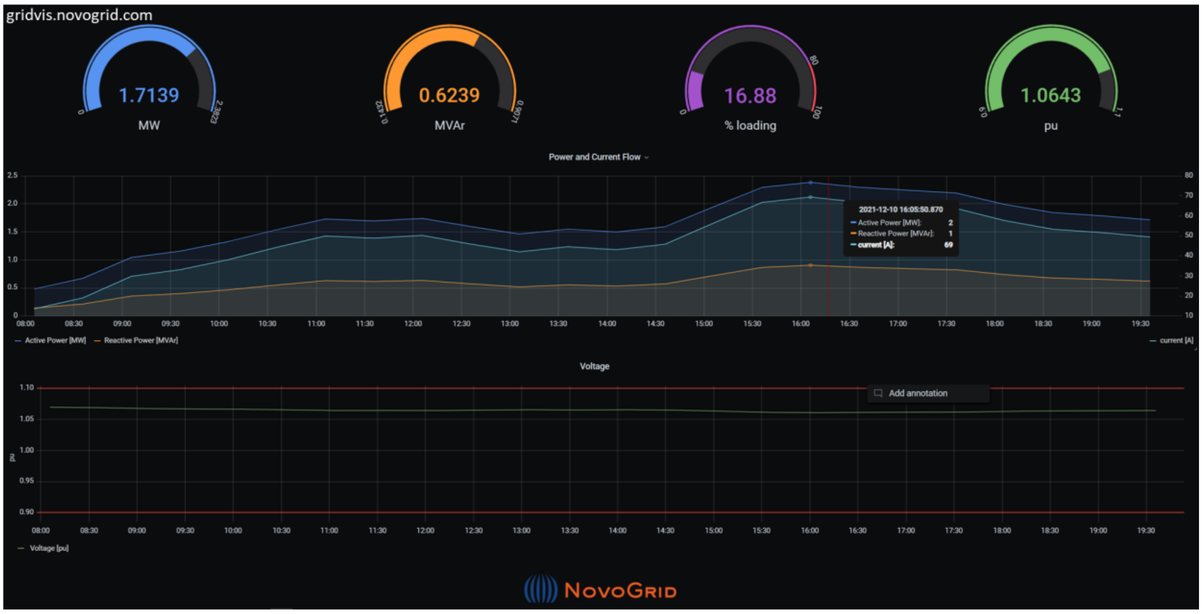

FIGURE 14. ESTIMATION DASHBOARD DISPLAYING LIVE CONDITION OF REMOTE ASSET

This dashboard displays live estimates of active power flow, reactive power flow, ampacity loading and voltage. The estimates are also shown as a timeseries plot and results for a section are searchable in a historical log. Users of the GridVis Map can click on a section of the MV feeder are navigated to the GridVis Dashboard for that section. Figure 15 shows the goodness of fit found from an endpoint for located on a spur of a feeder operating at 20kV.

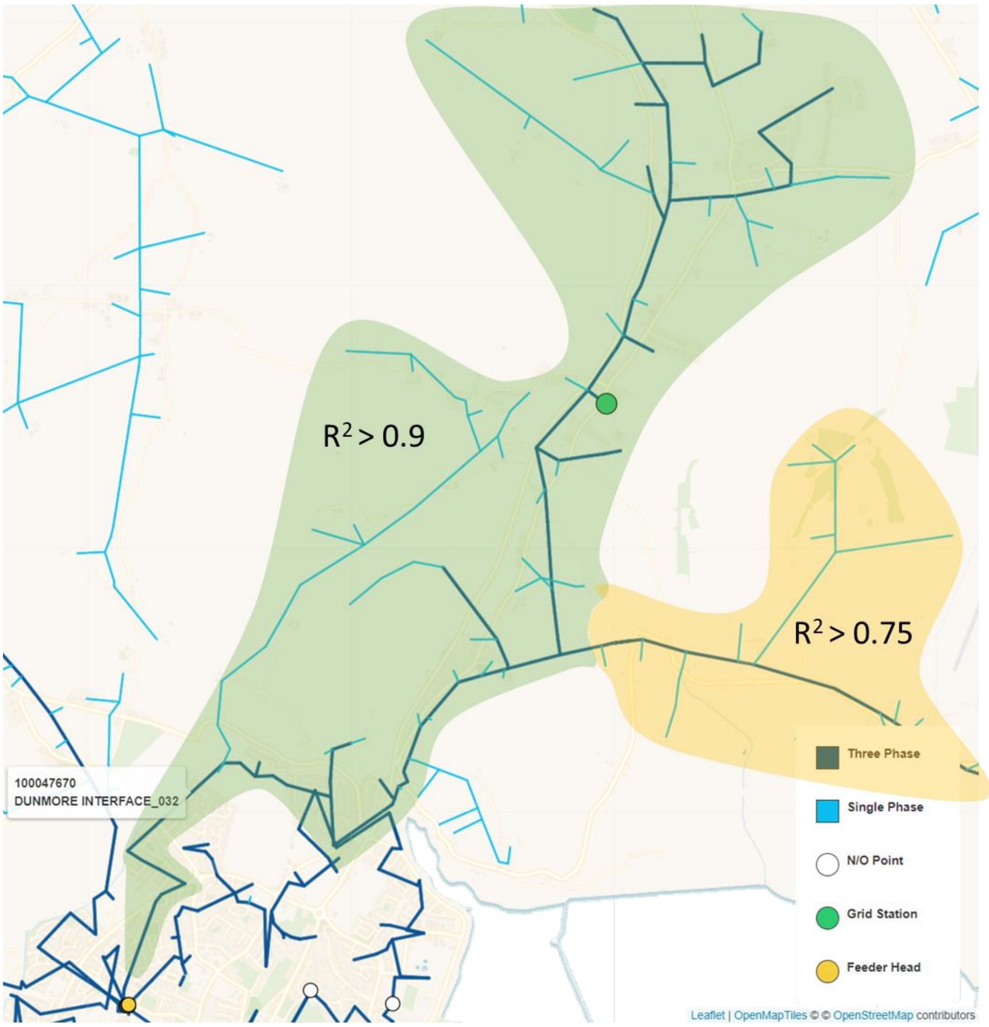

FIGURE 15. GOODNESS OF FIT - GEOGRAPHIC DISPLAY

This feeder is supplied from a 38kV HV Station at 10kV, an IFT within the station compound raises the voltage to 20kV to supply the catchment area. The resulting voltage from the power flow for these network sections are normalised to per unit, each section assigned their operating voltage as a base. As shown the R^2 comparing live-estimates against known data and simulated flows achieves is over 0.9 for all sections downstream of the spur and back to the head of the feeder. Where the MV feeder branches off to the east, a reduced goodness of fit is observed. Nonetheless results for these sections in terms of, voltage and power flows, are above 0.75.

GridVis Back-End

The final three services developed as part of this demonstration project are the back-end services: **Datastore**, **Simulator**, and **Application**.

The **Datastore**, as depicted in in the centre of Figure 11, is the central storage space for all aspects of the GridVis Platform. The database, using postgresSQL, partitions and stores static meta data of the distribution network, the estimation equations coefficients, live measurements of endpoints and results of live estimates corresponding to sections of distribution network.

The **Simulator** container is a development space on the platform where the key algorithms powering GridVis estimation are housed. Here, a database capturing live readings is ingested into NovoGrid algorithms (produced from the Estimation Technique) to calculate and populate a results database. These results are then passed to the GridVis Dashboard, where they are accessible and searchable from the GridVis Map.

The GridVis **Application** is a dedicated site for administration and management of users and endpoints by NovoGrid personnel. Hosted on Django[14], the site enables the creation of users and their basic permissions, endpoint information to be uploaded and maintained, and the formulated estimation equations for network sections to be declared.

The offline power flow and regression analyses, depicted in Figure 10, produce a condensed set of .csv files which are uploaded in bulk to the Application service. Figure 16 shows a sample extract of these .csv files which contain coefficients that combine to formulate an equation of the form seen in (1). These coefficients are used to solve for the real-time flows and voltages of the assets using the live measurements obtained from the linked endpoints. These calculations take place in the Simulator container.

station	SectionId	Sup	Iup	control	p22_A	p22_B	p22_C	p22_D	p22_E	p22_F	q22_A	q22_B	q22_C	q22_D	q22_E	q22_F	v22_A	v22_B	v22_C	v22_D	v22_E	v22_F
STN-0327	86429	3568	206	no	0.030	-0.010	0.380	-0.017	-0.160	0.091	-0.053	-0.020	-0.308	0.070	0.118	-0.020	1.066	-16622.851	-111.373	60.870	15.556	-5872.552
STN-0327	86403	2373	137	no	3.670	-3.060	38.984	-0.177	-21.322	20.377	-1.666	-1.954	-7.248	3.644	-8.054	24.514	1.067	21345.288	-3045.626	217.348	68.205	-2292.301
STN-0327	86991	2373	137	no	3.562	-3.155	38.644	0.026	-21.071	20.145	-1.736	-2.017	-7.259	3.777	-8.024	24.477	1.067	7698.038	-641.820	-334.917	-113.352	534.907
STN-0327	501065447	2373	137	no	0.305	-0.141	4.135	-0.136	-1.673	0.825	-0.582	-0.221	-3.448	0.782	1.353	-0.245	1.066	-2452.259	841.996	11.379	-0.946	1681.294
STN-0327	506308778	3326	192	no	0.268	-0.125	3.635	-0.118	-1.469	0.722	-0.512	-0.195	-3.031	0.687	1.190	-0.216	1.066	-3976.575	1330.774	-11.766	-8.558	2667.263
STN-0327	87408	2373	137	no	0.232	-0.111	3.173	-0.099	-1.282	0.629	-0.447	-0.170	-2.645	0.601	1.039	-0.189	1.066	21294.580	943.454	-397.450	-135.351	9794.637
STN-0327	100047697	3326	192	no	0.171	-0.083	2.363	-0.072	-0.954	0.467	-0.333	-0.127	-1.970	0.448	0.774	-0.141	1.066	7472.419	-864.979	-9.601	-7.890	-250.876
STN-0327	86932	2373	137	no	0.084	-0.042	1.169	-0.035	-0.471	0.230	-0.165	-0.063	-0.975	0.222	0.383	-0.070	1.066	-2835.860	-839.787	-26.062	-13.315	-3562.663
STN-0327	87411	3326	192	no	0.064	-0.032	0.891	-0.026	-0.359	0.175	-0.126	-0.048	-0.743	0.169	0.292	-0.054	1.066	-12942.064	2014.758	40.333	8.499	1800.190
STN-0327	504815468	3326	192	no	0.082	-0.266	0.322	0.207	-0.401	0.852	-0.045	-0.063	-0.176	0.108	-0.917	2.248	1.067	-292.229	44.206	71.917	19.703	-14.679

FIGURE 16. EXTRACT OF COEFFICIENTS FOR ASSETS TO BE ESTIMATED FROM LINKED ENDPOINTS

The Application service reads in each endpoint information and assets to be estimated and assigns a UUID, see Figure 17 and Figure 18. The UUID identifier conceals the actual section name and substation ID and uniquely identifies the object, acting as a key for secure reference across each service. These are linked securely to the GridVis Map and GridVis Dashboard services.

[14] The Django Project: Link to Site

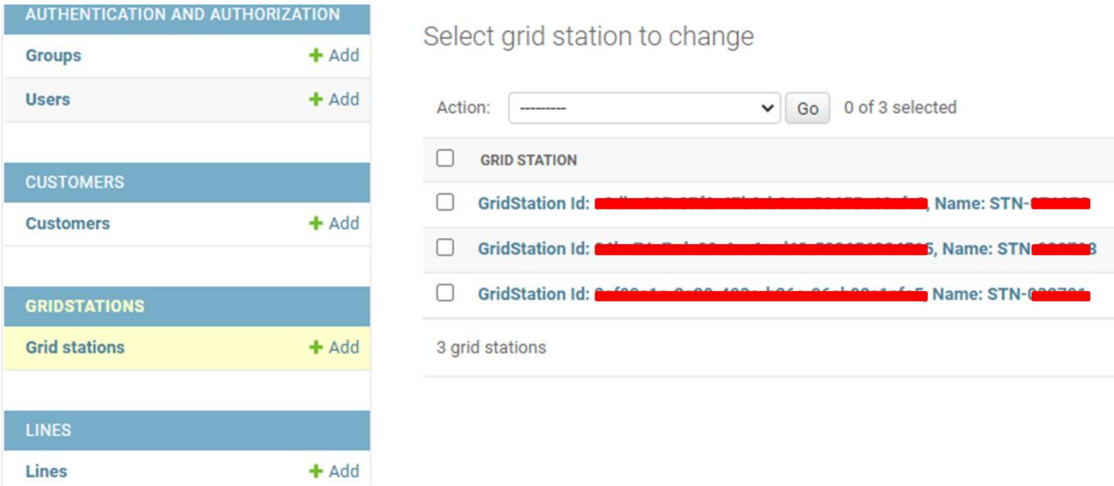

FIGURE 17. ADMIN SITE SHOWING ENDPOINT LOCATION INFORMATION AND (REDACTED) UUID

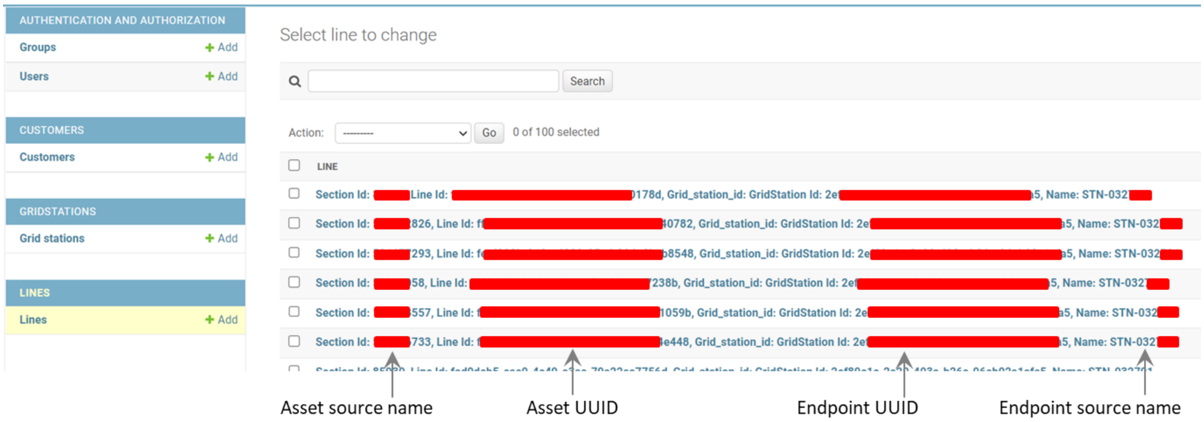

FIGURE 18. ADMIN SITE SHOWING ASSETS TO BE ESTIMATED FROM LINKED ENDPOINTS

Dissemination

NovoGrid personnel travelled to Milan, Italy in the last week of November 2021 to attend to the Enlit Europe Utility Conference[15]. A project stand, situated in the EU Projects Zone was staffed for the duration of the conference where a live demonstration of the GridVis platform was provided to interested conference attendees. The project objectives, results, and the real-time platform were presented in a session called "Interoperability and data exchange to support the digitalisation of smart energy systems" on December 1st. Immediately following the presentation, a NovoGrid speaker took part in a panel discussion fielding questions from the audience and chair.

FIGURE 19. NOVOGRID PRESENTING AT THE ENLIT EUROPE UTILITY CONFERENCE

The project be showcased on the ESB Networks Innovation Webinar Series 2022. The RD&D project is also a project under the Network Resilience Pillar of the ongoing ESB Networks initiative: Innovating to Connect a Clean Electric Future[16]. Upon the submission of the final report to the SEAI, a separate close-out report will be made available on ESB Networks website.

[15] https://www.enlit-europe.com/
[16] Innovating to Connect a Clean Electric Future: Link to PDF see page 64.

Conclusion

This project has demonstrated real-time estimation of remote system conditions using existing measurement locations on the Irish Distribution System.

The GridVis Platform was purpose built to showcase the results of cloud calculations pertaining to sections of distribution network, estimating conditions as often as endpoint measurements are received. The modelling capability and network catchment of the estimation platform was developed to cater for the entire MV distribution network.

There is an abundance of use cases for use of real-time state-estimation: for example, the platform could be used

- to monitor the performance and health of assets,
- as a real-time input for energy aggregators,
- as a planning tool for network owners to determine available head room for new generation or demand customers on existing assets,
- as an operational tool to manage network flows through constrained assets,
- as a live view for network technicians to inform the viability of switching live network assets in order to avoid constraining the network.

Recommendations for future development

Central to the accuracy of the estimations produced by the platform is the initial representation of the network flows in the offline power flow analysis. The better this analysis represents actual system flows and voltages, the better the real-time estimation results. Where data was unavailable at different points in the network, the DNO operating assumptions were adopted. For example, the planning assumptions used for power profiles at MV/LV subs can be substituted with actual power profiles, aggregated from the Smart Meter roll out, when these become available. Presently the estimates are producing accurate flow conditions and network states based on these planning assumptions, actual power profiles would enhance the results obtained.