QUEST Research

Electricity Northwest Limited

Modelling Regime

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2. EXECUTIVE SUMMARY

The objective of the QUEST overarching software can be summarised as: *control and coordinate conflicts across multiple operational systems and control method objectives operating upon the ENWL network and provide voltage optimisation where possible.*

To determine whether QUEST can achieve its objectives and to aid the development of the operational system, a modelling regime must be created that encapsulates:

- the existing and potential network control methods applied to ENWL's network
- how these control methods are applied to a simulated ENWL network,
- and how these control methods are controlled and coordinated by an overarching QUEST software.

To identify the benefits, such as resolution of conflicts between the network control methods, and limitations, such as compromises to the benefits on network control methods as a result of coordination, of the QUEST software.

The existing and potential control methods applied within ENWLs network are implemented as either, a part of an existing operational system, a potential operational system, or as new control method functionality integrated into the QUEST software.

The existing operational systems can be described as:

- CLASS: provides four quadrant P (MW) real power, Q (MVar) reactive power control through the use of voltage control, from increasing/decreasing network real power demand via leveraging voltage-demand relationships, to increasing/decreasing network reactive demand via leveraging reactive demand through transformer pair circulating current control. The provision of this control satisfies thermal, frequency and voltage control objectives required from the system.
- Smart Street: reduces (MW) real power demand via the Conservation Voltage Reduction (CVR) methodology.
- ESO Services: (Operation Code 6 (OC6) e.g., OC6.6 Low Frequency Demand Disconnection (LFDD)) trips CBs in line with its objective.[1]

The potential operational systems can be described as:

- ANM Flexible Connections: maintains network thermal flow limits by curtailing generation in real time, enabling quicker connection time and network investment deferral.
- ANM Flexible Services: is the forecasting of exceeding thermal flow limits, coupled with the procurement and dispatching of DER flexible demand and generation services to mitigate the forecast thermal flow exceedance. Execution of services provide a dispatch schedule to the flexible DER as part of the ANM flexible services platform. This service provides an alternative to, or deferral of network reinforcement investment.

New control method functionality integrated into QUEST can be described as:

[1] The "ESO/DSO Services" include the OC6 emergency demand reduction services provided to the ESO. These external services are largely initiated by control room staff actions in response to ESO requests.

- Network Efficiency: increases system voltages by adjusting transformer target voltage settings, enabling reducing of I^2R losses.[2]
- Tap Stagger: Providing voltage support via reactive power absorption at the BSP level.

The high-level structure of the modelling regime is presented in Figure 1.

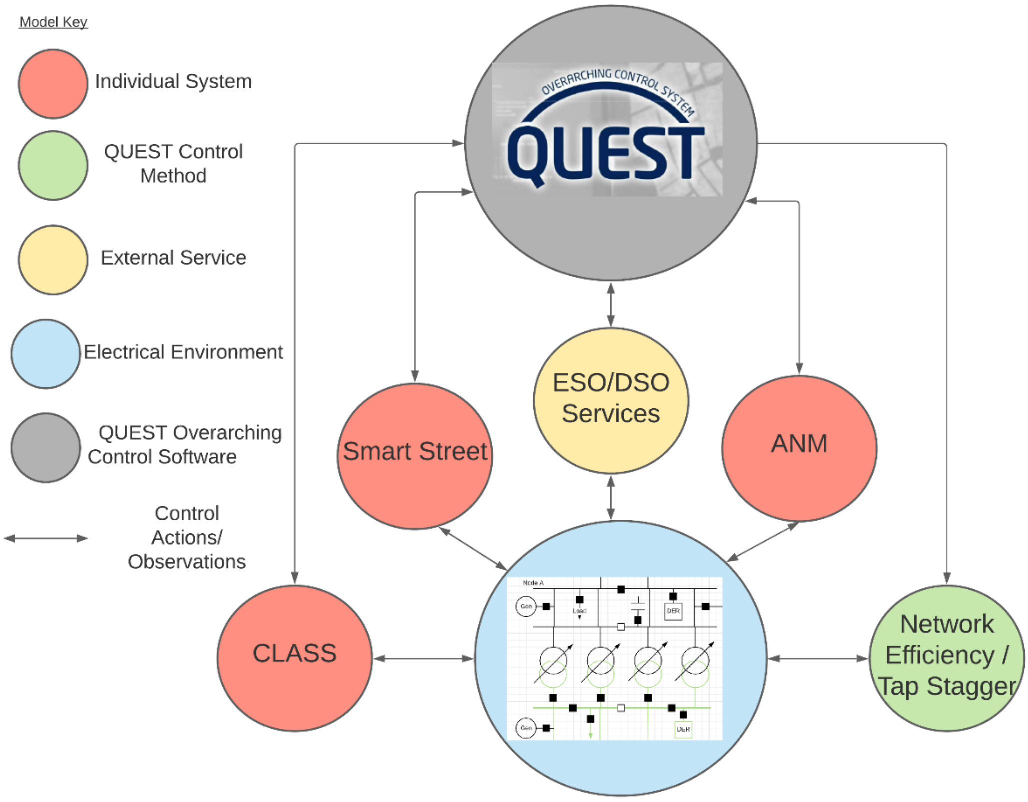

Figure 1: High-Level Modelling Regime

An adequate modelling regime will enable:

- simulation of representative and accurate electrical network modelling for both time-step and time-series analysis, observing key performance indicators:
    - System Losses
    - System Demand
    - System Generation
    - System Carbon Intensity
- application of each individual system's (CLASS, Smart Street, ANM), ESO/DSO services (LFDD) or QUEST control methods (Tap Stagger (BSP Level), Network Efficiency) upon pertinent network assets within the electrical model and their effects on electrical network parameters,

[2] The network efficiency and tap stagger (BSP level) control methods are integrated as part of QUEST.

for example bus-bar voltages and thermal branch flows, and key performance indicators as above,

- identification of issues within the modelled electrical network, caused by conflicts between system control methods achieving their objectives, to determine how QUEST's coordination algorithm can resolve these issues,
- analysis of QUEST's overarching control and impacts upon the simulated electrical network; in order to optimise and validate its algorithm development and how the operation impacts the key performance indicators associated with the network.

The document is split into two parts that achieves the modelling regime above:

1. **Determining Network Model Adequacy:** The electrical network simulation is implemented via an IPSA+ network model. The model has been analysed to determine whether it can achieve the controls and accurate observations required to meet each individual system's control method objectives.
2. **Test Bench Process:** A test bench process has been created to deliver the modelling regime realised in python, where:
    a. A python method has been created to execute time-series scenario analysis to the simulated electrical network, allowing for operational behaviour from typical load and generation profiles to be applied.
    b. Python based representations of Schneider Electric's and SGS's operational systems and the algorithms of each individual system's control method, as well as QUEST control methods and ESO/DNO services have been created and can be applied to the IPSA+ simulation of the electrical network.
    c. The time-series scenario analysis is extended to enable blends[3] of all control methods to be applied in parallel to identify conflict and examine effects on the network key performance indicators.
    d. Finally, the proposed QUEST software architecture is created as a python representation[4]. Applying a model of an overarching control method to coordinate conflicts between individual system control method and control methods applied as part of QUEST. This will allow algorithm optimisation and validation of the QUEST overarching control method. Furthermore, it will enable examination of the impact to network key performance indicators , as a result of the coordination method.

Satisfaction of both these parts detailed within this document will result in a successful modelling regime for supporting development of the QUEST architecture design as well as providing evidence to satisfy the QUEST project objectives.

2.1. Part One: Determining Network Model Adequacy

QUEST must coordinate conflict between all control methods, where conflict is defined by a system's control method ability to achieve its own objective but causing either:

- a wider network issue in contravention of statutory limits or the distribution code,

[3] In a later stage of the project, how each system's control method variables will be blended will be defined.
[4] Python is an interpreted high-level general-purpose programming language.

- causing another system to not achieve their objective, or
- causing other systems actions to induce a network issue in contravention to grid codes.

To achieve coordination of conflict, QUEST must be able to identify possible conflicts observed from applying any control method uncoordinated to the network model, then update control actions to resolve the conflict.

Therefore, if all controls and observations for all control methods are achievable from applying the method to the model, then it stands to reason that the model can also provide to the QUEST design, the observation and controls required to identify conflict and apply corrective coordination to the control method.

Furthermore, in concert with QUEST's software objectives are the project objectives for identifying benefits and limitations of the QUEST software operations. Similar to identifying conflict between the control methods (Network Efficiency, CLASS, Smart Street and ANM etc.), the electrical parameter observations (voltages, thermal flows etc.) from the electrical network model can be used to identify either positive or negative impacts on the real network before and after the implementation of the QUEST software controls.

In summary, identifying whether the control method applied, and observations can be achieved by applying them to the model, will result in determining whether the network model is adequate for testing QUEST's software objectives and providing data to determine that QUEST has met its wider project objectives.

The model was reviewed at each voltage level to test its adequacy for use in the project. Three adequacy requirements were assessed per voltage level for this purpose:

- Control Requirements (CR): The model contains the electrical control parameters that enable each control method, to be coordinated by QUEST, to be implemented.
- Observation Requirements (OR): The model contains the electrical parameters required to observe the effect of each of the control methods to confirm correct control operation and to analyse the benefits and limitations of the QUEST coordination method.
- Accuracy Requirements (AR): The modelled control actions and the observation of electrical parameters associated with the control actions effect, at each voltage level, are an accurate approximation of the control methods and observations associated with the real-world system. Furthermore, the data used to populate the model must be an accurate representation of the real-world objects they are simulating, for example impedance data.

Meeting the adequacy requirements determines the model adequacy.

The existing baseline IPSA+ model was not adequate. It neither allowed for the control methods associated with QUEST (CLASS, Smart Street, ANM, Network Efficiency, etc.) to be implemented fully, nor did it allow for the effects of the electrical parameters induced by these control methods to be observed fully. Therefore, extensions have been made to the IPSA+ model to ensure that all control methods, and observations can be fully realised, thus making the model adequate.

These extensions have focused on:

- The introduction of voltage-power demand relationships, to allow voltage control effects from systems such as CLASS and Smart Street to induce changes in power demand within the network.

- The introduction of lower voltage level bus and branch models including distribution substation transformers with voltage controlled auto tap changing, to allow Smart Street methods to be applied to lower voltage level assets and have their control effects induce changes in demand within the network.
- Modelling an acceptable level of network, to observe each systems' controls and observation of effects to confirm system objectives, whilst identifying any benefits and limitations satisfying these objectives may achieve.
- Introducing a representation for flexible DER (associated with either Flexible Connections or Flexible Services or both), noting that none presently exist on the Whitegate GSP supplied network. At this stage, implementation of this extension as an example to satisfy the modelling requirements is all that is needed. The exact details of the flexible connection DER site or flexible service units can be altered in line with future scenarios requirements as required.
- Identifying the data sources to enable the accurate introduction of the extensions, such as,
    - extracting data from ENW sources for bus, branch and transformer models, Common Information Model (CIM) and Distribution Network Information System (DINIS)),
    - allow the proportion of load between constant impedance and constant power to be set as required.

For each of these extensions, care has been taken to achieve an acceptable level of accuracy by using, where possible, ENW databases that provide real-world data of any modelled representation. Where approximations have been used, these have been justified using proven mathematical approximation methods.

With the extensions applied, the IPSA+ model, including the control methods, observations and the accuracy requirements of each system to meet QUEST's modelling objectives, is now adequate.

However, as the project progresses, there may be opportunity to improve this model. Therefore, any improvements that can be made to the model, coupled with the justifications of why they should be made, will be added to this document as an appendix in future issued revisions.

2.2. Part Two: Test Bench Process

With an adequate network model created that enables the required control and observations from each control method to be achieved, a test bench process was created to:

- Implement a time-series simulation of the electrical network to observe the key performance indicators
- Consider scenario analysis to implement load and generation behaviours upon the electrical network.
- Simulate each control method upon the electrical network, so the impacts of their actions can be observed
- Extend the scenario analysis to enable a blend of control method application in parallel to identify conflict between objectives and analyse impacts to key performance indicators.
- Simulate QUEST's overarching algorithm to:
    - coordinate conflicts between control method objectives to optimise and validate the developed overarching algorithm and

- analyse impacts of the QUEST overarching control solution upon key performance indicators

Where both these bullet points help satisfy overall QUEST core project objectives.

The test bench process is constructed using a python platform[5].

- *Set Scenario Sub Process:* Scenario analysis can be configured as part of the process to test each individual control system in isolation or in parallel. Using a schedule to allow for a blend of control methods to be tested to analyse the conflicts that arise and the resulting impact on the key performance indicators. This can then be used to facilitate optimisation and validation of the QUEST overarching architecture options being developed by Schneider Electric[6]
- *Electrical Network:* This method applies time-step load and generation inputs to the electrical network model and the resulting state to be observed as it transitions from time-step to time step, allowing for the time-series behaviour of the electrical network to be simulated.
- *Network Control Systems*: Python based representations of each control method algorithm have been created to interact with the simulation of the IPSA+ distribution network model, as well as implementation of QUEST's overarching coordination method to be exhibited upon each control method.
- *QUEST Overarching Control:* Finally, the test bench implements a representation of the QUEST software overarching coordination algorithm in order to test that the QUEST software is adequate in resolving conflict and implementing its total functionality, as well as observing its impact on key performance indicators. This representation has been achieved by modelling the QUEST software architecture as close as possible to its operational system architecture, proposed by Schneider Electric, see Figure 2.

[5] Python is an interpreted high-level general-purpose programming language.
[6] Schneider Electric report "QUEST Architecture Options Detailed Design Subphase 2 Report" , Nov 2021.

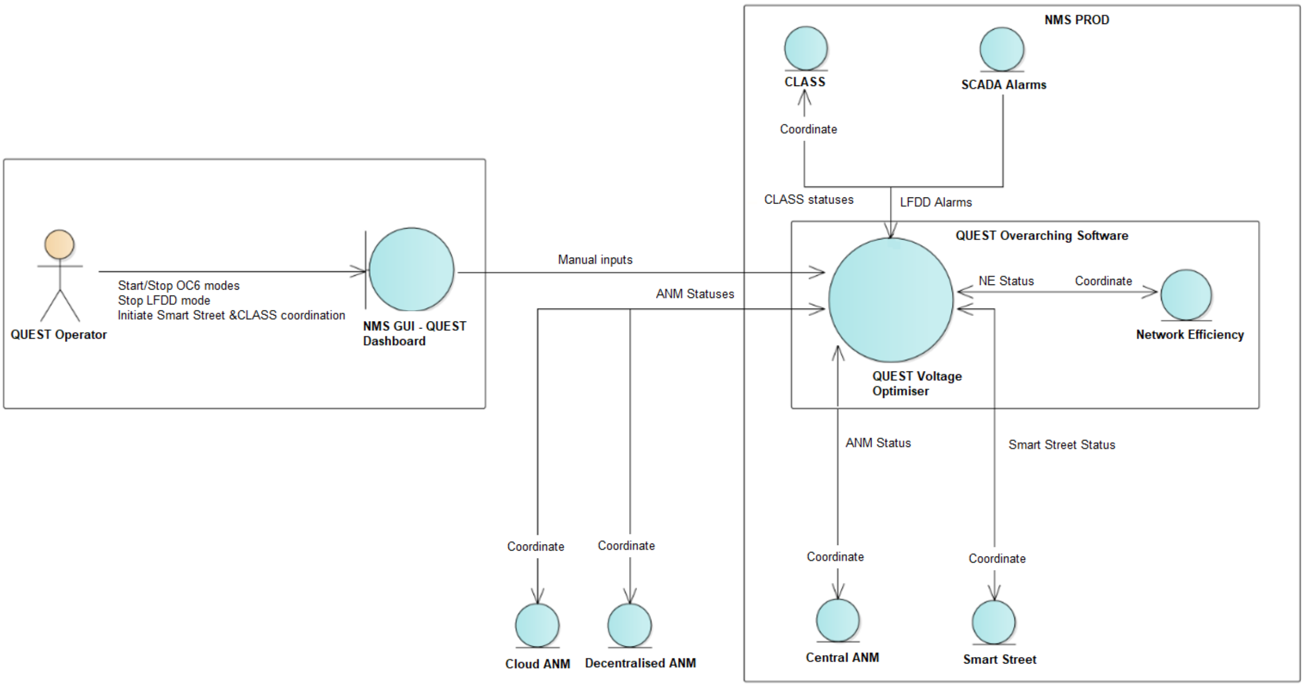

Figure 2: QUEST Voltage Optimiser – main architecture diagram

Modelling Limitations

The limit of the modelling is that steady state can only identify electrical parameter behaviour where transients have settled, this is an acceptable limitation since:

- QUEST's control methods do not directly deal with transient or sub transient issues such as fault behaviour.
- Although QUEST can respond to ESO services that do directly deal with transient or sub transient issues, such as LFDD, it is only after actions have already been taken by relays and QUEST cannot override these instructions.
- The transient and sub-transient issues caused by any action taken by QUEST fall within the tolerance of a network planned stability envelope.
- Fundamentally, the electrical behaviour determined from the settled steady state modelling can still provide satisfactory evidence of QUEST's core objectives being met or not met.

In future, if QUEST functionality is extended to directly deal with transient and sub transient issues, then the modelling will need to be extended to adequately consider these issues via, for example, Root Mean Square (RMS) or Electromagnetic Transient (EMT) analysis.

With the implementation of the test bench process, the modelling regime enables the development of the QUEST architecture as well as providing evidence to satisfy the QUEST project objectives.

The next stage of this project is to use the modelling regime to fully validate and optimise QUEST's overarching software in line with its operational platform implementation, and to analyse it benefits and limitations in regard to key performance indicators to satisfy the QUEST core project objectives.

Table 1 - Terminology

Term	Definition
ANM	Active Network Management
AR	Accuracy Requirements
BSP	Bulk Supply Point substation 132/66kV or 132/33kV.
CIM	Common Information Model
CLASS	Customer Load Active System Services
CB	Circuit Breaker
CR	Control Requirements
DB	Demand Boost
DER	Distributed Energy Resource
DINIS	Distribution Network Information System
DNO	Distribution Network Operator
DR	Demand Reduction
ENWL	Electricity North West Ltd
ESO	United Kingdom Electricity System Operator
GSP	Grid Supply Point substation 400/132kV or 275/123kV. These connected to the UK ESO operated transmission network at 400kV or 275kV and supply the BSP substations.
IPSA+	Interactive Power System Analysis 2.0
LDL	Lower Demand Limit
LFDD	Low Frequency Demand Disconnection
LL	Load Limiting (CLASS Function)
LV	Low Voltage (network)
NE	Network Efficiency
NOP	Normally Open Point
OR	Observation Requirements
OC6	Operating Code No.6
P	Real Electrical Power
PQ	Real and Reactive Electrical Power
PFR	Primary Frequency Response
Q	Reactive Electrical Power
SFR	Secondary Frequency Response (CLASS Function)
SGS	Smarter Grid Solutions

Term	Definition
TS	Tap Stagger
UDL	Upper Demand Limit

2.3. References

This report refers to the following documents associated with the QUEST project:

[1] QUEST Initial Report Use Cases Issue1
[2] SGS report number 200952 11 “ENWL, QUEST ANM Research, Trial Data Definition Report”
[3] Schneider Electric report “QUEST Architecture Options Detailed Design subphase 2 Report”

3. INTRODUCTION

To cater for the subsequent increase in electricity demand and generation caused by decarbonisation targets, DNOs have investigated and deployed control methods such as Customer Load Active System Services (CLASS), Smart Street and Active Network Management (ANM) optimisation systems. Whilst these systems have proven successful in helping DNO's to manage the network they do have limitations such as:

- They are often applied in isolation of one another and do not operate in a co-ordinated manner.
- It is possible that one technique could counteract another, resulting in reduced effectiveness and potentially failing to maintain operation within acceptable limits.
- They use worst-case planning assumptions, which build in large safety margins, resulting in operation below the theoretical maximum.
- They require a resilient communications infrastructure at all times and are set up to fail safe. Therefore, if there is a communications failure any voltage optimisation or ANM benefit is significantly reduced or removed.

With these limitations of the current operation of the individual optimisation systems, the main objective of the QUEST overarching software can be summarised as: *control and coordinate conflicts across multiple operational systems and control method objectives operating upon the ENWL network and provide voltage optimisation where possible.*

This splits into three core operational objectives as identified in "QUEST Initial Report Use Cases Issue1" [1]:

1. Coordinate operation of system voltage control and optimisation systems.
2. Identify and avoid potential conflicts between multiple systems, ensuring appropriate configuration of key voltage control and optimisation systems at all times.
3. Enhance operational efficiency.

To determine whether QUEST can achieve its core operational objectives a modelling regime must be created that encapsulates:

- the existing and potential network control methods applied to ENWL's network
- how these control methods are applied to a simulated ENWL network,
- and how these control methods are controlled and coordinated by the overarching QUEST software, identify the positive and negative impacts to operational efficiency and optimise the control methods to maximise operational efficiency.

For example, coordinating conflict between control methods may ensure no exceedance of a voltage limit, but results in setting certain system set points at a sub-optimal position, in regard to their own objectives. Therefore, having a modelling regime that can identify the issues and optimise the control method objectives, whilst considering other control method objectives, network electrical parameter constraints, and effect to key performance indicators, is key to satisfying QUEST's core objectives.

The existing and potential control methods applied within ENWLs network are implemented as either, a part of an existing operational system, a potential operational system, or as new control method functionality integrated into the QUEST software.

The existing operational systems can be described as:

- CLASS: provides four quadrant P (MW) real power, Q (MVar) reactive power control through the use of voltage control, from increasing/decreasing network real power demand via leveraging voltage-demand relationships, to increasing/decreasing network reactive demand via leveraging reactive demand through transformer pair circulating current control. The provision of this control satisfies thermal, frequency and voltage control objectives required from the system.
- Smart Street: reduces (MW) real power demand via the Conservation Voltage Reduction (CVR) methodology.
- ESO Services: (Operation Code 6 (OC6) e.g., OC6.6 Low Frequency Demand Disconnection (LFDD)) trips CBs in line with its objective.[7]

The potential operational systems can be described as:

- ANM Flexible Connections: maintains network thermal flow limits by curtailing generation in real time, enabling quicker connection time and network investment deferral.
- ANM Flexible Services: is the forecasting of exceeding thermal flow limits and the procurement and dispatching of DER flexible demand and generation services to mitigate the forecast thermal flow exceedance. This service provides an alternative to, or deferral of network reinforcement investment.

New control method functionality integrated into QUEST can be described as:

- Network Efficiency: increases system voltages by adjusting transformer target voltage settings, enabling reducing of I^2R losses.[8]
- Tap Stagger: Providing voltage support via reactive power absorption at the BSP Level.

The high-level structure of the modelling regime is presented in Figure 3.

[7] The "ESO/DSO Services" include the OC6 emergency demand reduction services provided to the ESO. These external services are largely initiated by control room staff actions in response to ESO requests.

[8] The network efficiency and tap stagger (BSP Level) control methods are integrated as part of QUEST.

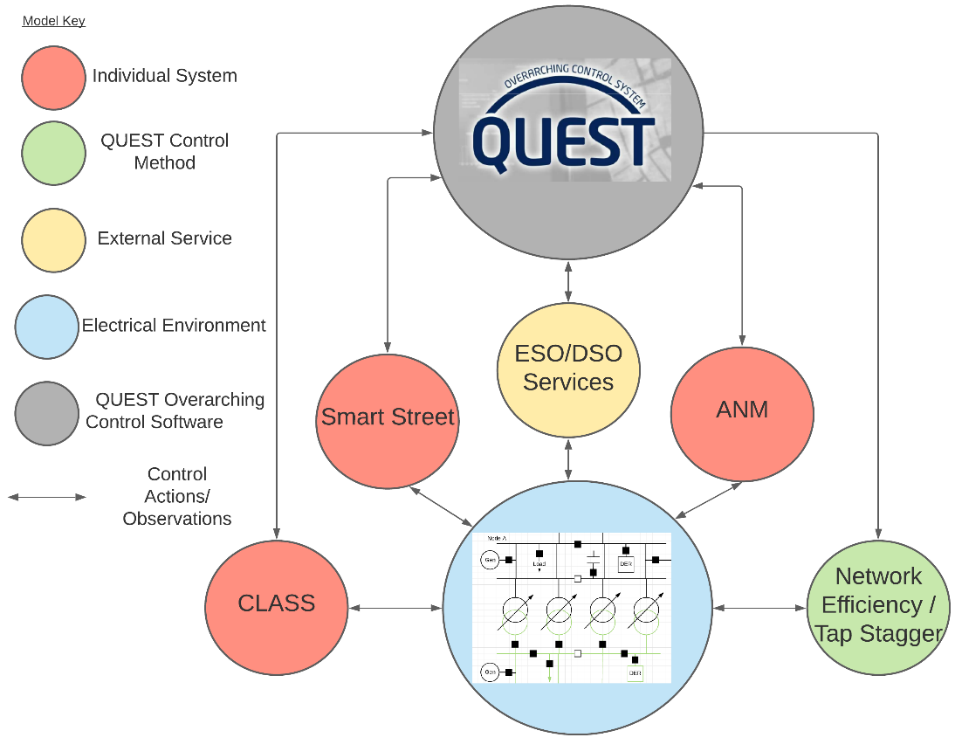

Figure 3: High-Level Modelling Regime

An adequate modelling regime will enable:

- simulation of representative and accurate electrical network modelling for both time-step and time-series analysis, observing key performance indicators:
    - System Losses
    - System Demand
    - System Generation
    - System Carbon Intensity
- application of each individual system's (CLASS, Smart Street, ANM), ESO/DSO services (LFDD) or QUEST control methods (Tap Stagger (BSP Level), Network Efficiency) upon pertinent network assets within the electrical model and their effects on electrical network parameters, for example bus-bar voltages and thermal branch flows, and key performance indicators as above,
- identification of issues within the modelled electrical network, caused by conflicts between system control methods achieving their objectives, to determine how QUEST's coordination algorithm can resolve these issues,
- analysis of QUEST's overarching control and impacts upon the simulated electrical network; in order to optimise and validate its algorithm development and how the operation impacts the key performance indicators associated with the network.

This document is split into two parts that details how the modelling regime above can be achieved:

1. **Determining Network Model Adequacy:** The electrical network simulation is implemented via an IPSA+ network model. The model has been analysed to determine whether it can achieve

the controls and accurate observations required to meet each individual system's control method objectives.

2. **Test Bench Process:** A test bench process has been created to deliver the modelling regime realised in python[9], where:
    a. A python method has been created to execute time-series scenario analysis to the simulated electrical network, allowing for operational behaviour from typical load and generation profiles to be applied.
    b. Python based representations of Schneider Electric's and SGS's operational systems and the algorithms of each individual system's control method, as well as QUEST control methods and ESO/DNO services have been created and can be applied to the IPSA+ simulation of the electrical network.
    c. The time-series scenario analysis is extended to enable blends[10] of all control methods to be applied in parallel to identify conflict and examine effects on the network key performance indicators.
    d. Finally, the proposed QUEST software architecture is created as a python representation. Applying an overarching control method to coordinate conflicts between individual system control method and control methods applied as part of QUEST. This will allow algorithm optimisation and validation of the QUEST overarching control method. Furthermore, it will enable examination of the network key performance indicator impacts , as a result of the coordination method.

Satisfaction of both these parts detailed within this document will result in a successful modelling regime for supporting development of the QUEST architecture design as well as providing evidence to satisfy the QUEST project objectives.

3.1. Part One: Determining Network Model Adequacy

To determine whether QUEST can achieve its objectives to aid the development of the operational system, a model of all the control methods to be coordinated by the QUEST software must be tested to show that they can solve realistic simulated ENWL network issues.

This section examines the IPSA+ model of the trial area[11] to test adequacy: *does the model represent enough of the ENWL network to test QUEST's control methods to accurately observe their effects?* An adequate model will enable:

- application of each control method (CLASS, Smart Street, ANM, QUEST Control Methods etc.) upon pertinent network assets,
- accurate observation of each control method's effect upon the network to identify network efficiency benefits, and
- identify conflicts between control methods, in order to determine how QUEST's coordination can resolve these issues as part of the test-bench regime.

The work performed and described in part one of this document covers two stages:

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[9] Python is an interpreted high-level general-purpose programming language.

[10] In a later stage of the project, how each system's control method variables will be blended will be defined.

[11] The Whitegate GSP was selected as the trial area, the justification of its selection is outlined as part of an ENWL-SGS deliverable *SGS report number 200952 11 "ENWL, QUEST ANM Research, Trial Data Definition Report"*

1. **Stage A: Network Model Analysis:** Analyse the baseline IPSA+ network planning model's adequacy by identifying:
    - it's suitability to implement each systems' control methods upon pertinent network assets,
    - provide the required network observations to determine the benefits of the individual system action, and
    - ensure the observations provide an acceptable level of accuracy.
2. **Stage B: Network Model Extension:** Extend the baseline IPSA+ network planning model to ensure system control methods and their observed effects missing from the baseline model can be accurately implemented.

3.2. Part Two: Test Bench Process

With an adequate network model created that enables the required control and observations from each control method applied, a test bench process is required to:

- implement a time-series simulation of the electrical network to observe the following key performance indicators:
    - System losses
    - System Demand
    - System Generation
    - System Carbon Intensity.
- Consider scenario analysis to implement load and generation behaviours upon the electrical network.
- Simulate each control method upon the electrical network, so the impacts of each individual control methods can be observed.
- Extend the scenario analysis to enable a blend of all control method operations in parallel to identify conflict between control method objectives and analyse impacts to key performance indicators.
- Simulate QUEST's overarching algorithm to:
    - coordinate conflicts between control method objectives to optimise and validate the developed overarching algorithm and
    - analyse impacts of the QUEST solution upon key performance indicators.

    Where both these points help satisfy the overall QUEST project objectives.

With a test bench process developed, the modelling regime will be realised. The document will now undertake part one.

4. PART ONE: DETERMINING NETWORK MODEL ADEQUACY- STAGE A: NETWORK MODEL ANALYSIS

The baseline IPSA+ model of the Whitegate GSP supplied network area selected for the QUEST trial [1] consists of the network modelled explicitly down to the secondary bus-bar of each primary substation.

4.1. Network Overview

The network model provides a representation of the network topology and the resulting electrical parameter data that arises from the load flow solution. Encapsulated within the model is the equipment ratings and statutory limits, as well as most control models. The Whitegate GSP consists of multiple BSPs and Primaries, some of which have CLASS or Smart Street systems embedded. Furthermore, the GSP supplied network currently contains no ANM Flexible Connections, however, there is a large potential for these connections. The Whitegate GSP network is summarised in Table 2.

Table 2: Whitegate GSP Overview

GSP 400/132kV	BSP 132/33/66kV	Primaries 33/11/6.6kV/11kV	CLASS Operational	Distribution Substations 11/6.6/0.415kV	SS Operational	Inverter Based Headroom (MW)	Synchronous Headroom (MW)
Whitegate	Chadderton	8	7	320	6	8	2
	Redbank	4	2	279	4	155	40
	Royton	3	3	181	9	0	0
	Greenhill	6	4	264	4	120	27

4.2. QUEST Software Overview

As discussed in section 3, the overall aim of QUEST is to control and coordinate multiple control methods trying to achieve multiple objectives. Some of these objectives are autonomous: being achieved constantly, others are manual: triggered by a service requirement. The result of achieving these objectives is an observed impact on the network, which can be a benefit or cause issues to the network. For example, raising voltages at a primary substation secondary busbar can reduce losses on the connected feeders, but all nodes on that feeder must remain within the statutory voltage limits. Therefore, a control method that benefits system losses needs to be able to accurately observe, or calculate its impact to the wider electrical parameters, or other control methods to make sure it is not causing an issue in pursuit of a benefit.

To test whether the model can implement control methods and observe their impacts, each individual control method identified as existing (CLASS, Smart Street) or has the potential to exist (ANM, Network

Efficiency etc.) must be applied to a model of the electrical network and the resulting behaviours induced by these controls observed.

Where:

- Control Method Objectives: Describe the goals of the control methods
- Control Requirements: What the system must control in order to achieve its operational objective, within a steady state solution space.
- Observation requirements: What the system must observe in order to execute its control methods and determine its system objective has been achieved.

A high-level description of each control method is presented:

ANM Flexible Connections

- Control Method Objective (Autonomous): This control method will constantly ensure any constraint and its associated generators are constantly controlled and coordinated to ensure constraint limit compliance.
- Control Requirements: P and Q import/export of DER.
- Observation Requirements: Thermal constraint flows are observed and compared against compliance limits. DER setpoints are observed against instructions issued, failure to meet an instruction results in a fail to a safe condition.

ANM Flexible Services

- Control Method Objective (Autonomous): This control method will constantly ensure any DER scheduled to provide a constraint mitigation service is dispatching in line with its schedule.
- Control Requirements: P and Q import/export of DER.

Both ANM systems share similar observations and controls. Therefore, simulation of the ANM Flexible Connection control method also enables delivery of the ANM Flexible Service method and both will be appraised together.

CLASS Demand Reduction (DR)

- Control Method Objective (Manual): At the request of the Electricity System Operator (ESO)/Distribution Network Operator (DNO). This control method reduces power demand in the network but can increase losses.
- Control Requirements: This is achieved by adjusting the target voltage at a primary substation to reduce the secondary busbar voltage by altering the tap positions, for the pair of transformers, at the primary bus-bar.
- Observation Requirements: This voltage change action results in a power demand reduction observed at loads whose power demand reduces when voltage reduces and an increase in system losses (due to higher current demand) where power demand is constant. The difference in power flow through the primary transformer before CLASS actions compared to after CLASS actions result in the power reduction service provided to the ESO. The difference in system losses before CLASS actions compared to after CLASS actions result in the loss increase effect as a result of delivering this service.

CLASS Demand Boost (DB)

- Control Method Objective (Manual): At the request of the ESO/DNO. This control method increases demand in the network but can decrease system losses.
- Control Requirements: This is achieved by adjusting the target voltage at the primary substation to increase the secondary busbar voltage by altering the tap positions, for the pair of transformers, at the primary bus-bar.
- Observation Requirements: This action results in a power demand increase, observed at loads whose power demand increases when voltage increases and a reduction in system losses (due to lower current demand) where power demand is constant. The difference in power flow through the primary transformers before CLASS actions compared to after CLASS actions result in the MW increase service provided to the ESO. The difference in system losses before CLASS actions compared to after CLASS actions result in the loss decrease effect as a result of delivering this service.

CLASS Primary Frequency Response (PFR)

- Control Method Objective (Autonomous): This control method will constantly monitor the network frequency and act if it detects an excursion outside of acceptable parameters.
- Control Requirements: When PFR is enabled the tap-stagger is put in place. The voltage control relay will operate automatically on detection of a frequency below 49.7Hz[12] tripping the LV CB on one of a pair of primary transformers (as long as the substation is within its firm capacity). Once the frequency threshold is exceeded, PFR becomes automatically activated by the on-site CLASS relay. The 11/6.6kV CB of the primary transformer (33/11/6.6kV) which is on the higher tap position out of the primary transformers, is opened.
- Observation Requirements: This voltage change action results in a power demand reduction observed at loads whose power demand reduces when voltage reduces and an increase in system losses (due to higher current demand) where power demand is constant. The difference in power flow through the primary transformer before CLASS actions compared to after CLASS actions result in the power reduction service provided to the ESO. The difference in system losses before CLASS actions compared to after CLASS actions result in the loss increase effect as a result of delivering this service.

CLASS Secondary Frequency Response (SFR)

- Control Method Objective (Autonomous): This control method will constantly monitor the network frequency and act if it detects an excursion outside of acceptable parameters.
- Control Requirements: The voltage control relay will operate automatically on detection of a frequency below 49.7Hz[13]. This system decreases demand in the network via controlling the taps at a primary substation causing both primary transformers to tap down reducing the voltage on the substation LV side busbars.
- Observation Requirements: This voltage change action results in a power demand reduction observed at loads whose power demand reduces when voltage reduces and an

[12] This is a configurable setting which ENWL normally set at 49.7Hz.
[13] This is a configurable setting which ENWL normally set at 49.7Hz.

increase in system losses (due to higher current demand) where power demand is constant. The difference in power flow through the primary transformer before CLASS actions compared to after CLASS actions result in the power reduction service provided to the ESO. The difference in system losses before CLASS actions compared to after CLASS actions result in the loss increase effect as a result of delivering this service.

CLASS Load Limiting (LL)

- Control Method Objective (Autonomous): This control method will constantly monitor the primary substation load level and act if it detects an excursion outside of defined limits to reduce the LV voltage to reduce power demand. This is a DSO local service to delay the need to reinforce local network areas due to rising demand. It is not a service to the ESO.
- Control Requirements: When load increases to a pre-set upper demand level (UDL) of 98.5 % of substation firm capacity, the relay drops the voltage target to its lower pre-set (adjustable) threshold of 95% of nominal voltage. The function remains active as long as the load stays above the allowed bandwidth (i.e., between 98% and 85% of substation firm capacity) or until it is remotely switched off by the control engineer. Where the load falls below the lower demand level (LDL) of 85% of the site firm capacity, the relay waits for a specified (time delay) period of one minute after which the function is deactivated, and the voltage target goes back to nominal.
- Observation Requirements: This system decreases power demand in the network by controlling primary substation secondary side target voltages. The difference in power flow through the primary substation transformers before CLASS actions compared to after CLASS actions results in the power decrease. The difference in system losses before CLASS actions compared to after CLASS actions result in the loss increase effect as a result of delivering this service.

Tap Stagger (TS)[14]

- System Objective (Manual): At the request of the ESO. This control method increases MVAr absorption in the DSO network.
- Control Requirements: This is achieved via controlling each of the transformer pair taps at a primary substation resulting in a higher tap on one transformer and a lower tap on the other.
- Observation Requirements: This action results in voltage at the secondary busbar remaining constant, but a circulating current forming between the two transformers, due to imbalance in the transformer turns ratio, with a magnitude equal to the voltage difference between the transformers, connected in series with the impedance of each transformer. Since this impedance is predominantly reactive, the result is an increase in MVAr absorption, observed as the sum of the MVAr flow through the transformers. The difference in MVAr flow through the primary transformers before TS actions compared to after actions result in the MVAr absorption service provided to the ESO.

Network Efficiency Mode

[14] Tap Stagger functionality exists at primary substation level as part of CLASS functionality, and at BSP level as part of QUEST control method functionality. In future this distinction maybe further developed.

- System Objective (Manual): At the request of the DSO. This control method optimises voltage profiles on the 33kV network to reduce 33kV circuit current flows and hence reduce circuit losses.
- Control Requirements: This is achieved via controlling the transformer voltage set points at BSP substations to increase the secondary busbar voltage (33kV) by altering the tap positions, for the pair of transformers, at the primary bus-bar (132kV). The increased voltage reduces the 33kV current flows required to deliver the network demand, reducing the current (I) related I^2R losses in the network where R is the resistance of the 33kV circuits the current flows through.
- Observation Requirements: This action results in a real power (MW) system loss decrease, observed through network branches in the associated 33kV system. The difference in power losses through monitored network assets before Network Efficiency actions compared to after the actions result in the power loss decrease provided by the Network Efficiency operation.

Smart Street

- Control Method Objective (Autonomous): This control method will constantly try to maintain a low voltage profile across the 0.4kV network to reduce the demand at voltage-dependent loads.
- Control Requirements: This is achieved via controlling the LV voltage setpoint at a distribution substation to reduce the secondary busbar voltage by primarily altering the transformer tap positions. Noted that Smart Street has other controlled elements that support achieving the target LV voltage such as LV circuit meshing but to a lesser extent than changing transformer tap position. Only transformer tap position to control LV voltages is considered in the IPSA+ network model.
- Observation Requirements: This action results in a demand reduction, observed at loads that have a non-constant voltage demand relationship. The difference in power flow at the loads and through the distribution substation transformer before Smart Street actions compared to after Smart Street actions results in the power reduction provided to Low Voltage (LV) network connected customers.

DSO/ESO Services

- Control Method Objective (Manual and Autonomous): This control method will take actions to reduce demand to support system Frequency or transmission level constraints such as Voltage or Thermal limits[15].
- Control Requirements:
    - Manual ESO demand services can be implemented by applying 3% or 6% reduction in target voltage at transformer groups, via the control room.
    - Automatic ESO demand services: LFDD is achieved using frequency relay controlled CB opening at pre-determined loading groups at both BSP and Primary substations once a low frequency event action has been triggered.

[15] https://www.nationalgrid.com/sites/default/files/documents/36903-OC6%20Demand%20Control.pdf

- Observation Requirements: This action results in a demand reduction observed across the primary transformers and verified by the flows across the GSP transformers. The difference in MW flow through the primary substation transformers and GSP transformers, before actions compared to after actions results in the power decrease observed.

To determine whether the distribution network model is adequate, the model has been analysed to determine whether it can achieve the controls and observation required to meet the objectives of each control method.

However, QUEST must also coordinate conflict between each control method, where conflict is defined by one control method's ability to achieve its objective causing either:

- a wider network issue in contravention to the Distribution Code or Grid Code,
- causing another system to not achieve their objective, or
- causing other control method actions to induce a network issue in contravention to the Distribution Code or Grid Code.

To achieve coordination of conflict, QUEST must be able to identify conflict observed on the model, then update control actions to resolve the conflict.

Therefore, if all controls and observations for each control method are achievable from applying the control method to the model, then it stands to reason the model can also provide to QUEST the observation and controls required to identify conflict and apply corrective coordination to all the control methods.

Furthermore, in concert with QUEST's overarching software objectives are the core project objectives for identifying the benefits and limitations of the QUEST software operations. Similar to identifying conflict between the individual systems (CLASS, Smart Street, ANM and Network Efficiency), the electrical parameter observations from the electrical network model can be used to identify either positive or negative impacts to the network before and after the implementation of the QUEST overarching software controls.

In summary, identifying whether the individual control methods and observations can be achieved by applying them to the model, will result in determining whether the electrical network model is adequate for testing QUEST's system objectives and providing data to determine QUEST has met its wider project objectives.

4.3. Model Adequacy Test Criteria

The model has been reviewed at each voltage level to test adequacy; three adequacy requirements were assessed per voltage level to test adequacy:

- Control Requirements (CR): The model contains the electrical control parameters that enable each control method, to be coordinated by QUEST, to be implemented.
- Observation Requirements (OR): The model contains the electrical parameters required to observe the effect of each of the control methods to confirm correct control operation and to analyse the benefits and limitations of the QUEST coordination method.
- Accuracy Requirements (AR): The modelled control actions and the observation of electrical parameters associated with the control actions effect, at each voltage level, are an accurate approximation of the control methods and observations associated with the real-world

system. Furthermore, the data used to populate the model must be an accurate representation of the real-world objects they are simulating, for example impedance data.

Meeting the adequacy requirements determines model adequacy. Where, for each system and voltage level, the model does not meet the adequacy requirement, it is identified which requirement has failed. Failure to meet the system requirements, stated in the system descriptions, results in the identification of a required extension to meet the adequacy requirements.

Each voltage level reviews the control methods applied at the specific voltage level, where effects are sensitive across voltage levels these are highlighted accordingly.

4.4. Whitegate 132kV Network

The GSP is fully electrically represented by load flow approximations of the associated super grid 400kV/132kV transformers. The 132kV network supplies the four BSPs associated with the Whitegate GSP, see Figure 4.

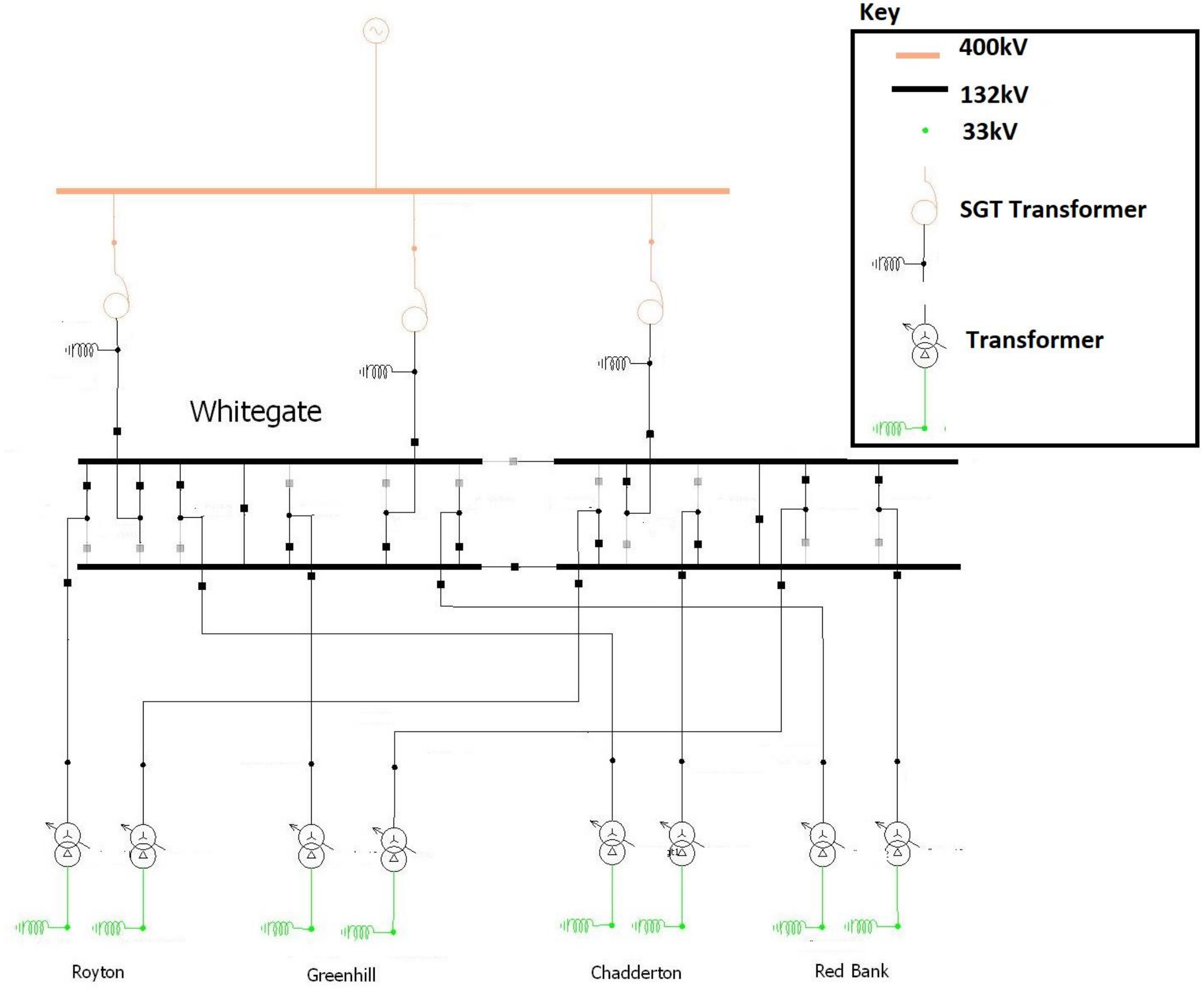

Figure 4: Whitegate 132kV Network

4.4.1. QUEST Control Methods Applied

The control methods that are applied at the 132kV voltage level are:

- ANM Flexible Connections/Services
- Network Efficiency Mode (NEM)
- Tap Stagger Mode (BSP)

Whether these systems can be modelled is reviewed in Table 3:

Table 3: 132kV QUEST Control Methods IPSA+ Model Review

QUEST Control Methods	Voltage Level	Control Requirement	Observation Requirement	Accuracy Requirement	IPSA+ Model Achieved?	Proposed Extension
ANM Flexible Connections/Services	132kV	PQ Control on DER	Thermal flows through sensitive constraints at 132kV. PQ export from site.	CR: P and Q Resolution >1 kW/kVAr OR: P and Q flow Resolution >1kW	CR: PQ Control at DER OR: PQ export from site.	Add representation of a plausible DER connection. • Control: PQ control at DER • Observation: New DER connection PQ flows • Accuracy: P and Q set point Resolution 1 kW/kVAr

QUEST Control Methods	Voltage Level	Control Requirement	Observation Requirement	Accuracy Requirement	IPSA+ Model Achieved?	Proposed Extension
Network Efficiency	132kV	Tap Control at BSP Transformers	Voltage at BSP Secondary Busbar Losses across branches. Observation of bus-bar potentials across all voltage levels.	CR: Tap range >+10% to -20%, typically in 18 steps of 1.67%. OR: Voltage Resolution >0.01 p.u. CR: Line Drop Compensation % data. OR: P and Q Losses Resolution >1kW	Yes	None

QUEST Control Methods	Voltage Level	Control Requirement	Observation Requirement	Accuracy Requirement	IPSA+ Model Achieved?	Proposed Extension
Tap Stagger (BSP)	132kV	Tap Control of BSP Transformers	Voltage at BSP Substation Secondary Busbar PQ flows through GSP transformer to confirm service provision.		Yes	None

4.5. Whitegate 33kV Network

Each BSP is fully electrically represented by load flow approximations of their grid supply transformers and the 33kV network. As an example, Royton BSP is presented in Figure 5, which shows three primary substations connected to it. Each primary substation's online-tap control and impedance parameters are a representative model of the real-world transformer, as well as any line drop compensation considerations; the 6.6kV/11kV/0.415kV network and its loading have been aggregated as a constant power load.

It is assumed the secondary busbar arrangement, either coupled or decoupled within the baseline model, will be maintained.

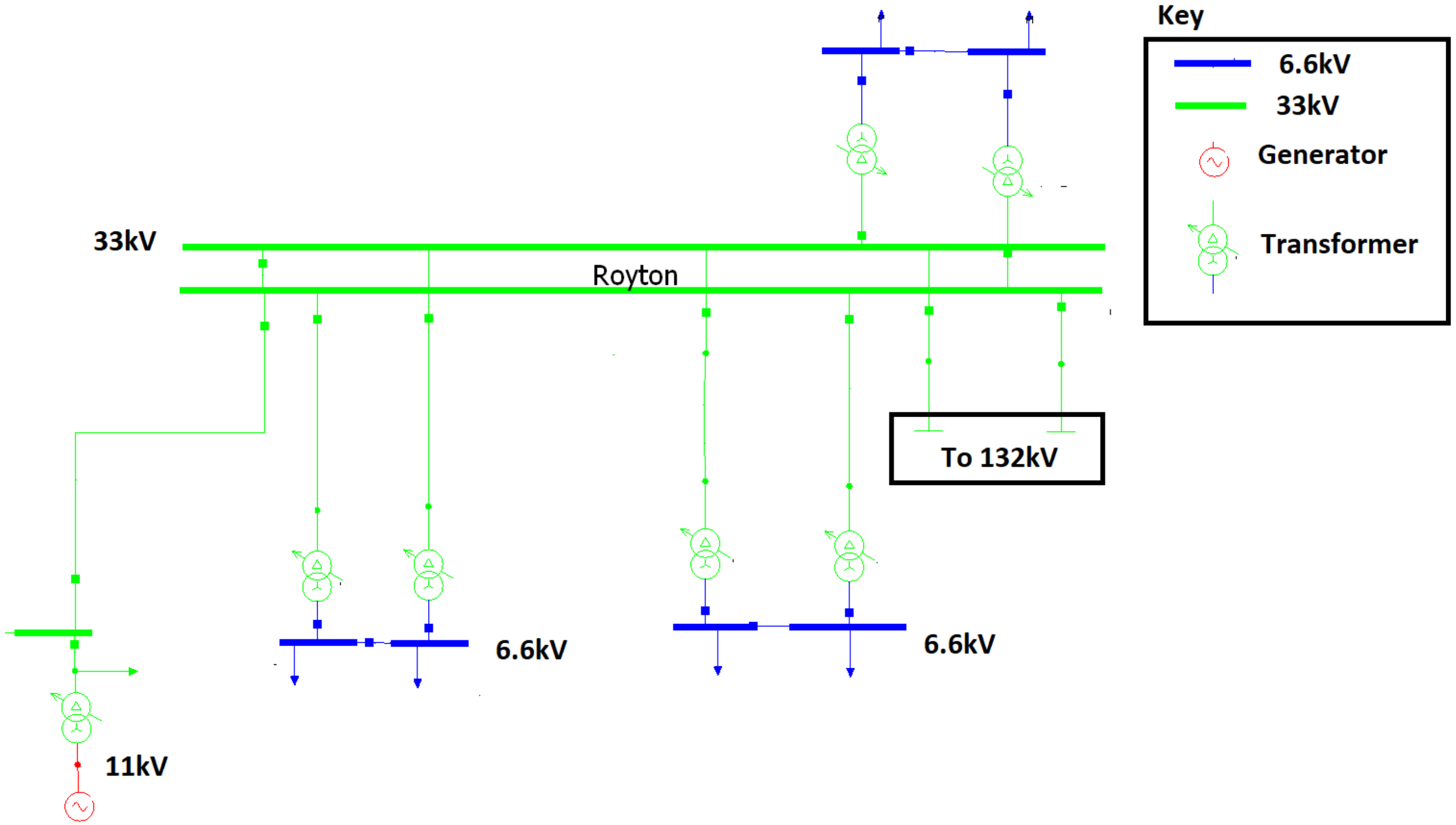

Figure 5: Royton BSP and Primaries

4.5.1. QUEST Control Methods Applied

The QUEST control methods that are applied at this voltage level are:

- ANM Flexible Connections/Services
- Network Efficiency Mode (NEM)
- CLASS (DR)
- CLASS (DB)
- CLASS (PRF)
- CLASS (SRF)
- CLASS (LL)
- CLASS (Tap Stagger)
- ESO Services: Automatic Low Frequency Demand Disconnection (OC6.6-LFDD)

Whether these control methods can be modelled is reviewed in Table 4:

Table 4: 33kV QUEST Control Methods IPSA+ Model Review

QUEST Control Methods	Voltage Level	Control Requirements (CR)	Observation Requirements (OR)	Accuracy Requirements (AR)	Requirements Not Met	Proposed Extension
ESO/DSO Service	132kV	CB Control on BSP	Thermal flows across the GSP and BSP.	OR: P and Q flow Resolution >1kW	Yes	N/A
ANM Flexible Connections/Services	33kV	PQ Control at DER	Power flows through sensitive constraints (33kV and above) PQ export from site.	CR: P and Q Resolution 1 kW/kVAr OR: P and Q flow Resolution 1kW/kVAr	CR: PQ Control at DER OR: PQ export from site.	Add representation of a plausible DER connection. • Control: PQ control at DER • Observation: New DER connection P Q flows • Accuracy: P and Q set point and observation of electrical parameters Resolution 1 kW/kVAr

QUEST Control Methods	Voltage Level	Control Requirements (CR)	Observation Requirements (OR)	Accuracy Requirements (AR)	Requirements Not Met	Proposed Extension
Network Efficiency[16]	33kV	Tap control at primary transformers	Voltage at primary substation secondary busbar Power losses through branches to confirm change. Observation of bus-bar potentials across all voltage levels.	CR: Tap Setting range >+5.72% to -17.16%, in 16 steps of 1.43%. CR: Line Drop Compensation % data. OR: Voltage Resolution >0.01 p.u. OR: P and Q Losses Resolution: 1 kW/kVAr	Yes	None
CLASS (DR)	33kV	Tap control at primary transformers	Voltage at primary substation secondary busbar 6.6kV/11kV Power flows through the primary substation transformers to	CR: Tap Setting range >>+5.72% to -17.16%, in 16 steps of 1.43%. CR: Load Drop Compensation % data.	OR: Thermal flow change at demands due to voltage changes	Introduction of shunt objects to represent constant impedance loads to exhibit voltage-demand relationship

[16] Network efficiency mode is presently only proposed for the 33kV network through voltage control at the BSP 132/33kV transformers only. The network model has made provision for this to be extended to the 11kV/6.6kV network by controlling the primary substation transformers which is not presently part of the proposed network efficiency mode.

QUEST Control Methods	Voltage Level	Control Requirements (CR)	Observation Requirements (OR)	Accuracy Requirements (AR)	Requirements Not Met	Proposed Extension
			confirm demand change in 6.6kV/11kV network. Power flows through GSP transformers to confirm service provision. 400kV/132kV transformer power flow changes to confirm service provision. Power flow change at demands due to voltage changes.	OR: Voltage Resolution >0.01 p.u. OR: P and Q Branch Flows 1 kW/kVAr OR: P and Q Demand Flow 1 kW/kVAr		• Control: Since the proportion of a load, split between constant power and constant load, can alter. The R and X values set points must be calculated as a function of P and Q load values. • Observation: New constant impedance load P Q flows • Accuracy: The historical demand, that represents the constant impedance,

QUEST Control Methods	Voltage Level	Control Requirements (CR)	Observation Requirements (OR)	Accuracy Requirements (AR)	Requirements Not Met	Proposed Extension
						assigned as proportion of the total load.
CLASS (DB)	33kV	Tap control at primary transformers	Voltage at primary substation secondary busbar Power flows through the primary substation transformers to confirm demand change in 6.6kV/11kV network. Power flows through GSP transformers to confirm service provision.	CR: Tap Setting range: +5.72% to -17.16%, in 16 steps of 1.43%. CR: Line Drop Compensation % data. OR: Voltage Resolution >0.01 p.u. OR: P and Q Branch Flows 1 kW/kVAr OR: P and Q Demand Flow 1 kW/kVAr	OR: Thermal flow change at demands due to voltage changes	Introduction of shunt objects to represent constant impedance loads to exhibit voltage-demand relationship • Control: Since the proportion of a load, split between constant power and constant load, can alter. The R and X values set points must be calculated

QUEST Control Methods	Voltage Level	Control Requirements (CR)	Observation Requirements (OR)	Accuracy Requirements (AR)	Requirements Not Met	Proposed Extension
			400kV/132kV transformer power flow changes to confirm service provision. Power flow change at demands due to voltage changes.			as a function of P and Q load values. • Observation: New constant impedance load P Q flows. • Accuracy: The historical demand, that represents the constant impedance, assigned as proportion of the total load.
CLASS (PFR)	33kV	CB control at primary transformers	Voltage at primary substation secondary busbar Power flows through		OR: Thermal flow change at demands due to voltage changes	Introduction of shunt objects to represent constant impedance loads to exhibit voltage-demand relationship

QUEST Control Methods	Voltage Level	Control Requirements (CR)	Observation Requirements (OR)	Accuracy Requirements (AR)	Requirements Not Met	Proposed Extension
			the primary substation transformers to confirm demand change in 6.6kV/11kV network (power flow on transformer switched out will drop to approximately zero). Power flows through GSP transformers to confirm service provision. 400kV/132kV transformer power flow changes to confirm service provision.			• Control: Since the proportion of a load, split between constant power and constant load, can alter. The R and X values must be set points must be calculated as a function of P and Q load values. • Observation: New constant impedance load P Q flows • Accuracy: The historical demand, that represents the

QUEST Control Methods	Voltage Level	Control Requirements (CR)	Observation Requirements (OR)	Accuracy Requirements (AR)	Requirements Not Met	Proposed Extension
			Power flow change at demands due to voltage changes.			constant impedance, assigned as proportion of the total load.
CLASS (SFR)	33kV	Tap control at primary transformers	Voltage at primary substation secondary busbar Power flows through the primary substation transformers to confirm demand change in 6.6kV/11kV network. Power flows through GSP transformers to confirm service provision.		OR: Thermal flow change at demands due to voltage changes.	Introduction of shunt objects to represent constant impedance loads to exhibit voltage-demand relationship • Control: Since the proportion of a load, split between constant power and constant load, can alter. The R and X values must be set points must be calculated as a

QUEST Control Methods	Voltage Level	Control Requirements (CR)	Observation Requirements (OR)	Accuracy Requirements (AR)	Requirements Not Met	Proposed Extension
			400kV/132kV transformer power flow changes to confirm service provision. Power flow change at demands due to voltage changes.			function of P and Q load values. • Observation: New constant impedance load P Q flows • Accuracy: The historical demand, that represents the constant impedance, assigned as proportion of the total load.
CLASS (LL)	33kV	Tap control at primary transformers	Voltage at primary substation secondary busbar 6.6kV/11kV Power flows through the primary substation	CR: Tap Setting range: +5.72% to -17.16%, in 16 steps of 1.43%. CR: Load Drop Compensation % data.	OR: Thermal flow change at demands due to voltage changes	Introduction of shunt objects to represent constant impedance loads to exhibit voltage-demand relationship

QUEST Control Methods	Voltage Level	Control Requirements (CR)	Observation Requirements (OR)	Accuracy Requirements (AR)	Requirements Not Met	Proposed Extension
			transformers to confirm demand change in 6.6kV/11kV network. Power flows through GSP transformers to confirm service provision. 400kV/132kV transformer power flow changes to confirm service provision. Power flow changes at demands due to voltage changes.	OR: Voltage Resolution >0.01 p.u. OR: P and Q Branch Flows 1 kW/kVAr OR: P and Q Demand Flow 1 kW/kVAr		• Control: Since the proportion of a load, split between constant power and constant load, can alter. The R and X values set points must be calculated as a function of P and Q load values. • Observation: New constant impedance load PQ flows. • Accuracy: The historical demand, that represents the constant impedance,

QUEST Control Methods	Voltage Level	Control Requirements (CR)	Observation Requirements (OR)	Accuracy Requirements (AR)	Requirements Not Met	Proposed Extension
						assigned as proportion of the total load.
CLASS (Tap Stagger)	33kV	Tap control of primary transformers	Voltage at primary substation secondary busbar PQ flows through GSP transformer to confirm service provision.		Yes	None

4.6. Whitegate 6.6kV/11kV network.

The 6.6kV/11kV primary substation transformer on secondary busbars is the extent of the network assets the baseline model encapsulates, therefore, most of the baseline model extensions will be needed at the lower voltage levels to achieve model adequacy.

4.6.1. QUEST Control Methods Applied

The QUEST control methods that are applied at this voltage level are:

- ANM Flexible Connections/Services

- Smart Street

Table 5: 6.6kV/11kV QUEST Software IPSA+ Model Review

QUEST Control Methods	Voltage Level	Control Requirement (CR)	Observation Requirements (OR)	Accuracy Requirements (AR)	Requirements Not Mer	Proposed Extension
ANM Flexible Connections/Servi ces	6.6kV /11kV	PQ Control on DER	Power flows through sensitive constraints PQ export from DER site.	CR: P and Q Resolution 1 kW/kVAr OR: P and Q flow Resolution 1kW/kVAr	CR: PQ Control on DER OR: PQ export from DER site.	Add representation of a plausible DER connection. • CR: PQ control at DER • Observation: New DER connection P Q flows Accuracy: P and Q set point and observation of electrical parameters Resolution 1 kW/kVAr

QUEST Control Methods	Voltage Level	Control Requirement (CR)	Observation Requirements (OR)	Accuracy Requirements (AR)	Requirements Not Mer	Proposed Extension
Smart Street	6.6kV /11kV	Tap Control of Distribution Transformers	Voltage at Distribution Secondary Busbar Voltage across 0.415kV Feeders Power flows through loads to confirm demand change.	CR: Tap Setting range: +5% to -5%, in 5 steps of 2.5%. OR: Voltage Resolution >0.01 p.u. OR: P and Q Branch Flows 1 kW/kVAr OR: P and Q Demand Flow 1 kW/kVAr	CR: Tap Control of Distribution Transformers OR: Voltage at Distribution Secondary Busbar OR: Voltage across 0.415kV Feeders OR: Power flows through loads to confirm demand change.	Introduction of 6.6kV/11kV branch and buses • Observation: power flows and losses through branch, voltage at busbars • Accuracy: electrical parameter data representative of real-world network data. Introduction of new Distribution Substations • Control: Tap Control of 6.6/0.415 kV new transformer models • Observation: Voltage at new distribution substation secondary busbar

QUEST Control Methods	Voltage Level	Control Requirement (CR)	Observation Requirements (OR)	Accuracy Requirements (AR)	Requirements Not Mer	Proposed Extension
						• Accuracy: Tap control set point as a percentage on voltage increment/decrement. Electrical parameter data representative of real-world network data. Introduction of shunt objects to represent constant impedance loads to exhibit voltage-demand relationship • Control: Since the proportion of a load, split between constant power and constant load, can alter. The R and X values must be set points and must be

QUEST Control Methods	Voltage Level	Control Requirement (CR)	Observation Requirements (OR)	Accuracy Requirements (AR)	Requirements Not Mer	Proposed Extension
						calculated as a function of P and Q load values. • Observation: New constant impedance load PQ flows • Accuracy: The historical demand, that represents the constant impedance, assigned as proportion of the total load. Introduction of LV feeder approximation models. • Observation: power flows and losses through branch, voltage at busbars • Accuracy: electrical parameter data

QUEST Control Methods	Voltage Level	Control Requirement (CR)	Observation Requirements (OR)	Accuracy Requirements (AR)	Requirements Not Mer	Proposed Extension
						representative of real-world network data.

4.7. Model Adequacy Summary

Each voltage level can be summarised in regard to whether a model update is required or not.

Table 6: Model Adequacy Summary

QUEST Control Methods	132kV Model Requirements Met	33kV Model Requirements Met	6.6kV/11kV and 0.415kV Model Requirements Met	Proposed Model Extensions
ESO/DSO Service	Yes	Yes	N/A	• N/A
ANM Flexible Connections/Services	CR: PQ Control on DER OR: PQ export from DER site.	CR: PQ Control on DER OR: PQ export from DER site.	CR: PQ Control on DER OR: PQ export from DER site.	• Add representation of a plausible DER flexible connection.
Network Efficiency	All Requirements Met	Yes	YES	N/A
Tap Stagger (BSP)	N/A	Yes	N/A	• N/A
CLASS (DR)	N/A	OR: Power flow change at demands due to voltage changes	OR: Power flow change at demands due to voltage changes	• Introduction of shunt objects to represent constant impedance loads.
CLASS (DB)	N/A	OR: Power flow change at demands due to voltage changes	OR: Power flow change at demands due to voltage changes	• Introduction of shunt objects to represent constant impedance loads.
CLASS (PFR)	N/A	OR: Power flow change at demands due to voltage changes	OR: Power flow change at demands due to voltage changes	• Introduction of shunt objects to represent constant impedance loads.
CLASS (SFR)	N/A	OR: Power flow change at demands due to voltage changes	OR: Power flow change at demands due to voltage changes	• Introduction of shunt objects to represent constant impedance loads.

QUEST Control Methods	132kV Model Requirements Met	33kV Model Requirements Met	6.6kV/11kV and 0.415kV Model Requirements Met	Proposed Model Extensions
CLASS (LL)	N/A	OR: Power flow change at demands due to voltage changes	OR: Power flow change at demands due to voltage changes	Introduction of shunt objects to represent constant impedance loads.
CLASS (Tap Stagger)	N/A	Yes	N/A	N/A
Smart Street	N/A	N/A	CR: Tap Control of Distribution Transformers OR: Voltage at Distribution Substation Secondary Busbar OR: Voltage across 0.415kV Feeders OR: Power flows through loads to confirm demand change.	• Introduction of 6.6kV/11kV bus branch model • Introduction of 6.6/0.415kV Distribution Substations with voltage controlled auto tap changing. • Introduction of 0.415kV feeder model approximations. • Introduction of shunt objects to represent constant impedance LV loads.

For each area where the model is not adequate, the model will be extended and checked that it meets the requirements to achieve adequacy.

5. PART ONE: DETERMINING NETWORK MODEL ADEQUACY-STAGE B: NETWORK MODEL EXTENSION

In the previous section, where the baseline IPSA+ model has not met the required criteria to appropriately model the QUEST software system, the model is extended in order to meet the criteria.

5.1. Whitegate 132kV Network Model Issues and Extension

5.1.1. Whitegate 132kV Network Model Issues

In Table 6, it has been identified that ANM Flexible Connections are not adequately represented in the model.

5.1.2. Whitegate 132kV Network Model Extension

The Whitegate 33kV networks are extended in Figure 6.

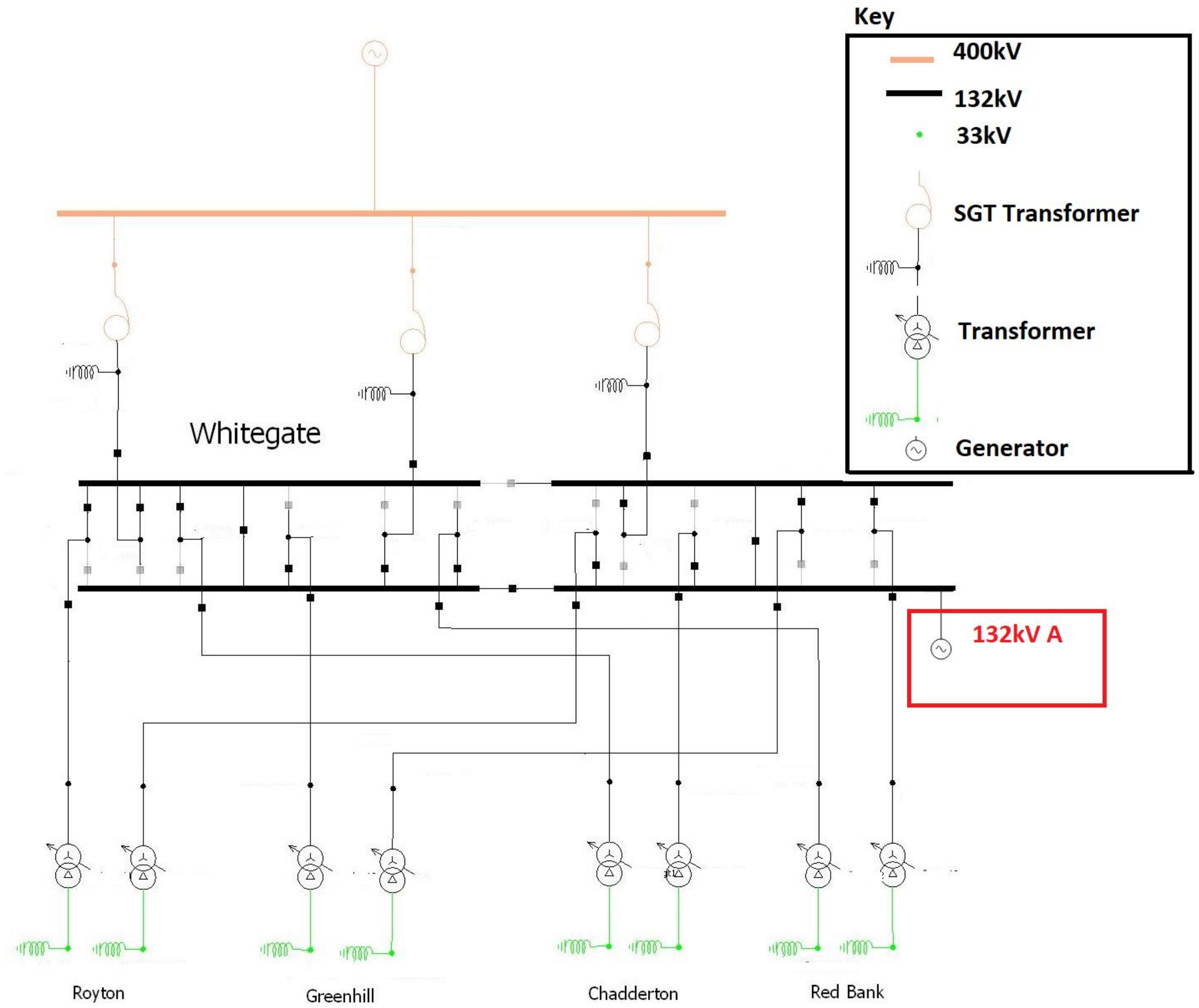

Figure 6: Whitegate 132kV Network Extension

- **132kV network extension (132kV A, Figure 6):** A single ANM flexible DER is introduced as a direct connection to the existing GSP substation board where the potential connection capacity identified in Table 2 exists. The exact details of the flexible DER site can be altered in line with ENW Distribution Future Electricity Scenarios (DFES), at this stage, implementation of the extension as an example to satisfy the modelling requirements is all that is needed.
    - **Control:** The object allows for its P and Q set point to be controlled in order to represent the control requirement from either the ANM Flexible Connection or Service control method.
    - **Observation:** The objects alteration to P and Q import/export will alter power flows across branches sensitive to the connection.
    - **Accuracy:** The set points for P and Q must be a resolution similar to that of the real-world control system, 1kW/kVAr, this discrete set point is achievable from the model input. The specific electrical parameters can be updated to represent a real-world connection or a potential connection if real-world connections are not forth coming.

This extension has made the 132kV network adequate.

5.2. Whitegate 33kV Network Model Issues and Extension

5.2.1. Whitegate 33kV Network Model Issues

In Table 6, it has been identified that:

- Voltage-dependent power loads, and
- ANM Flexible Connections/Services

are not adequately represented in the model.

5.2.2. Whitegate 33kV Network Model Extension

An example of the Whitegate 33kV network extensions are shown in Figure 7.

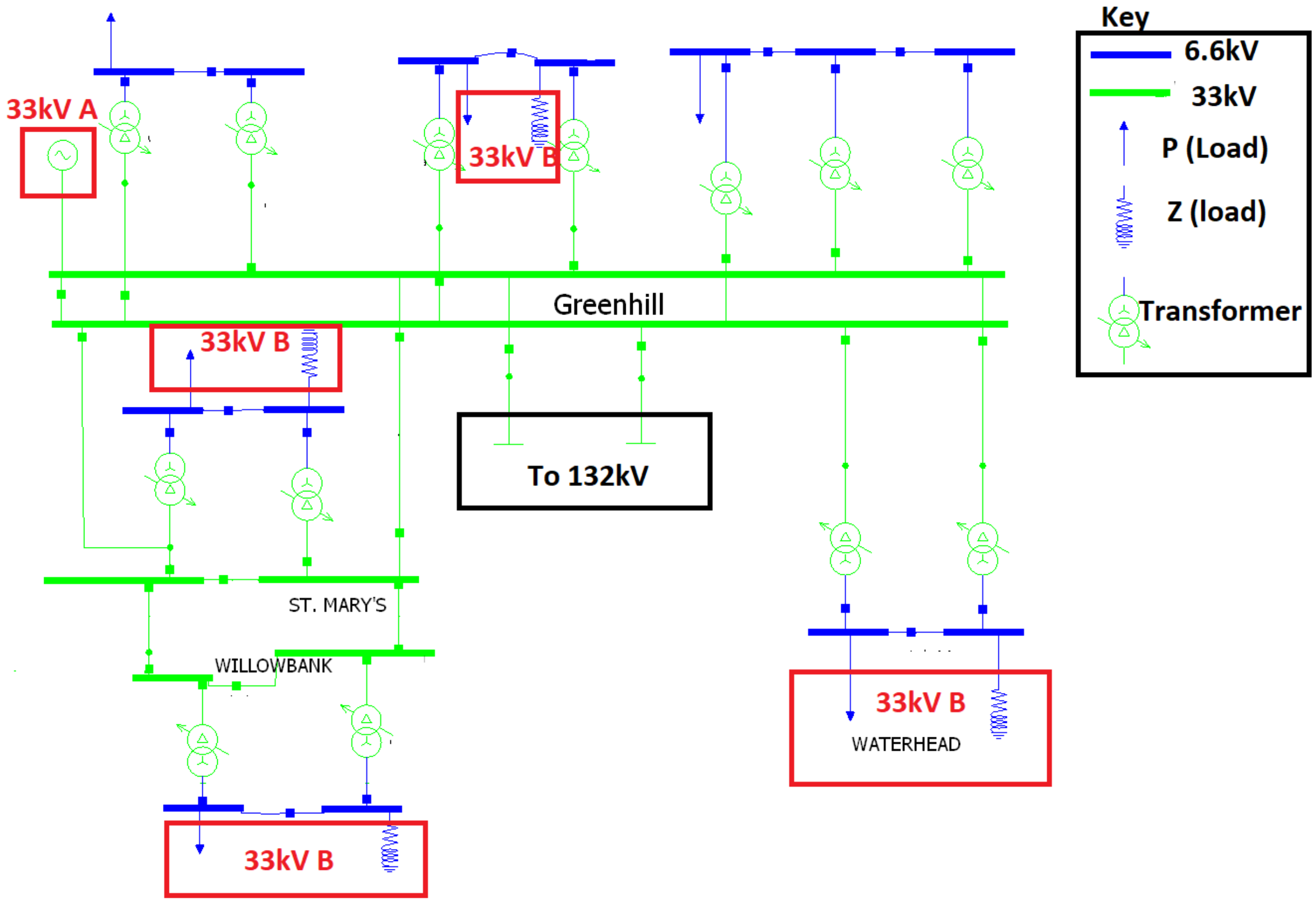

Figure 7: Example of Whitegate 33kV Network Extension

33kV network extension (33kV A): single ANM DER flexible connection is introduced as a direct connection to the existing BSP substation board to each BSP where the potential connection capacity identified in Table 2 exists. The exact details of the flexible connection DER site can be altered in line with ENW future electricity scenarios, at this stage, implementation of the extension as an example to satisfy the modelling requirements is all that is needed.

- **Control:** The object allows for P and Q set points to be controlled in order to represent the control requirement from either the ANM Flexible Connection or Service control method.
- **Observation:** The objects alteration to P and Q import/export will alter power flows across branches sensitive to the connection.
- **Accuracy:** The set points for P and Q must be a resolution similar to that of the real-world control system, 1kW/kVAr, this discrete set point is achievable from the model input. The specific electrical parameters can be updated to represent a real-world connection or a potential connection if real-world connections are not forth coming.

33kV Network Extension (33kV B): constant impedance objects are introduced to primary substations at the 6.6kV/11kV busbar.

- **Control**: The load R and X impedance value in per unit can be calculated from the P and Q demand required using the following equation:
    - $R_n = P_n {V_n}^2/(P_n + jQ_n)$ where V_n=1p.u
    - $X_n = Q_n {V_n}^2/(P_n + jQ_n)$ where V_n=1p.u
- **Observation**: This enables a voltage-dependent relationship to be encapsulated in the model so when voltages change, so do voltage-dependent demands. This allows for the wider benefits of this relationship to be considered within QUESTs systems (CLASS, Smart Street and ANM), as well as any conflict it may cause between the systems or effects on network compliance.
- **Accuracy**: The load demand, provided by historical loading data can be portioned by a percentage relative to the assumed constant power vs constant impedance split for the data point. How close this proportion is to reality will affect the benefits or issues derived from the relationships it affects.

These extensions have made the 33kV network adequate.

5.3. Whitegate 6.6kV/11kV and 0.415kV Network

5.3.1. Whitegate 6.6kV/11kV and 0.415kV Network Model Issues

In Table 6, it has been identified that:

- Voltage-dependent loads,

- ANM Flexible Connections/Services, and
- Smart Street Controls.

are not adequately represented in the model.

5.3.2. Whitegate 6.6kV/11kV and 0.415kV Network Model Extension

An example of the Whitegate 6.6kV and 0.415kV network extensions are shown in Figure 8.

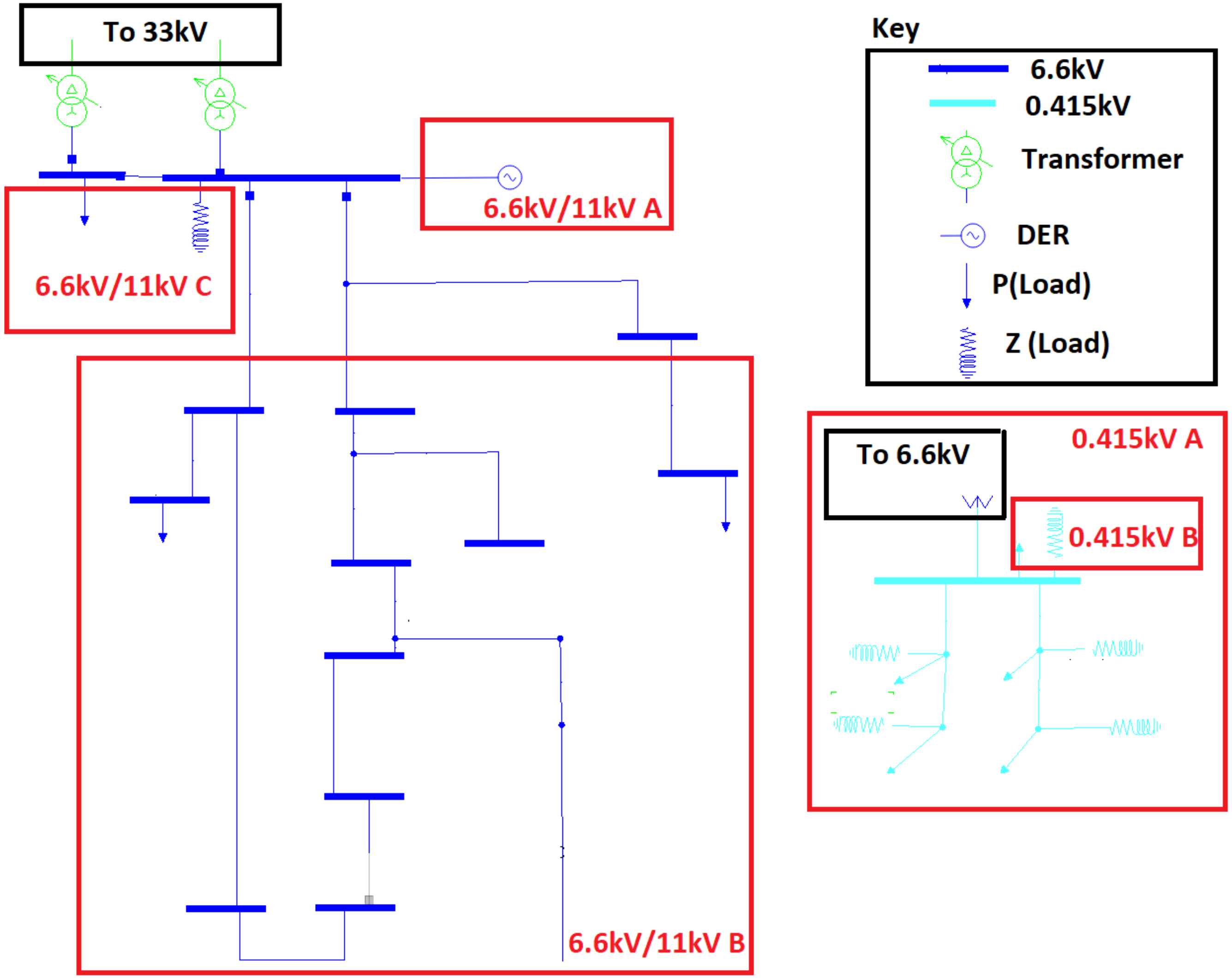

Figure 8: Example of Whitegate 6.6kV Network Extension

6.6kV/11kV network extension (6.6kV/11kV A): single ANM DER flexible connection is introduced as a direct connection to the existing primary substation board where the potential connection capacity identified in Table 2 exists. The exact details of the DER flexible connection site can be altered in line with ENW future electricity scenarios, at this stage, implementation of the extension as an example to satisfy the modelling requirements is all that is needed.

- **Control:** The object allows for its P and Q set point to be controlled to represent the control requirement from the from either the ANM Flexible Connection or Service control method.
- **Observation:** The objects alteration to P and Q import/export will alter power flows across branches sensitive to the connection.
- **Accuracy:** The specific electrical parameters can be updated to represent a real-world connection or a potential connection if real-world connections are not forth coming.

6.6kV/11kV Network Extension (6.6kV/11kV B): 6.6kV/11kV circuits out of the primary are modelled.

- **Control:** The extension of the 6.6kV/11kV circuits allows the distribution transformers to be modelled enabling Smart Street control to be applied to the model.
- **Observation**: This enables the voltage profile across the 6.6kV/11kV feeder to be observed, as well as the losses through these branches.
- **Accuracy**: To reduce computational burden, not all circuits are required to be fully modelled to this level, only those circuits are modelled which provide more accuracy on voltage drop and system losses at this voltage level. Introducing feeders where smart street systems exist, fed from modelled distribution transformers, will provide adequate observation of the individual QUEST software control effects.

Therefore, where smart street is identified to exist, the 6.6kV network will be extended to include these systems.

6.6kV/11kV Network Extension (6.6kV/11kV C): for all 6.6kV/11kV circuits NOT modelled, constant impedance objects are introduced, alongside the existing constant power objects, to primary substations at the 6.6kV/11kV busbar to act as an aggregation of the load behaviours of these circuits.

- **Control**: The load R and X impedance value in per unit can be calculated from the P and Q demand required using the following equation:
    - $R_n = P_n {V_v}^2/(P_n + jQ_n)$ where V_v=1p.u
    - $X_n = Q_n {V_v}^2/(P_n + jQ_n)$ where V_v=1p.u

- **Observation**: This enables a voltage-dependent relationship to be encapsulated in the model so when voltages change, so do voltage-dependent demands. This allows for the wider benefits of this relationship to be considered within QUEST systems (CLASS, Smart Street and ANM), as well as any conflict it may cause between the systems or effects on network compliance.
- **Accuracy**: The load demand, provided by historical loading data can be portioned by a percentage relative to the assumed constant power vs constant impedance split for the data point.

0.415 kV Network Extension (0.415kV A): 0.415kV circuits out of the primary are approximately modelled.

- **Observation**: This enables an approximation of the voltage profile across the 0.415kV feeder to be observed, as well as the losses through these branches.
- **Accuracy**: The electrical parameter data needs to be representative of the real-world assets extracted from ENW databases e.g., CIM/DINIS. To reduce computational burden, not all circuits are required to be fully modelled to this level, only those circuits are modelled which provide more accuracy on voltage drop and system losses at this voltage level. Introducing two 0.415kV feeders, fed from modelled distribution transformers, will provide adequate observation of the individual QUEST software control effects.

  For further reduction of the computational burden, the two feeders modelled, will consist of a lumped approximation of the ENW CIM model of the full LV circuit to provide enough accuracy of the voltage drop across the circuit. Where, for the feeders modelled, the sum of the R X parameters is used to create a two-bus equivalent of the feeder, this is then evenly split at a mid-point. Load on the circuit is then redistributed evenly at the head, mid-point and the end of the feeder. The full process is presented in the appendix (section 10)

0.415 kV Network Extension (0.415kV B): for all 0.415kV circuits NOT modelled, constant impedance objects are introduced to distribution substations at the 0.415 kV busbar to act as an aggregation of the behaviours of these circuits.

- **Control**: The load R and X impedance value in per unit can be calculated from the P and Q demand required using the following equation:
  - $R_n = P_n {V_n}^2/(P_n + jQ_n)$ where V_n =1p.u
  - $X_n = Q_n {V_n}^2/(P_n + jQ_n)$ where V_n =1p.u
- **Observation**: This enables a voltage-dependent relationship to be encapsulated in the model so when voltages change, so do voltage-dependent demands.

- **Accuracy**: The load demand, provided by historical loading data can be portioned by a percentage relative to the assumed constant power vs constant impedance split for the data point. How close this proportion is to reality will affect the benefits or issues derived from the relationships it affects.

These extensions have made the 6.6kV/11kV and the 0.415kV network fit for purpose.

5.4. Network Extension Summary

The model becomes fit for purpose by applying the extensions described in section 5.3.2 and as shown in Table 7:

Table 7: Model Adequacy Summary

QUEST Control Method	132kV Model Adequate	33kV Model Adequate	6.6kV/11kV and 0.415kV Model Adequate	Model Extensions	Model Extension Data
ESO/DNO Services	Yes	Yes	N/A	N/A	
ANM Flexible Connections/Services	Yes	Yes	Yes	• Representation of a plausible DER connection added	• Real-World connections or potential connections.
Network Efficiency	Yes	Yes	N/A	N/A	
Tap Stagger (BSP)	N/A	Yes	N/A	• N/A	
CLASS (DR)	N/A	Yes	Yes	• Introduction of shunt objects to represent constant impedance loads in areas with CLASS active. Introduced at model voltage levels as appropriate.	• Proportion of load demand split between constant impedance and constant power configurable as required.

QUEST Control Method	132kV Model Adequate	33kV Model Adequate	6.6kV/11kV and 0.415kV Model Adequate	Model Extensions	Model Extension Data
CLASS (DB)	N/A	Yes	Yes	• Introduction of shunt objects to represent constant impedance loads in areas with CLASS active. Introduced at model voltage levels as appropriate.	• Proportion of load demand split between constant impedance and constant power configurable as required.
CLASS (PFR)	N/A	Yes	Yes	• Introduction of shunt objects to represent constant impedance loads in areas with CLASS active. Introduced at model voltage levels as appropriate.	• Proportion of load demand split between constant impedance and constant power configurable as required.
CLASS (SFR)	N/A	Yes	Yes	• Introduction of shunt objects to represent constant impedance loads in areas with CLASS active. Introduced at model voltage levels as appropriate.	• Proportion of load demand split between constant impedance and constant power configurable as required.
CLASS (LL)	N/A	Yes	Yes	N/A	

QUEST Control Method	132kV Model Adequate	33kV Model Adequate	6.6kV/11kV and 0.415kV Model Adequate	Model Extensions	Model Extension Data
CLASS (Tap Stagger)	N/A	Yes	N/A	• N/A	•
Smart Street	N/A	N/A	Yes	• Introduction of at least two 6.6kV/11kV bus and branch models out of a primary substation, on at least one primary per BSP. • Introduction of 6.6/0.415kV Distribution Substations with voltage controlled auto tap changing • Introduction of at least two 0.415kV bus and branch models out of a distribution substation, on at least one distribution substation per primary substation.	• Real-world asset data extracted from ENW databases i.e., CIM/DINIS.

QUEST Control Method	132kV Model Adequate	33kV Model Adequate	6.6kV/11kV and 0.415kV Model Adequate	Model Extensions	Model Extension Data
				• Introduction of shunt objects to represent constant impedance LV loads in areas with Smart Street.	

6. PART ONE: NETWORK MODEL SUMMARY

The existing baseline IPSA+ model of the Whitegate GSP supplied distribution network was not adequate. It neither allowed the control methods associated with QUEST's individual systems (CLASS, Smart Street and ANM) to be implemented fully, nor did it allow the effects of the electrical parameters induced by these control methods to be observed fully. Therefore, extensions have been made to the IPSA+ model to ensure that all the control methods and observations can be fully realised, thus making the model adequate.

These extensions have focused on:

- The introduction of voltage-power demand relationships, to allow the voltage control effects from systems such as CLASS and Smart Street to induce changes in power demand within the network.
- The introduction of lower voltage level bus and branch models, to allow Smart Street methods to be applied to lower voltage level assets and have their control effects induce changes in LV power demand within the network.
- Modelling an acceptable level of the network to monitor each control method and observation of effects to confirm control method objectives, whilst identifying any benefits and limitations satisfying these objectives may achieve.
- Introducing a representation for flexible DER, noting that none presently exist on the Whitegate GSP supplied network. At this stage, the implementation of this extension as an example to satisfy the modelling requirements is all that is needed. The exact details of the flexible connection DER site can be altered in line with future scenarios requirements as necessary.
- Identifying the data sources to enable the introduction of the extensions, such as:
    - extracting data from ENW sources for bus, branch and transformer models (CIM and DINIS),
    - allowing the proportion of load between constant impedance and constant power to be set as required.

For each of these extensions, care has been taken to achieve an acceptable level of accuracy by using, where possible, ENW databases that provide real-world data of any modelled representation. Where approximations have been used, these have been justified using proven mathematical approximation methods.

With the extensions applied, the IPSA model is now adequate, regarding the control methods, observations and accuracy requirements of each system to meet QUEST's modelling objectives.

However, as the project progresses, there may be an opportunity to improve this model. Therefore, any improvements that can be made to the model, coupled with the justifications for why they should be made, will be added to future issues of this document as an appendix.

With an adequate electrical network simulation developed, the full modelling regime can be realised.

7. PART TWO: TEST BENCH PROCESS

The objective of the modelling regime can be split into two parts:

- provide a platform in which to test QUEST's overarching control and coordination algorithms to highlight the benefits of the system regarding key performance indicators, for example, system demand, system losses.
- highlight limitations within QUEST's outcome to help improve, optimise and validate the control algorithm being implemented by Schneider Electric.

To meet these objectives, the modelling regime must simulate both the electrical environment and the control environment to an adequate level of detail.

The high-level structure of the modelling regime is presented in Figure 9.

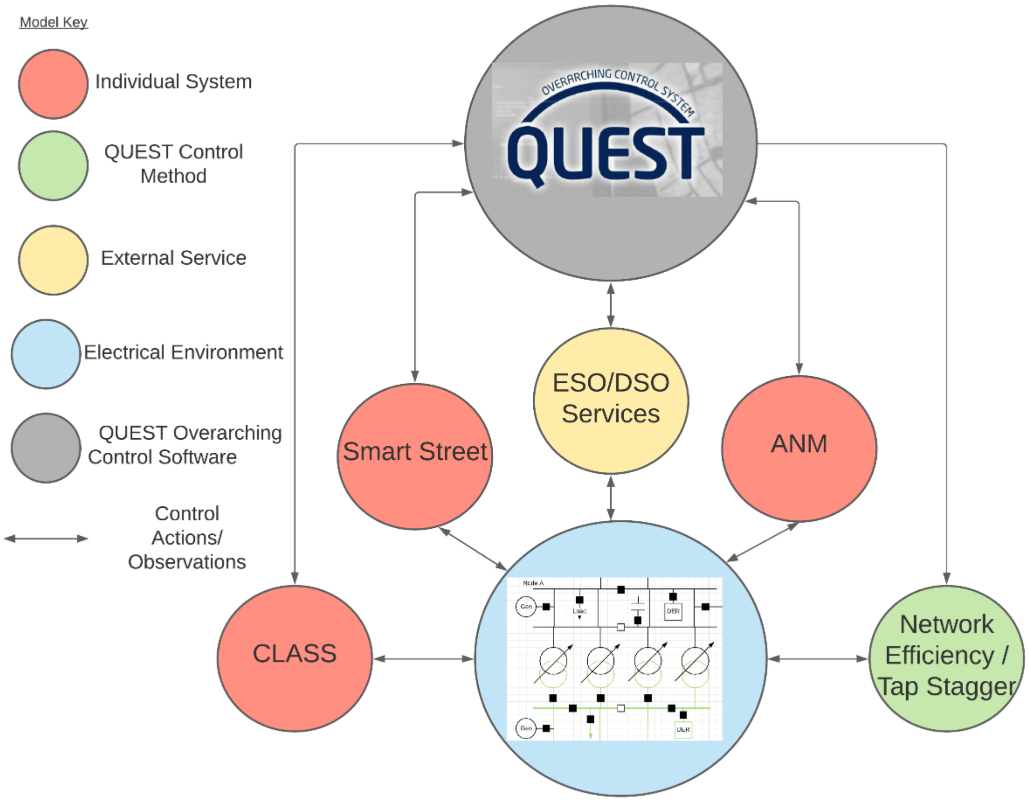

Figure 9: Modelling Regime High-Level[17]

An adequate modelling regime will enable:

- Implementation of a representative electrical environment to provide key performance indicators of the network, for both time-step and time-series analysis.

[17] The "ESO/DSO Services" in the figure include the OC6 emergency demand reduction services provided to the ESO. These services are largely initiated by control room staff actions in response to ESO requests

- application of each control method (CLASS, Smart Street, ANM, Network Efficiency etc.) upon pertinent network assets,
- accurate observation of each control action's effect upon the network to identify key performance indicator effects, and
- identification of conflicts between control methods to determine how QUEST's coordination can resolve these issues whilst optimising the impacts against network key performance indicators.

7.1. Key Performance Indicators

To monitor and improve key performance indicators, they must be defined, and that definition must be linked to the objectives QUEST must achieve. Therefore, the key performance indicators for the network are:

- **Total System Demand:** Since this is a parameter that CLASS and Smart Street seek to reduce, or increase, it must be observed.
- **Total System Losses:** Since this is a parameter that Network Efficiency will look to reduce, it must be observed.
- **Total System Generation:** Since this is a parameter that ANM will alter, it must be observed.
- **Total System Carbon Intensity:** By converting external network MWh generation (ESO) and internal network MWh generation (DNO), to $CO2$ per kWh ENWL's carbon intensity can be determined. Showing how impacts to demand and generation can affect external and internal carbon intensity.

The following modelling regime objectives will be achieved:

- Creation of a platform, integrated with the network models, to enable time-series analysis and key performance indicator observation upon the simulated electrical network.
- Implementation of the individual system's control algorithms as part of the platform to observe and control the simulated electrical network.
- Implementation of QUEST's overarching control upon the individual systems and the electrical network, for its own objectives, in line with the operational system architecture.
- Scenario analysis of each individual system operating in isolation and in parallel.

Satisfaction of these objectives is a modelling regime to which QUEST can validate and optimise its operational objectives, as well as analyse impacts to key performance indicators. Both allow for QUEST's wider project objectives to be achieved.

The modelling regime objectives will be achieved through the implementation of a Test Bench Process that will simulate the operation of the QUEST software overarching control upon each control method (Smart Street, CLASS, ANM and Network Efficiency etc.) and its interaction with the electrical network. To enable the outputs to be used for the development of QUEST's operational objectives, the modelling regime will be structured as closely to the real-world systems as the modelling limitations allow.

7.2. Test Bench Process

To ensure the modelling regime meets its objectives, the test bench process must simulate as closely as possible:

- the present electrical environment, and
- the management system that provides a platform to observe the electrical network and implement its control methods, in order to produce an adequate representation of both aspects.

Therefore, outputs from the modelling regime cannot only be used to highlight performance benefits, but lend themselves to improve, optimise and validate Schneider Electric's QUEST control algorithms developed as part of the project.

7.2.1. Electrical Environment

The network planning models, analysed in part one of this document, are created in IPSA+. This will provide the test electrical network environment that must be observed and controlled by QUEST as part of the modelling regime.

7.2.2. Management System

ENWL's electrical network is controlled using Schneider Electric's Network Management System (NMS). It observes the pertinent electrical system parameters and feeds them into manual and autonomous control systems.

Some of the existing and potential control methods, and QUEST's control algorithms are currently, or in the future will be applied, on Schneider Electric's NMS real-time platform (Smart Street, Central ANM, Network Efficiency, CLASS).

Using the NMS platform to implement the modelling regime would require the development of I/O with IPSA that at this stage in the project does not exist.

Therefore, a representation of each control algorithm must be achieved on a platform that must be able to interact with the IPSA+ electrical environment.

Since IPSA+ has a python API, python seems the logical choice as the platform in which to create a representation of the management system that will replicate:

- the NMS real-time platform for electrical parameters observation from the electrical environment (IPSA+) and,
- each individual system's control algorithms and the overarching control algorithms provided by QUEST.

To aid the development of the test bench, to create a representation of the control method as close to the operational platform as possible, Schneider Electric have provided the QUEST software architecture as a component of the NMS for SGS to align the test bench process against, illustrated in Figure 10.

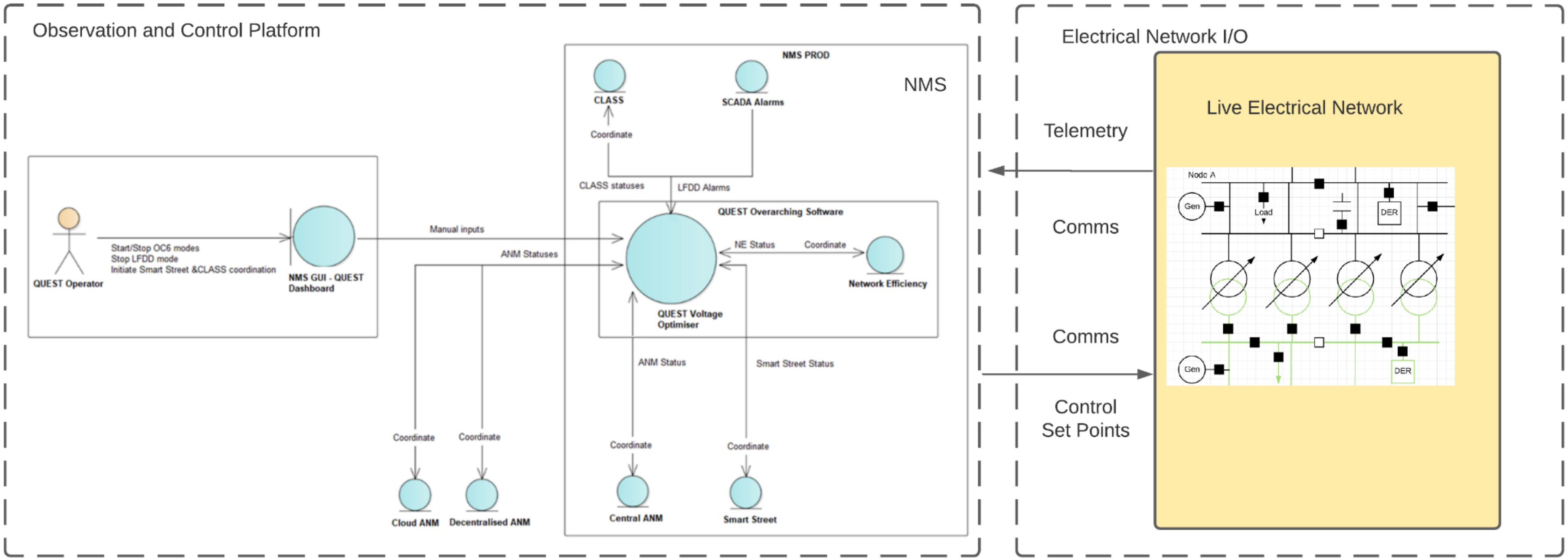

Figure 10: QUEST Voltage Optimiser – main architecture diagram

The NMS (left) takes observations from the live electrical network (right) via telemetry between the live electrical network assets and the NMS and controls network assets through control set points, determined from the control methods. In the central part of the NMS system, the QUEST overarching software is presented. Since it is located within the NMS system, QUEST is aware of the statuses of all the other systems and their control methods existing on the NMS system (Enhanced AVC including CLASS, Smart Street and Central ANM).

In the test bench architecture, Figure 11, the live electrical network (right), is simulated as a steady state load flow in IPSA+. The NMS is emulated as a python platform extracting electrical state observation from load flow solutions via the IPSA+ API, and setting control set points by altering the load-flow input data via the API. The python platform will implement the NMS, which encapsulates the individual systems and QUEST (left).

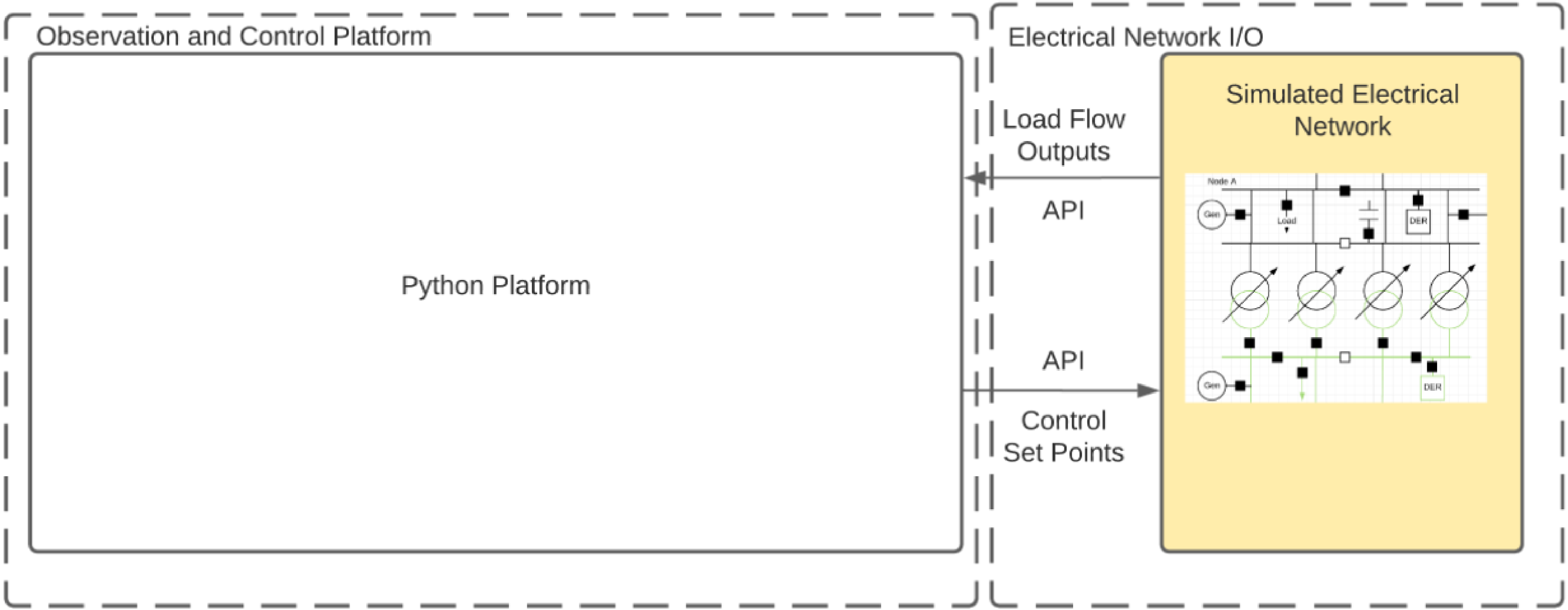

Figure 11: Test Bench Architecture

The test bench process, which realises both the observation of the simulated network and the implementation of the individual systems and QUEST control algorithms is shown in Figure 12, where the Electrical Network I/O architecture shown in Figure 11, is implemented as a python I/O method shown in Figure 12.

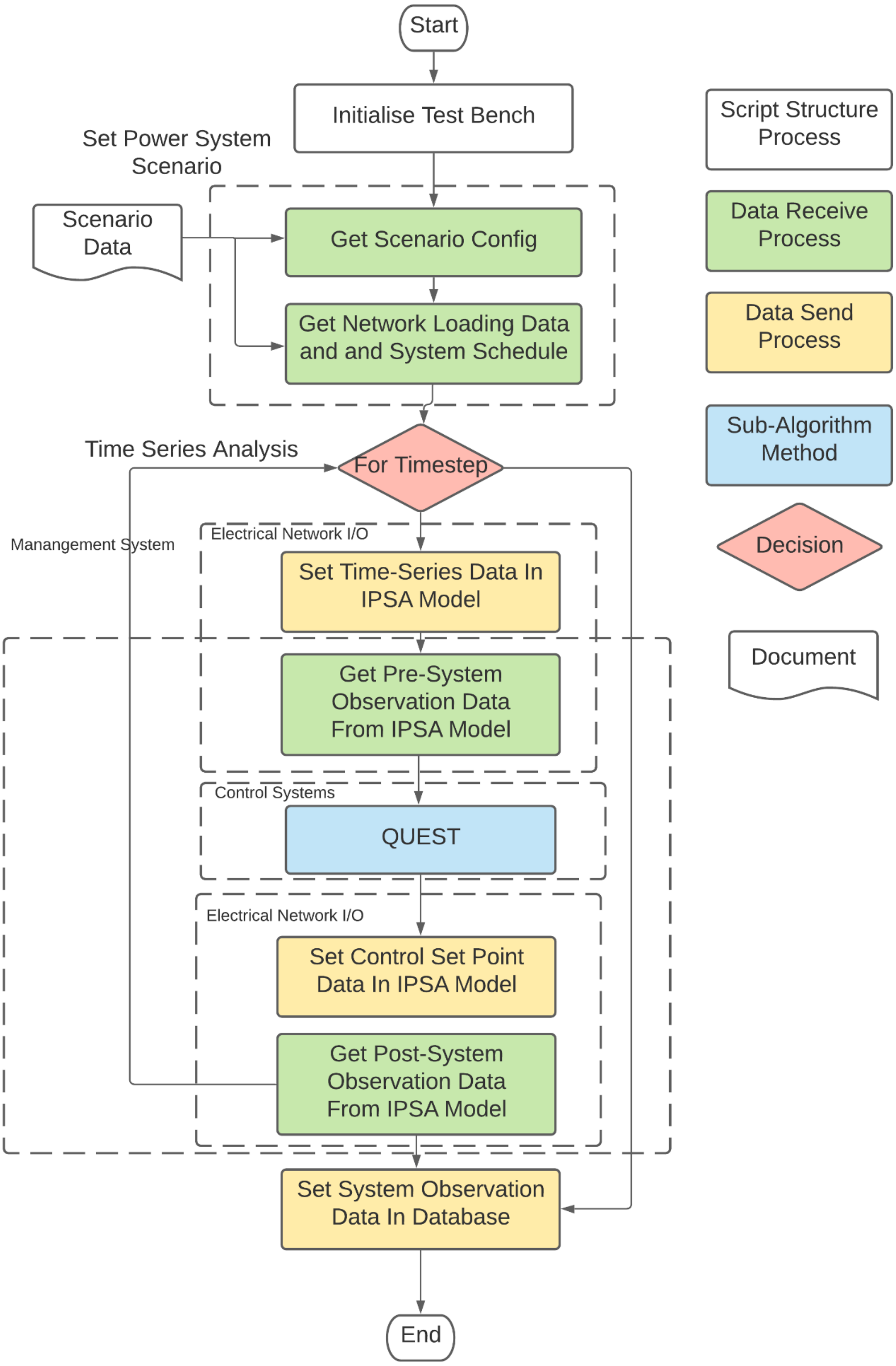

Figure 12: High-Level Test Bench Process

The test bench process is split into four parts to satisfy the modelling regime objectives:

- Initialisation of Test Bench: the python functionality libraries called to instantiate the test bench.

- Set Scenario: This configures the test scenario, setting input parameters that define the scenario. For example, selecting the study resolution, the online systems and the electrical network parameter data inputs to be set and outputs to be observed.
- Time-Series Analysis: For each timestep, the method:
    - updates the electrical network state, using generation and load data,
    - enables the control methods to observe and take actions upon the resulting electrical state,
    - allows for QUEST to apply overarching control to coordinate these actions
    - Allows for the impacts of these controls to be implemented and observed upon the simulated electrical network.
- Set System Observation Data in Database: Saves observed parameters for each network state to undertake exploratory data analysis to evaluate key performance indicators for all control methods.

Each point in the list above will now be discussed in greater detail to satisfy the modelling regime objectives.

7.3. Initialisation of Test Bench

The test bench is set up using python 2.7 and its open-source libraries which include:

- Pandas,
- Matplotlib,
- NumPy.

Proprietary API libraries from IPSA+ are also used to interface with the IPSA load flow software.

7.4. Scenario Analysis

The scenario analysis functionality allows for the test bench to configure the input data for

- the electrical network inputs, and
- control method inputs

applied to the electrical network, for specific scenarios under test. It also defines the type of study being run, time-step of time-series.

7.4.1.Electrical Network Inputs

The electrical network inputs set the behaviour of the electrical network during the scenario. The variables to which the electrical inputs have control over are:

- Load set points (P/Q)
- Firm Generator set points (P/Q)
- ANM Generator set points (P/Q)

For a time-step analysis, all types of these objects will be given a single set-point, this will result in the power flow behaviour for this state. For a time-series analysis, a profile of time steps is assigned. This encapsulates the objects behaviour per time step, altering the resulting power flow behaviour for each state.

An example of the time-series inputs is shown in Table 8.

Table 8: Electrical Network Time-Series Input Data Example

Time Step	Shaw Primary Demand (MW)	Shaw Primary Demand (MVAr)	Stockley Lane Gen (MW)	Stockley Lane Gen (MVAr)	ANM Royton Development (MW)	ANM Royton Development (MVAr)
04/10/2021 16:00	1.2	0.012	15	0	1	-0.1
04/10/2021 16:30	1.22	0.0122	15	0	0.8	-0.08
04/10/2021 17:00	1.24	0.0124	15	0	0.4	-0.04
04/10/2021 17:30	1.26	0.0126	15	0	0.2	-0.02
04/10/2021 18:00	1.28	0.0128	15	0	0.1	-0.01
04/10/2021 18:30	1.3	0.013	15	0	0.05	-0.005
04/10/2021 19:00	1.32	0.0132	15	0	0	0
04/10/2021 19:30	1.34	0.0134	15	0	0	0
04/10/2021 20:00	1.36	0.0136	15	0	0	0
04/10/2021 20:30	1.38	0.0138	15	0	0	0

The electrical network scenarios are then defined by:

- what the analysis window is,
- the resolution to be applied, and
- profile data to be assigned to the electrical inputs.

An example of the Electrical Network Scenarios is shown in Table 9.

Table 9: Electrical Network Scenarios Example

Scenario	Analysis Window	Resolution	Load Inputs	Firm Generator Inputs	ANM Inputs
1	1 Day	30 Minutes	Historical Half-Hour Data	Historical Half Hour Data	Synthesized Technology Half Hour Data

7.4.2. Control Method Inputs

Each control method can either run by itself or in parallel and, operationally, control methods are either applied continuously or on schedule. Therefore, similar to the electrical network scenario inputs, a time-series profile for each control method can be created to determine the schedule of the control method applied to each time step and whether it is operating in parallel with other methods or not. The control method inputs are:

- ANM Flexible Connections/Services
- Network Efficiency Mode
- Tap Stagger Mode (BSP)
- CLASS (DR) – where multiple levels of reduction can be applied e.g. demand reduction half.
- CLASS (DB)- where multiple levels of boost can be applied e.g. demand boost half.
- CLASS (PRF)
- CLASS (SRF)
- CLASS (LL)
- CLASS (Tap Stagger)
- ESO Services: Automatic Low Frequency Demand Disconnection (OC6.6-LFDD)

For each input, the control method can also be enabled, or active.

An example of how this translates into a time-series profile is shown, for simplicity, an example on applying CLASS and Smart Street only is shown in Table 10, where green (1) means true and red (0) means false.

Table 10: CLASS and Smart Street Time-Series Profile Example

Time Step	CLASS (Demand Reduction Half) Enabled	CLASS (Demand Reduction Half) Active	Smart Street
04/10/2021 16:00	1	0	1
04/10/2021 16:01	1	0	1
04/10/2021 16:02	1	0	1
04/10/2021 16:03	1	1	1
04/10/2021 16:04	1	1	1
04/10/2021 16:05	1	1	1
04/10/2021 16:06	1	1	1
04/10/2021 16:07	1	1	1
04/10/2021 16:08	1	1	1
04/10/2021 16:09	1	1	1
04/10/2021 16:10	1	1	1

The control method scenarios are then defined by what the analysis window is, the resolution to be applied and profile data to be assigned to the electrical network inputs, illustrated in Table 11.

Table 11: Control Method Scenario Example

Scenario	Analysis Window	Resolution	CLASS Demand Reduction Half	Smart Street
1	4 hours	30 Minutes	Enabled (All) Active (16:15-16:30)	Active (All)

The electrical network and control method scenarios can be combined with the electrical network scenarios to define the complete test bench scenario under analysis, see Table 12.

Table 12: Test Bench Scenarios Example

Scenario	Analysis Window	Resolution	CLASS Demand Reduction Half	Smart Street	Load Inputs	Firm Generator Inputs	ANM Inputs
1	4 hours	1 Minute	Enabled (16:00-17:00) Active (16:15-16:30)	Active (All)	Historical Minute Data	Historical Minute Data	Synthesised Technology Data
2	1 Year	30 Minute	Enabled (Daily 16:00-17:00) Active (Daily 16:15-16:30)	Active (All)	Historical Half-Hour Data	Historical Half-Hour Data	Synthesised Technology Data

In summary, for each test bench scenario, the following can be applied:

- The behaviour of the electrical network, based on load and generator input data,
- The behaviour of the control methods, based on their objectives,
- QUEST's overarching control objective to coordinate all control methods.

For each test bench scenario, the pertinent KPIs will need to be observed (e.g. System Losses), as well as additional electrical network parameters (e.g. thermal power flows) that confirm the correct implementation of the control methods objectives, or QUEST's overarching control objectives.

The scenario inputs to the test bench process allows for adequate testing of each of the control method algorithms in isolation and parallel. The total amount of scenarios required will be defined using the outputs of Schneider Electric's architecture options, which highlight the control method architecture of particular relevance to achieving QUEST's objectives.

The next section explains how the scenario inputs are used to execute the time-series analysis.

7.5. Time-Series Analysis

To implement time-series analysis, in line with the defined test bench scenarios. The test bench process must:

- apply the time-series data to the electrical network,
- apply the time-series data to the control methods to schedule their methods appropriately,
- correctly implement a representation of the control methods to behave similarly to the operational algorithm,
- observe the pertinent electrical parameters to determine control methods that have been successfully achieved and the key performance indicators have been extracted for exploratory analysis.

7.5.1. Applying Electrical Network Inputs

The test bench updates the electrical network with load and generator input data to achieve the electrical network state associated with the time-step. To achieve the outputs for the study resolutions, the correct provision of data resolution as an input must be provided.

7.5.2. Applying the Control Inputs

If the control method is scheduled to operate for the timestep, the test bench will allow the control algorithm to interact with the electrical network model by:

- Observing electrical parameter data pertinent to its calculations
- Applying control set-points to assets in the model as a consequence of its calculations.

7.5.3. Implement the Control Methods

The control methods are analogues of the operational algorithms, rationalised to observe data from the simulated electrical network and act upon these observations in line with its control objectives.

Each control method has a configuration file that sets the rules under which its control method is bounded. To bring the test bench into line with the QUEST operational architecture, a QUEST control method coordinates each system per timestep by altering their configurations where necessary to ensure the correct behaviour is exhibited by each individual system to ensure coordination and eliminate conflict.

The python representation of the algorithm of each control method is described in detail in its relevant appendix:

- CLASS: Appendix B
- Smart Street: Appendix C
- Network Efficiency: Appendix D
- ANM Flexible Connections: Appendix E
- QUEST: Appendix F – This algorithm shows how the test process makes provisions to enable QUEST to interact with all applied control methods and execute the required coordination methods. The exact details of the coordination and control methods will be developed from the outputs of Schneider Electric's QUEST architecture options detailed design [3] in the next stage of the project, therefore, this algorithm will be updated accordingly.

- ESO/DSO Services: There is no presented control method for ESO/DSO as these are external services and will open circuit breakers instantaneously as defined by the test bench scenario, however, consideration of these impacts has been considered as part of QUEST's coordination method as it may have to coordinate and manage effects from these actions across control methods.
- ANM Flexible Services: There is no presented control method for ANM Flexible Services as the calculation of scheduled dispatch is not undertaken operationally, but as part of a day ahead forecast of requirement. Therefore DER implementing flexible services will be represented by a dispatch time-series profile. However, consideration of these impacts has been considered as part of QUEST's coordination method as it may have to coordinate and manage effects from these actions across control methods.

Note: Each algorithm is a representation of current understanding, it should be noted that due to the innovative nature of the project these algorithms are not final, and the test bench process provides the project with the flexibility to evolve the methods as the project develops.

The full test bench process is shown in Figure 13.

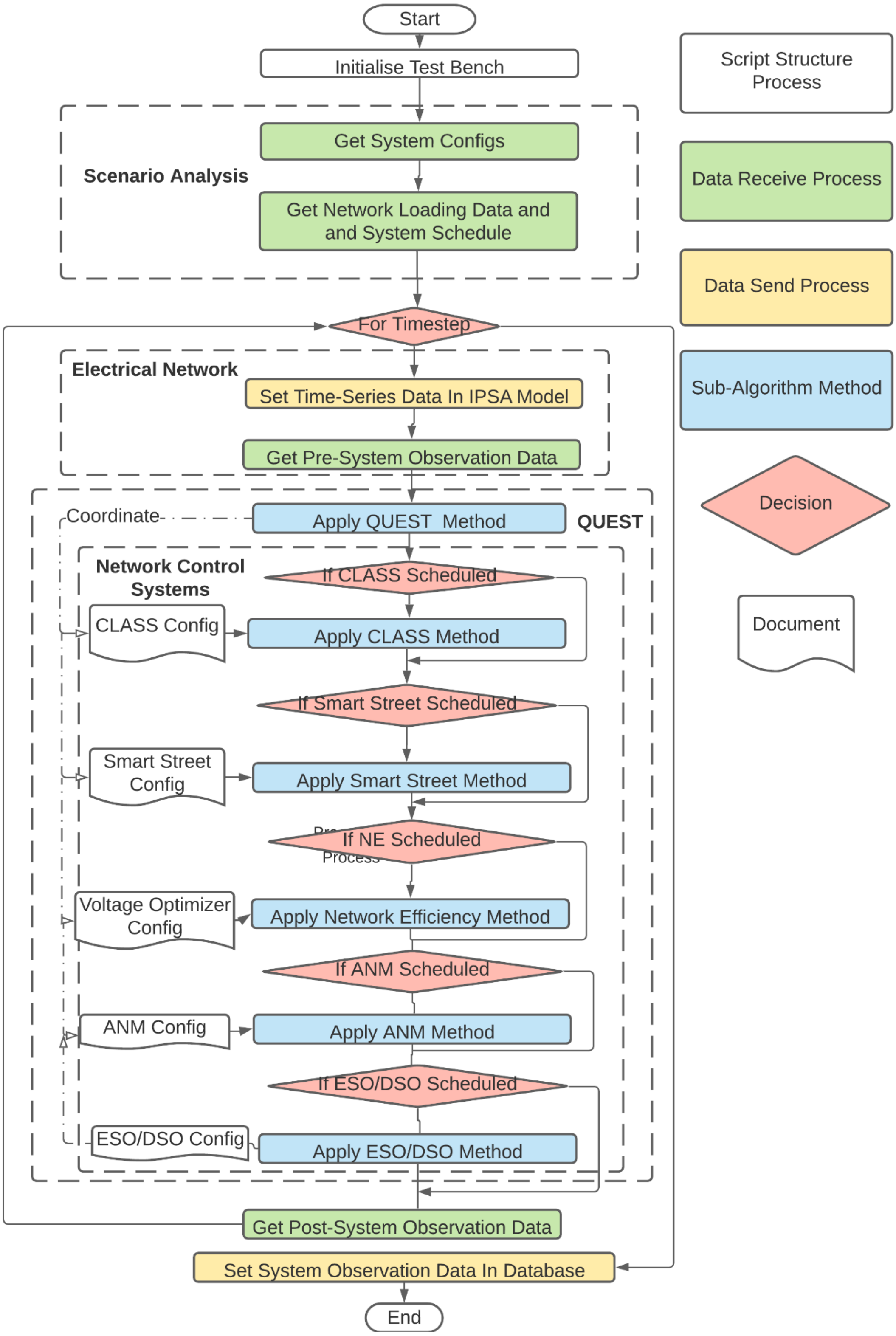

Figure 13: Full Test Bench Process

7.5.4. Observe the Pertinent Electrical Parameters

For each time step, if each control method is scheduled to be on, it will implement its objective bounded by the settings in its configuration file: a .csv file the control method reads for operational guidance, for example, for CLASS DB this configuration file will determine what the target increase in voltage should be if activated, i.e. 3% voltage, 6% voltage etc.

If the QUEST coordination method detects any conflict in operation, due to the scheduler or through observation, it will alter the control method configurations to resolve this conflict, for example altering CLASS DB configuration to not target its scheduled setting of 6%, but instead alter it to 3% if QUEST's coordination method has detected a conflict where this change will resolve the issue. This will be similar to the NMS platform architecture which will have the ability to coordinate the control methods by also interacting with the control method configuration. Thus, aligning the operational architecture with the test bench process.

The network's electrical state before and after control actions is saved for each time step. This allows for two important observations:

- the key performance indicators to be analysed per time-steps and across the time-series horizon.
- to determine the correct behaviour from the resulting network states that are exhibited

This will enable the testing of the QUEST control and coordination method performance across scenarios as well as the ability to test the architecture options that will be tested in the next work package, to tune QUEST's coordination methods to optimise its resulting actions for each of the control methods.

8. PART TWO: TEST BENCH PROCESS SUMMARY

In part one, an adequate network model was created which enables the required control and observations from each control method to be achieved. In this part, a test bench process was created to integrate with this model in order to:

- Implement a time-series simulation of the electrical network to observe the following key performance indicators:
    - System losses
    - System Demand
    - System Generation
    - System Carbon Intensity.
- Consider scenario analysis to implement load and generation behaviours upon the electrical network.
- Simulate each QUEST control method upon the electrical network, so the impacts of each method can be observed.
- Extend the scenario analysis to enable a blend of each control method in parallel to identify conflict between objectives and analyse impacts to key performance indicators.
- Simulate QUEST's overarching coordination method to:
    - coordinate conflicts between the individual system objectives to optimise and validate the developed algorithm and
    - analyse impacts of the QUEST control solution upon key performance indicators

Where both these bullet points help satisfy overall QUEST project objectives.

9. CONCLUSIONS AND NEXT STEPS

The objective of the QUEST software can be summarised as: control and coordinate conflicts across multiple system objectives operating upon the ENWL network and provide voltage optimisation where possible.

This can be broken down into three core objectives:

1. Coordinate operation of system voltage control and optimisation systems.
2. Identify and avoid potential conflicts between multiple systems, ensuring appropriate configuration of key voltage control and optimisation systems at all times.
3. Enhance operational efficiency.

In order to achieve these core objectives, the QUEST software architecture must be created and applied operationally to the live electrical network.

However, before this can be achieved, there must be a way to model QUEST's software operation on the distribution network, to determine if it can achieve its core objectives. The modelling regime was created for this project purpose and is realised as a test bench process which will enable satisfaction of these objectives to be tested in a safe simulated environment.

In this document, a steady state electrical network simulation has been created that encapsulates the general load and DER behaviour applied, as well as the :

- Control requirements
- Observation requirements, and
- Accuracy requirements

of all the control methods that are currently operating on the ENWL network and potential control method to be applied, all of which will be coordinated by QUEST.

To test each control method, or new control methods included as part of QUEST, a python representation of the QUEST architecture was created as well as a representation of each control method. This has enabled each control method to be applied to the electrical network simulation, determining their effects on key performance indicators, such as

- System Losses
- System Generation
- System Demand
- System Carbon Intensity

Finally, a time-series scenario analysis method was created to test a blend of each individual system's control methods applied to the electrical network simulation. This has provided the ability to test the QUEST software coordination of actions between control methods for each time step and across a time series.

This functionality allows for resolving conflict between the individual system control method objectives, and balancing those resolution affects against key performance indicators, providing the ability for both control methods and QUEST's algorithms to be validated and optimised.

In the next stage, the scenario analysis will be developed to test the QUEST architecture options developed by Schneider Electric to provide validation and optimisation. Further Scenarios will also be investigated to show the long-term operational effects of QUEST on key performance indicators by analysing typical network scenarios across a year, for both existing energy scenarios and future energy scenarios. This analysis will add further evidence of QUEST's satisfaction of its core objectives.

10. APPENDIX A: LOW VOLTAGE NETWORK MODELLING

ENWL provided the CIM models for all 0.415kV distribution transformers. A summary of the data is presented in Table 13.

Table 13: ENWL Distribution Transformer Circuit Data Summary

Name	Sub No.	TX size(kVA)	Customers	Feeders	Total Feeder (km)	Total R (Ohm)	Total X (Ohm)	SBase (MVA)	VBase (kV)	Total R(P.U.)	Total X(P.U.)	Single Feeder R(P.U.)	Single Feeder X(P.U.)
The Avenue	311212	500	108	4	2.927	0.044	0.010	100	0.415	25.333	6.083	6.333	1.521
Edward Rd	312874	500	127	4	2.055	0.030	0.010	100	0.415	17.458	5.761	4.365	1.440
Denbigh Dr	313254	500	141	4	1.923	0.020	0.009	100	0.415	11.430	5.345	2.857	1.336
Beal Ln	315536	315	151	2	1.065	0.026	0.011	100	0.415	14.809	6.404	7.405	3.202
Devon Cl	312733	500	179	5	2.409	0.028	0.010	100	0.415	16.224	5.713	3.245	1.143
Manor Rd	311001	1000	447	8	5.225	0.023	0.010	100	0.415	13.633	5.607	1.704	0.701

The total feeder's length is split evenly for a single feeder then applied to the model. This approach is used for all the extended feeders included in the model to provide an adequate observable representation of the LV network.

11. APPENDIX B CLASS PYTHON PLATFORM ALGORITHM

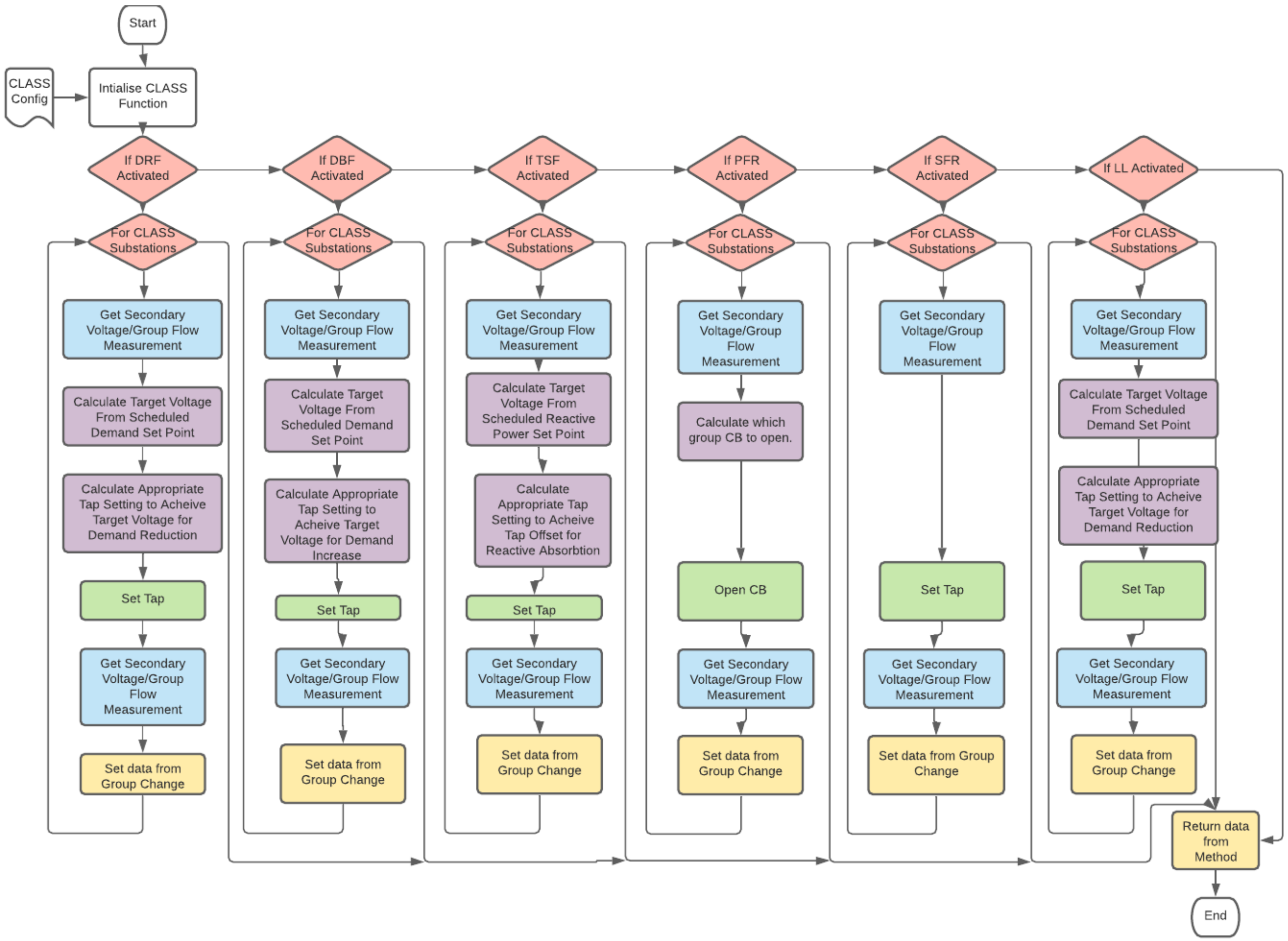

Figure 14: Test Bench Process: Flow Chart of CLASS Algorithm

12. APPENDIX C: SMART STREET PYTHON PLATFORM ALGORITHM

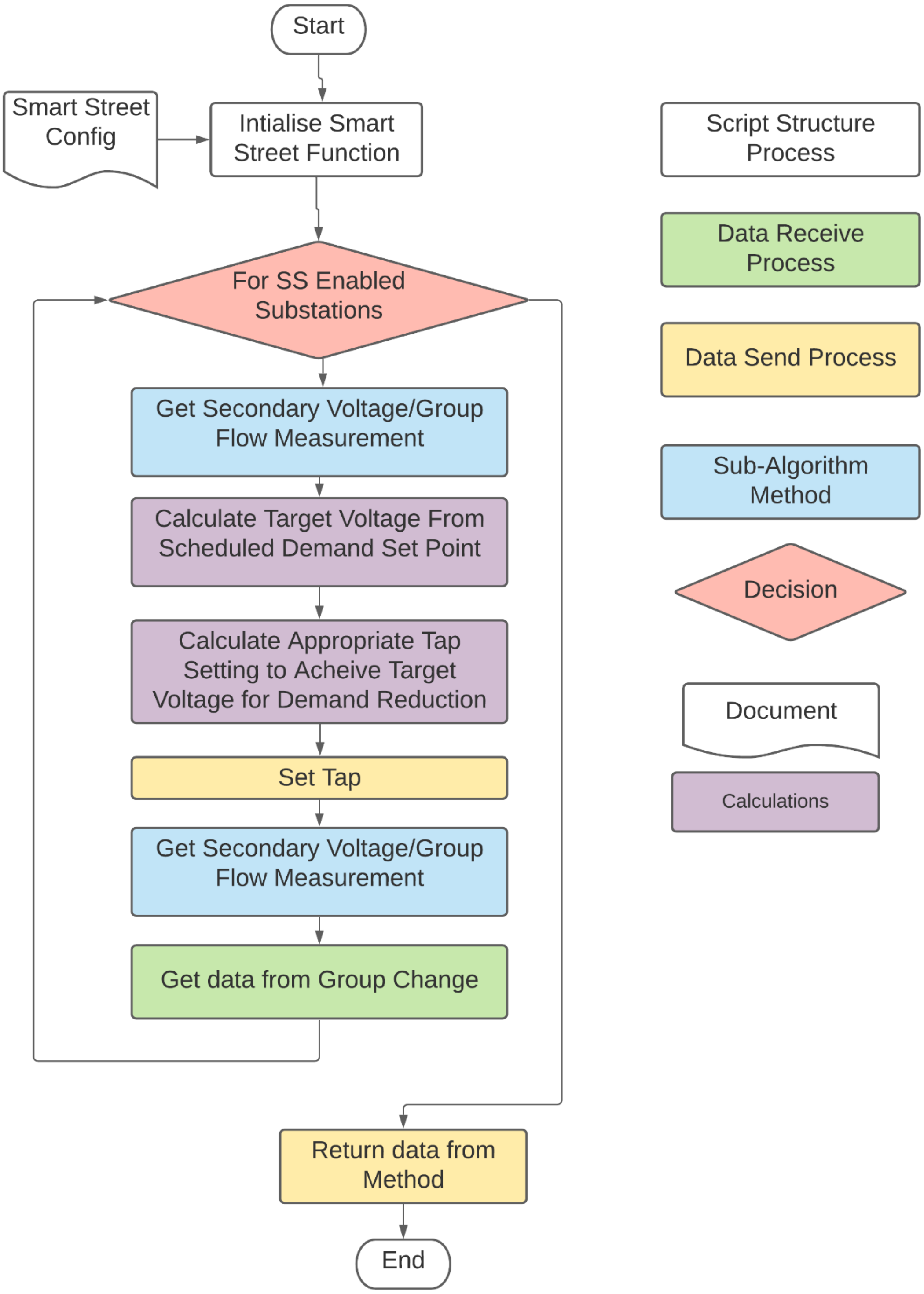

Figure 15: Test Bench Process: Flow Chart of Smart Street Algorithm

13. APPENDIX D: QUEST CONTROL METHODS PYTHON PLATFORM ALGORITHM

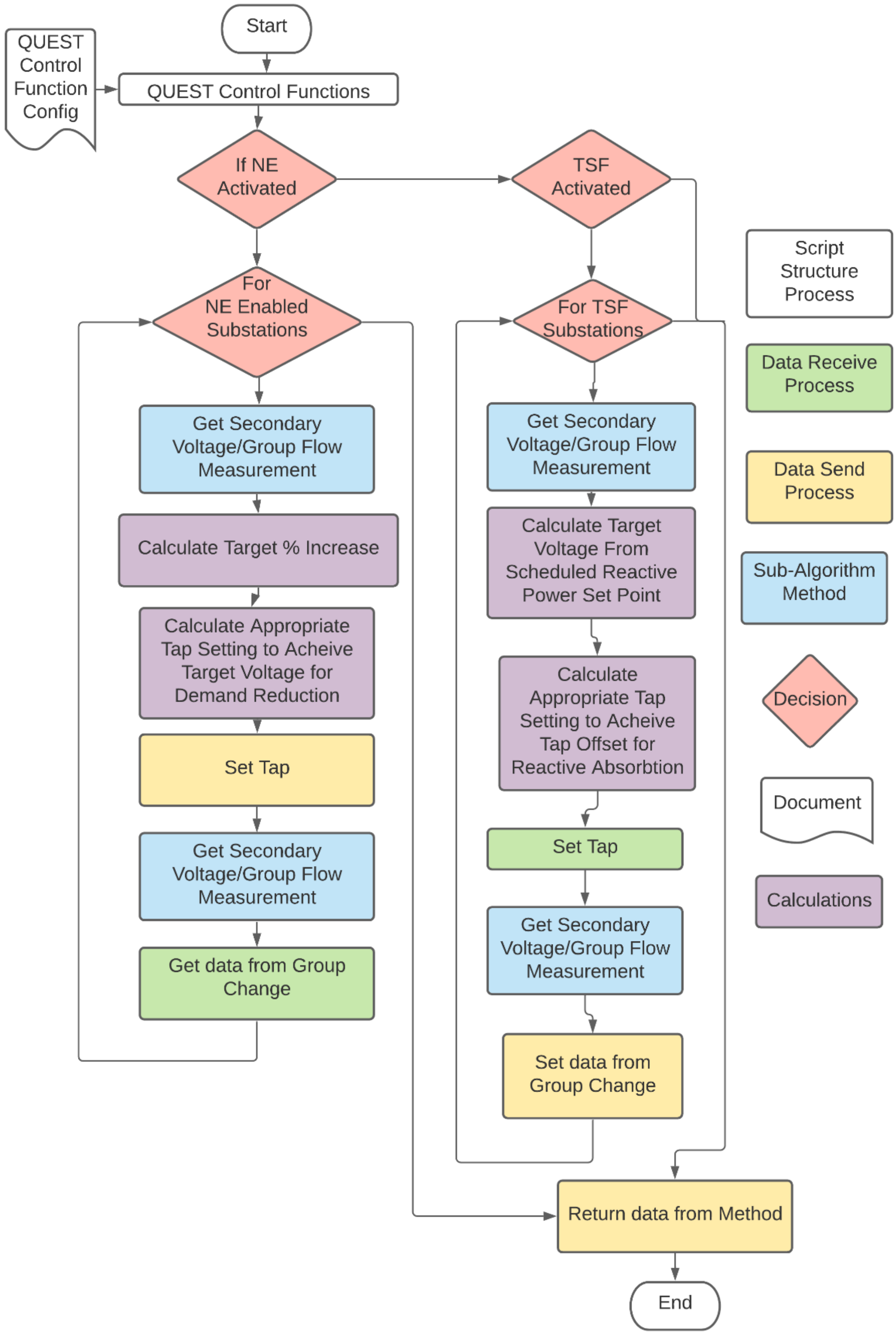

Figure 16: Test Bench Process: Flow Chart of QUEST Control Method Algorithms

14. APPENDIX E: ANM PYTHON PLATFORM ALGORITHM

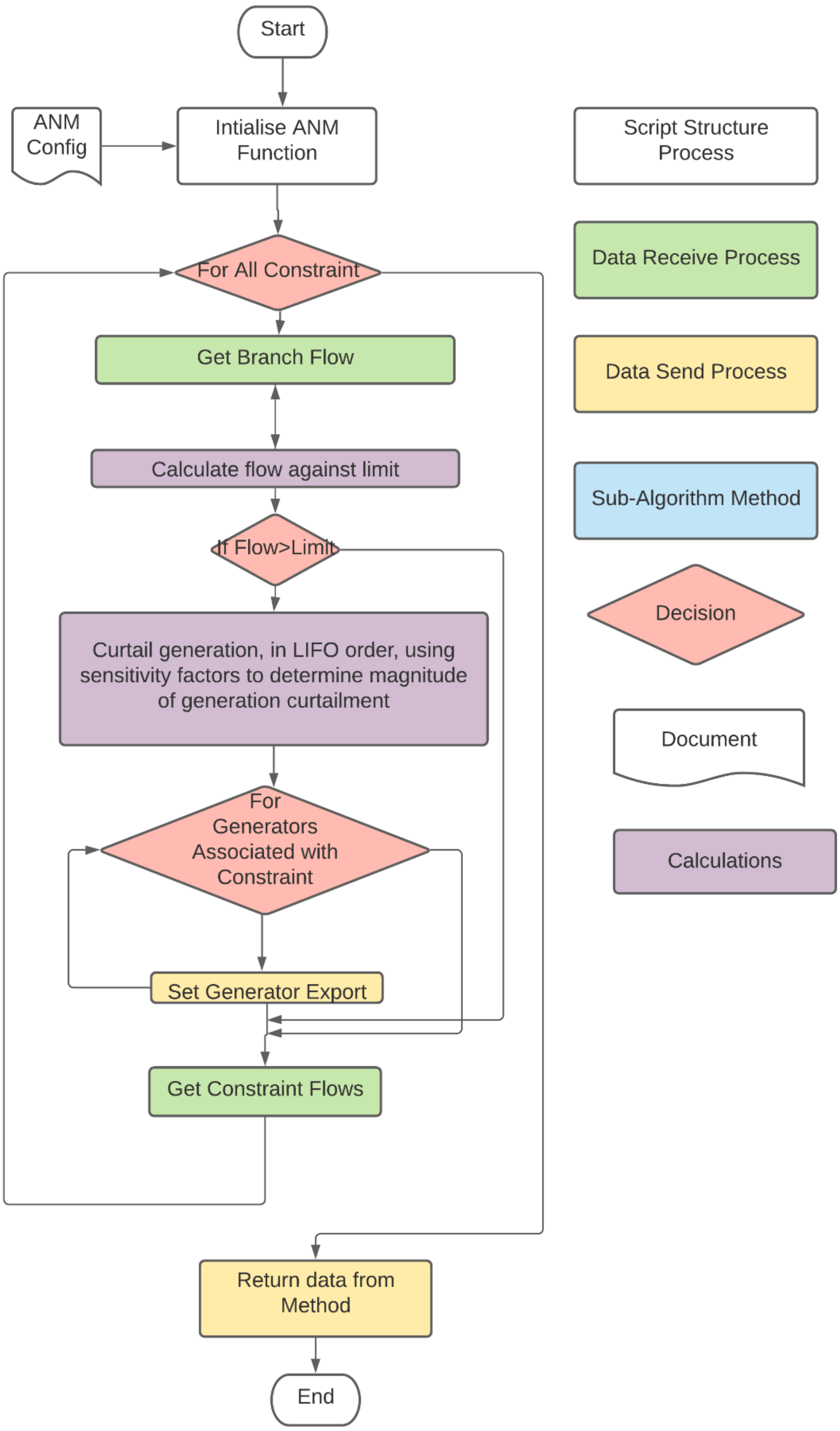

Figure 17: Test Bench Process: Flow Chart of ANM Algorithm

15. APPENDIX F: QUEST COORDINATION PYTHON PLATFORM ALGORITHM

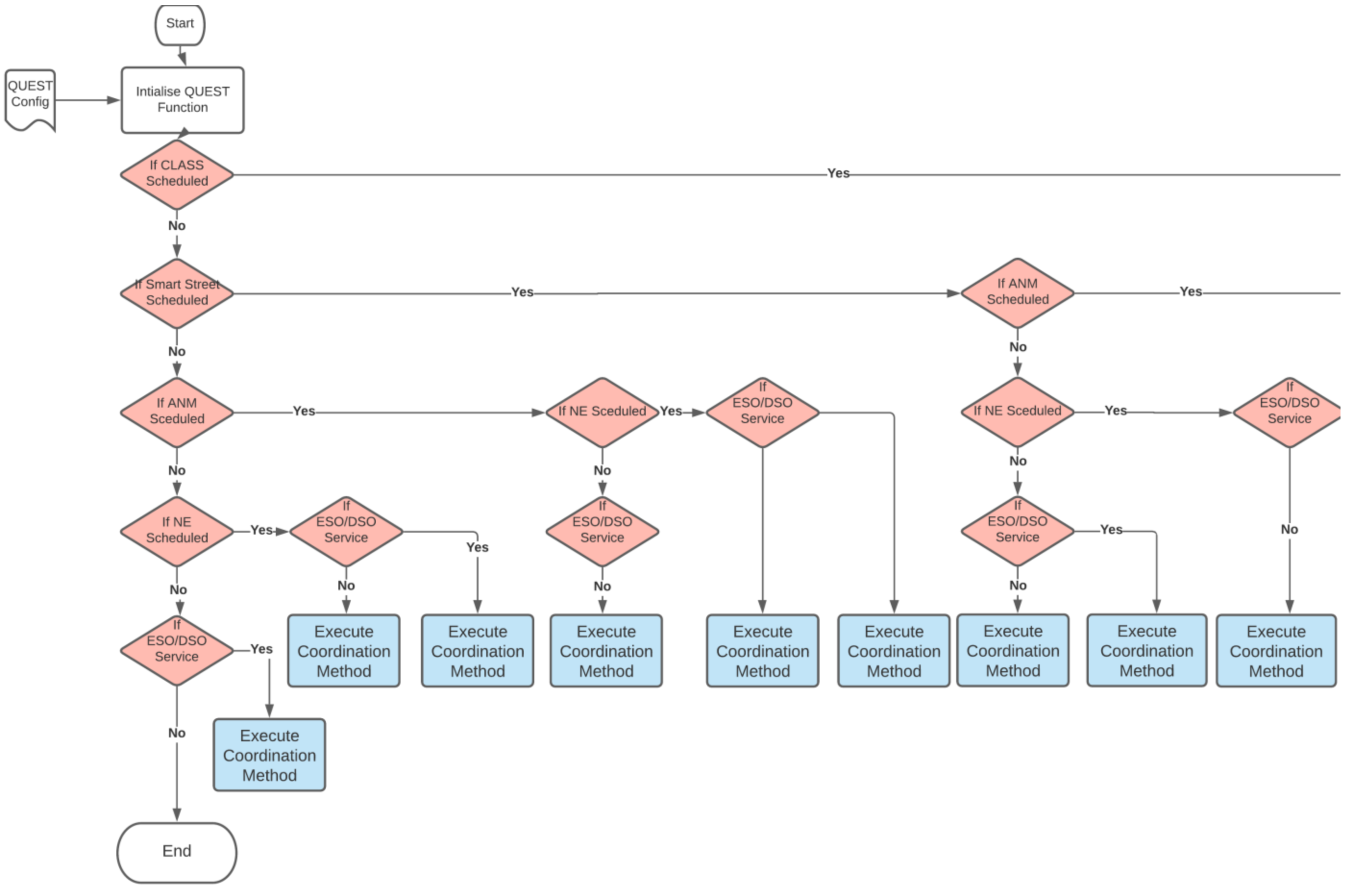

Figure 18: Test Bench Process: Flow Chart of ANM Algorithm (a)

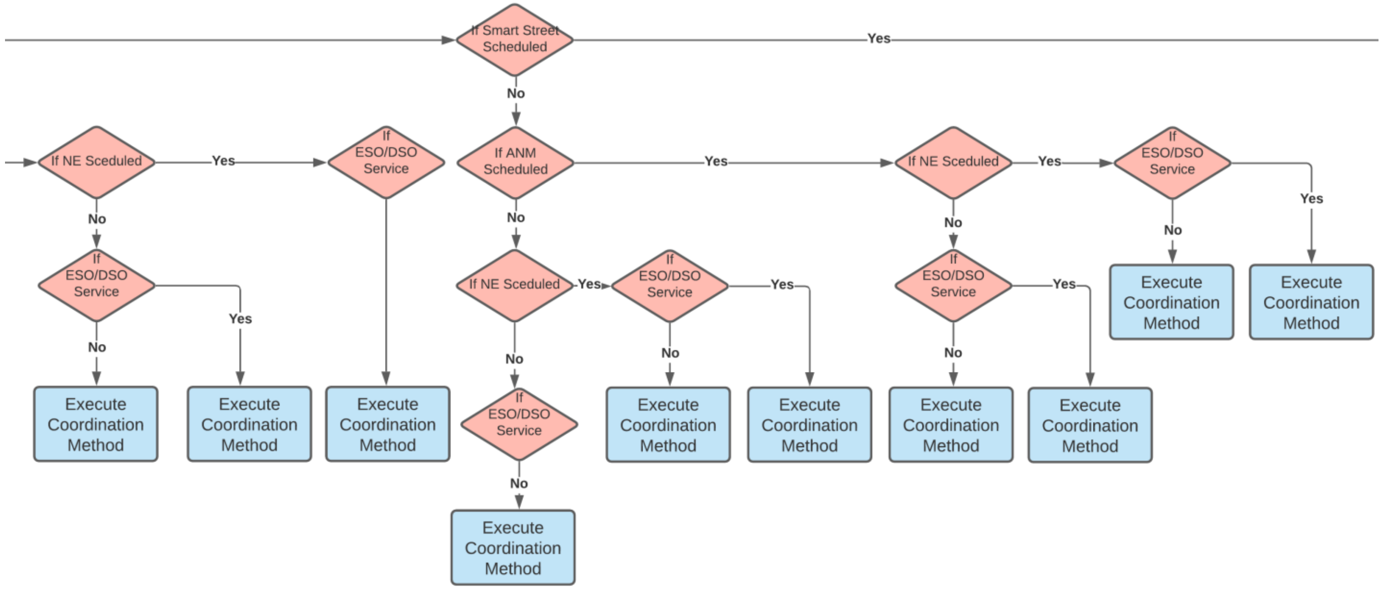

Figure 19: Test Bench Process: Flow Chart of ANM Algorithm (b)

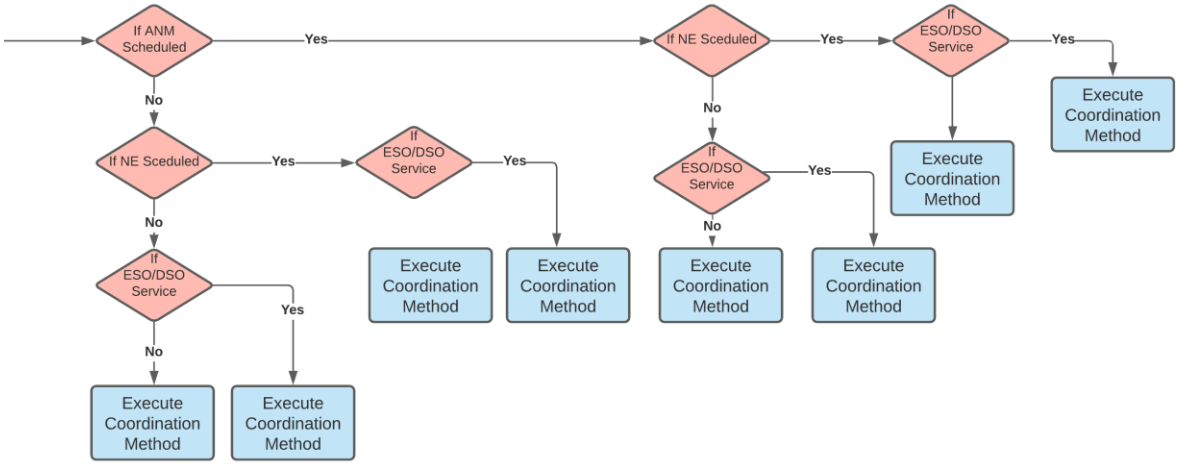

Figure 20: Test Bench Process: Flow Chart of ANM Algorithm (c)