QUEST Research

Electricity Northwest Limited

Functional Specification for Voltage Methodology and Scenario Analysis

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2. EXECUTIVE SUMMARY

In this document, the next stage in the project is delivered: to implement and test the functional specification for the voltage control methodology defined by Schneider Electric in their "QUEST Architecture" document.

This is achieved by:

- defining the QUEST philosophy which provides the function specification regarding how QUEST will deliver its voltage methods to achieve its objective for over-arching control and coordination of the many existing and potential system objectives.
- Using the modelling regime (constructed in a previous SGS QUEST Research work packages) to emulate a QUEST solution upon a simulation of ENWL's electrical network QUEST trial area.
- Creating a scenario analysis that test QUEST's functional specification for the voltage methodology and executing these scenarios to show how QUEST provides over-arching control and how these impacts are experienced by the network via key performance indicators.

Quest Philosophy

The philosophy provides the ontology, that is the set of concepts and categories in a subject area or domain that shows their properties and the relations between them, associated with QUEST.

For example, the philosophy introduces the language describing the QUEST state. Each QUEST state consists of a BLEND. The 'BLEND' is the selection of 'FUNCTIONS' chosen across the various voltage management 'TECHNIQUES' (individual voltage methods) to create a functional specification for a voltage methodology which delivers the BLEND of TECHNIQUES.

The existing and potential 'TECHNIQUES' applied within ENWLs network are implemented as either, a part of an existing operational system (e.g., CLASS), a potential operational system (e.g., Tap Stagger applied to Bulk Supply Points), or as new TECHNIQUEs integrated into the QUEST state. Each TECHNIQUE has a FUNCTION LEVEL, which allows for the QUEST state objective to provide more granularity in terms of the TECHNIQUEs objective.

The FUNCTION LEVELs achieved as part of each TECHNIQUE's objective combines as a BLEND of TECHNIQUES to deliver the overall QUEST state.

With the philosophy providing the descriptive language surrounding the QUEST state, the modelling regime provides the platform that emulates the QUEST state upon a simulation of ENWL electrical network.

The high-level structure of the modelling regime is presented in Figure 2.

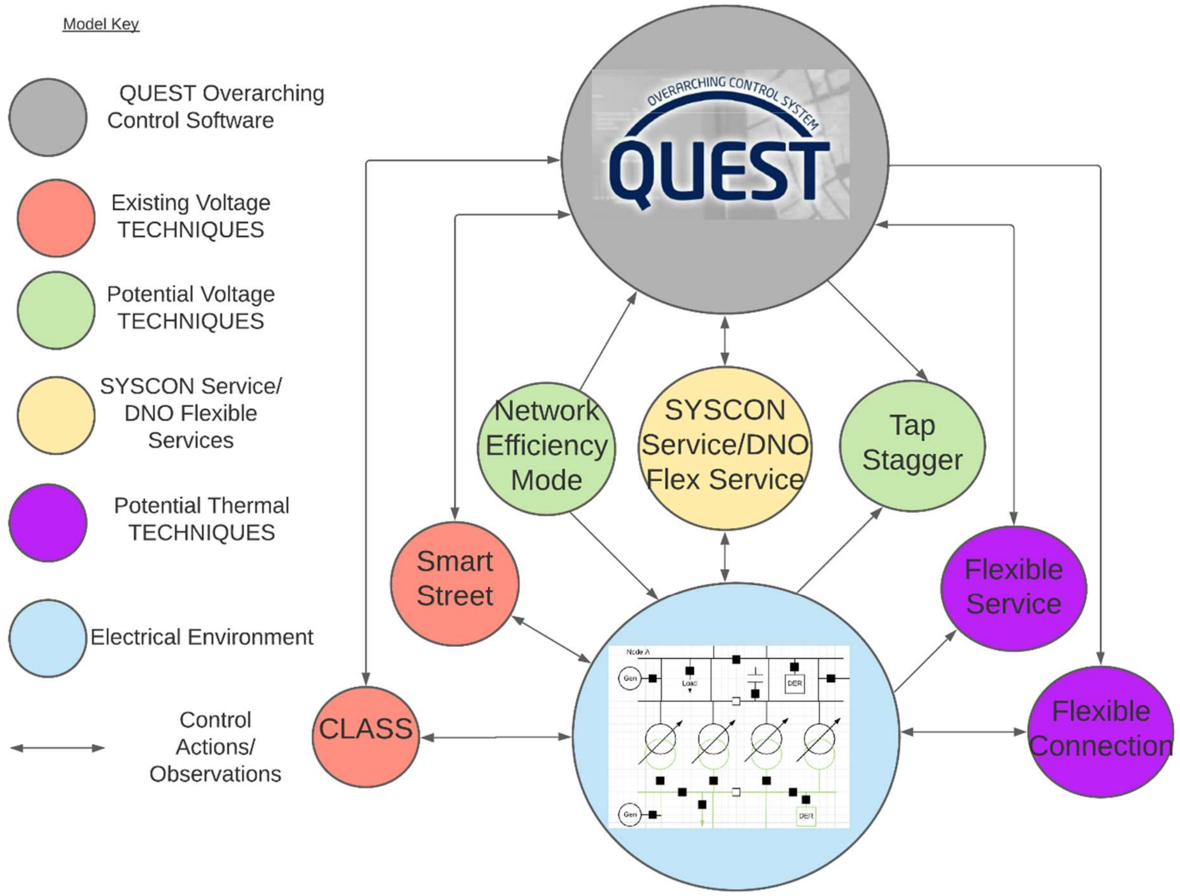

Figure 1: High-Level Modelling Regime

The modelling regime enables:

- Simulation representative of the ENWL electrical distribution system (blue) via network modelling for both time-step and time-series analysis, observing key performance indicators:
    - **Total System Demand:** Since this is a parameter that CLASS and Smart Street seek to reduce, or increase, it must be observed.
    - **33kV System Losses:** Since this is a parameter that Network Efficiency Mode will look to reduce, it must be observed.
    - **External Network Generation:** Since this is a parameter that will alter due to demand changes, it must be observed.
    - **Internal Network Generation:** Since this is a parameter that will alter due to demand changes, it must be observed.
    - **Total System Carbon Intensity:** By converting external generation to the 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.
- Application of each part of the modelling regime, these are
    - existing voltage TECHNIQUEs (Red):CLASS, Smart Street
    - potential voltage TECHNIQUES (Green): Network Efficiency Mode, Tap Stagger BSP

   - SYSCON Service/DNO Flexible Services (Yellow): Mandatory SYSCON Services such as LFDD and DSO Flexibility Services.
   - Thermal TECHNIQUES: Flexible Connections (Purple).

  These voltage, thermal TECHNIQUES and services, within the modelling regime are then applied upon pertinent network assets within the electrical model and their effects on electrical network parameters observed, for example bus-bar voltages and thermal branch flows and identified key performance indicators.

- Identification of issues within the modelled electrical network, caused by conflicts between voltage TECHNIQUES achieving their objective BLEND FUNCTION LEVEL, to determine how QUEST's voltage control methodology can resolve these issues.
- Analysis of QUEST's overarching voltage control methodology and impacts upon the simulated electrical network; in order to optimise and validate its methodology to shape the TECHNICAL PRIORITY LIST development and how the methodology impacts the key performance indicators associated with the network operation.

The modelling regime is used to facilitate scenario analysis upon specific QUEST States which are analysed and identified as the most pertinent scenarios, at the present stage of the project.

A set of scenarios is defined in order to test QUEST's TECHNIQUES, regarding the individual TECHNIQUES applied, their impacts to the network and how QUEST provides over-arching control to coordinate conflict between objectives and physical network limitations- all of which effect the key performance indicators of the network. The result of the scenario analysis is validation of the functional specification for QUEST's voltage methodology.

This is explained in detail in the body of the text, with the conclusions from the execution of these studies now presented.

General Conclusions

The Scenario Analysis has achieved the following objectives:

- validated the functional specification of the voltage control methodologies defined by the QUEST control system architectures and use cases, and
- provided the impact of key performance indicators associated with the network operation.

It has achieved this by implementing multiple scenarios using the modelling regime to thoroughly test the functional specification related to each voltage methodology in isolation and in concert with one another, with any conflicts between methods regarding either voltage methodology objective conflict or physical network limit compliance conflicts, being resolved by QUEST's overarching control. As well as showing the benefits and limitations to key performance indicators each combination of voltage methods will affect.

Furthermore, the outputs of the scenario analysis show that QUEST's overarching control solution is fit for purpose, and the functional specification of voltage methodology once applied as part of a real-time platform architecture, being delivered by Schneider Electric, fundamentally, will achieve the wider QUEST objectives upon ENWL's network.

Although, overall, the outputs from the scenario analysis have achieved the objectives above, it has also provided confirmations and insights into previous speculated benefits and limitations identified in the projects original use cases [1], these outputs can now be fed into the development of the QUEST architecture and QUEST trials to improve the delivery of the solution, both now and in the future.

Voltage TECHNIQUE Conclusions

CLASS: Delivering the CLASS demand reduction target will be affected by availability of assets and the voltage-demand relationship that exists in the model. Scenario 1 highlighted that to deliver the CLASS target, when it is achievable it might not need all assets. However, when the voltage-demand relationship is weaker at certain parts of the day, more assets need to be included to achieve the target- and in some cases not meet the target at all (albeit constrained by the scenario bounds). This means ENWL must be aware of the variance surrounding the delivery of the demand reduction target, as not to commercially offer what cannot be achieved.

Network Efficiency Mode (NEM): NEM can provide benefit to the network by reducing system losses in the 33kV, however, the magnitude of these benefits can be small regarding the loss reduction associated with reduced current. Therefore, it is suggested from the scenarios that NEM is best suited to support the likes of CLASS and Smart Street demand reduction targets, rather than as a priority in of itself.

Smart Street: Smart Street provides a demand reduction benefit, but, that benefit could be increased further by broadening the voltage targets associated with its function levels used in the scenario studies reported here. In the scenario analysis, the settings were kept in line with CLASS voltage targets, however, due to the p.u. statutory limits being lower at LV (400V), changes to the configuration of FUNCTION LEVEL would allow greater benefits to be unlocked. It has been noted that while the Smart Street FUNCTION LEVELs used reflect the FUNCTION LEVELs in the QUEST design [3], the reality is that present Smart Street transformers only have three tap steps to reduce voltage below the nominal tap setting, each tap step being 2.5% of nominal voltage- as presented in the final function design specification [4]. This would equate to Smart Street FUNCTION LEVELS of 100% with a 0.925 p.u. voltage target; 66% with a 0.95 p.u. voltage target and 33% with a 0.975 p.u. voltage target. While this does not impact the conclusions of the scenario studies carried out, this issue should be resolved to ensure maximum operational benefits are achieved for Smart Street, and any revised studies carried out during the QUEST trial phase to reflect the final agreed Smart Street FUNCTION LEVELS. This applies to the scenarios reported here that involve Smart Street. This will be investigated as part of the QUEST Trials.

Tap Stagger: Tap stagger can provide a MVAr absorption service to the DNO and TO, instead of the construction and installation of alternate voltage control systems such as a STATCOM. However, since this behaviour is induced by taking advantages of increased system losses there is an impact to carbon intensity when operating, therefore, a balance in benefits must be struck. Furthermore, tap stagger operations cause slight voltage rise on the secondary bus bar of the BSP, which needs to be monitored by QUEST to ensure this does not interfere with delivering other TECHNIQUE FUNCTION LEVELs.

QUEST Conclusions

Conflict satisfaction and coordination applied by QUEST allowed for all TECHNIQUEs to be applied in concert with one another, some important observations were:

In certain cases, uncoordinated responses would result in “known voltage excursions”, therefore, setting Smart Street to its FUNCTION LEVEL voltage target before CLASS has achieved its own, would cause a double impact to voltage reduction at LV. Therefore, QUEST must allow CLASS to achieve its FUNCTION LEVEL and associated voltage target first, then calculate the resulting FUNCTION LEVEL and subsequent voltage target for Smart Street to utilise post CLASS action.

This behaviour will be investigated, as part of the QUEST trials, to determine the worst-case impacts to uncoordinated actions across a year to allow proactive setting of Smart Street, where the activation of CLASS may potentially occur and cause an LV excursion. This option is only required if a fast tap solution does not exist, where this solution exists it would allow QUEST to place Smart Street into a safe mode instantaneously following CLASS activation, then QUEST would calculate the FUNCTION LEVEL due to the constraints applied under the CLASS activation.

Tap Stagger: Due to Tap Stagger slightly raising the secondary busbar voltage, if this voltage rise is not considered by QUEST, it can result in slight impacts to FUNCTION LEVEL delivery.

Flexible Connections: CLASS demand boost was shown to provide greater demand in the network to be satisfied by the higher voltage network as a service, however, previously curtailed generation was quick to utilise this released demand, cancelling our any CLASS boost service. QUEST must mitigate in this circumstance by holding DERMS/ANM setpoints to their pre-CLASS Boost calculated positions, in order to ensure this service can be delivered.

CLASS: CLASS objective delivery suffered in some cases from not being able to achieve voltage targets associated with its FUNCTION LEVEL due to discrete tap limits. Since QUEST offers much more observability of voltages across the network, it is possible that voltage targets associated with CLASS FUNCTION LEVEL can also be optimised, since these targets are conservative in nature to consider unobserved voltage drop across the network. This update would facilitate the delivery of CLASS targets and aid the delivery of FUNCTION LEVEL as part of being associated within a TECHNIQUE PRIORITY LIST.

Overall, QUEST offers benefit in not only delivering each individual TECHNIQUE but also in concert with one another, providing the actions to achieve over-arching control. The impact to this control is shown not only in the delivery of the objectives associated with each voltage TECHNIQUE but also the key performance indicators associated with the network.

For the most part each TECHNIQUE will improve these key performance indicators, such as demand reduction and system loss reduction reducing carbon emissions. However, certain TECHNIQUE objective fulfilment can reduce the overall impact of benefits and in some case reverse them, therefore, these benefits must be weighed against the limitations on a case-by-case bases. The importance being that visibility to make these decisions is required and provided by QUEST.

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 to perform optimally and are set up to fail safe. Therefore, if there is a communications failure any voltage optimisation or ANM benefit is significantly reduced, falling back on local autonomous control operations with limited observability and control on the network, or removed entirely.

With these limitations in the current operation of the individual optimisation systems, the main objective of the QUEST overarching software can be summarised as: '*control and coordinate multiple operational systems and control method objectives operating upon the ENWL network, whilst endeavouring to prevent conflicts between those systems and providing voltage optimisation where possible'.*

This splits into three core operational objectives as identified in "QUEST Initial Report Use Cases Issue 1" [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 was created in "200952 14B ANM Research (WP4) - Modelling Regime"[2] 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.

In this document, the next stage in the project is delivered: to use the modelling regime to implement the voltage control methodology defined by Schneider Electric in their "QUEST Architecture" [3] document.

This is addressed by implementing a scenario analysis that achieves the following objectives:

- validates the functional specification of voltage control methodologies defined by the QUEST control system architectures [3] and use cases [1], and

- provides the impact on key performance indictors associated with the network operation, as an outcome of delivering the functional specification of voltage methodologies upon modelled network operational conditions.
- A further set of work packages
  - (WP6) - Technical Benefits Report
  - (WP7) - Updated Project Business Case
  - (WP8) - Updated Carbon Benefits Case

  will use the outcome of this voltage methodology validation work, to provide more precise and accurate scenarios to support work featured in these packages to feed into the presentation of wider QUEST project objective fulfilment. Therefore, all outputs of this work package should be viewed as in support of the functional specification for voltage methodology validation, rather than used to interpret the final operational benefits and limitations of the QUEST system.

These objectives are achieved by undertaking the work described in the following sections:

- QUEST Philosophy (section 4): This section discusses the ontology i.e., a set of concepts and categories in a subject area or domain that shows their properties and the relations between them, associated with the QUEST software, and how this is used to manage the network through a voltage control methodology.
- Modelling Regime (section 5): This section discusses how the QUEST philosophy is delivered through the modelling regime.
- Scenario Analysis (section 6): This section discusses the important voltage control methodologies requiring test and validation at this stage in the project to support the QUEST architecture design.
- Scenario Outcomes (section 7): This section presents the validation of voltage control methodologies in achieving their objectives, as well as presenting outcomes of implementing the voltage control methodologies regarding the key performance indicators associated with the network.

The QUEST philosophy will now be discussed in section 4.

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

Term	Definition
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 275/132kV or 275/33kV. 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
NETS	National Electricity Transmission System
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
PSP	Primary Supply Point (A primary substation)
Q	Reactive Electrical Power
SFR	Secondary Frequency Response (CLASS Function)
SGS	Smarter Grid Solutions
TS	Tap Stagger
UDL	Upper Demand Limit

3.1. References

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

[1] ENWL document “QUEST Initial Report - Use Cases”, Issue 1

[2] SGS report number 200952 14B "ANM Research (WP4) - Modelling Regime"
[3] Schneider Electric report "QUEST Architecture Options Detailed Design subphase 2 Report"
[4] Schneider Electric report "QUEST Functional Specification"

4. QUEST PHILOSOPHY

Since the inception of the QUEST project, a philosophy has been developed that provides clarity regarding how QUEST will deliver its objective for over-arching control and coordination of the many existing and potential system objectives.

An abridged presentation of this philosophy is provided to give context of the "ontology" associated with QUEST and the language used to describe this ontology[1].

To achieve its overarching control objectives QUEST observes and controls the distribution network to achieve a QUEST State: this state mirrors the condition of the National Electricity Transmission System (NETS) so that the functional specification for QUEST's voltage methodology reacts as expected to normal or emergency situations on the NETS, to satisfy the objectives specific to the situation.

4.1. National Electricity Transmission System: Normal

For 99% of the time the National Electricity Transmission System (NETS) is in a normal operating condition (not in an emergency operating condition), it is under this condition that the QUEST state is applied for the majority of time. Therefore, we initially explain the QUEST objectives and voltage control methodology from the perspective of achieving the QUEST state for National Electricity Transmission System: Normal operating conditions.

Each QUEST state consists of a BLEND. The 'BLEND' is the selection of 'FUNCTIONS' chosen across the various voltage management 'TECHNIQUES' to create a functional specification for the voltage methodology which delivers the BLEND of TECHNIQUES.

The existing and potential 'TECHNIQUES' applied within ENWLs network are implemented as either, a part of an existing operational system, a potential operational system, or as new TECHNIQUEs integrated into the QUEST software. Each TECHNIQUE has a FUNCTION level, which allows for the objective to provide more granularity in terms of the TECHNIQUES objective.

The FUNCTION LEVELs achieved as part of each TECHNIQUE's objective combines as a BLEND of TECHNIQUES to deliver the overall QUEST state.

The existing TECHNIQUES, as defined in [3], can be described as:

- CLASS Demand Reduction: Uses voltage control to decrease network real power demand by leveraging voltage-demand relationships. Its FUNCTIONS enable the following granularity of objective:
    - 100% - Demand Reduction Full: Function Level of 100% applies a voltage target of 0.95 p.u. nominal voltage at the secondary busbars at primary substations to achieve CLASS demand MW target.
    - 75% - Demand Reduction Three Quarters: Function Level of 75% applies a voltage target of 0.9625 p.u. nominal voltage to achieve CLASS demand MW target.
    - 50% - Demand Reduction Half: Function Level of 50% applies a voltage target of 0.975 p.u. nominal voltage to achieve CLASS demand MW target.
    - 25% - Demand Reduction One Quarter: Function Level of 25% applies a voltage target of 0.9875 p.u. nominal voltage to achieve CLASS demand MW target.

[1] Quest Philosophy for initial SE architecture options_Rev01

- CLASS Demand Boost: Uses voltage control to increase network real power demand by leveraging voltage-demand relationships. Its FUNCTIONS enable the following granularity of objective to achieve its demand MW target:
  - 100% - Demand Boost Full: Function Level of 100% applies a voltage target from the relay of 1.05 p.u. nominal voltage to achieve CLASS demand MW target.
  - 75% - Demand Boost Three Quarters: Function Level of 75% applies a voltage target from the relay of 1.0375p.u. nominal voltage to achieve CLASS demand MW target.
  - 50% - Demand Reduction Half: Function Level of 50% applies a voltage target from the relay of 1.025 p.u. nominal voltage to achieve CLASS demand MW target.
  - 25% - Demand Reduction One Quarter: Function Level of 25% applies a voltage target from the relay of 1.0125 p.u. nominal voltage to achieve CLASS demand MW target.
- Smart Street: reduces (MW) real power demand via the Conservation Voltage Reduction (CVR) methodology. Its FUNCTIONS enable the following granularity of objective:
  - 100% - Smart Street Full: Function Level of 100% applies a voltage target from the relay of 0.95 p.u. nominal voltage [2]to achieve maximum LV efficiency.
  - 75% - Smart Street Three Quarters: Function Level of 75% applies a voltage target from the relay of 0.9625 p.u. nominal voltage to achieve reduced, but improved, LV efficiency relative to maximum.
  - 50% - Smart Street Half: Function Level of 50% applies a voltage target from the relay of 0.975 p.u. nominal voltage to achieve reduced, but improved, LV efficiency relative to maximum.
  - 25% - Smart Street One Quarter: Level of 25% applies a voltage target from the relay of targets 0.9875 p.u. nominal voltage to achieve reduced, but improved, LV efficiency relative to maximum.

The potential TECHNIQUES that are introduced as part of the QUEST project can be described as:

- Network Efficiency: increases 33kV system voltages by adjusting BSP transformer target voltage settings, enabling the reduction of I^2R losses.[3]
  - 100% - Network Efficiency Full: Function Level of 100% applies a voltage target of 1.05 p.u. nominal voltage at secondary busbar at bulk supply point substations to achieve maximum 33kV efficiency.
  - 75% - Network Efficiency Three Quarters: Function Level of 75% applies a voltage target of 1.0375p.u. nominal voltage at secondary busbar at bulk supply point substations to achieve, reduced, but improved 33kV efficiency relative to maximum.
  - 50% - Network Efficiency Half: Function Level of 50% applies a voltage target of 1.025 p.u. nominal voltage at secondary busbar at bulk supply point substations to achieve, reduced, but improved 33kV efficiency relative to maximum.
  - 25% - Network Efficiency Quarter: Function Level of 25% applies a voltage target of 1.0125 p.u. nominal voltage at secondary busbar at bulk supply point substations to achieve, reduced, but improved 33kV efficiency relative to maximum.

[2] All Smart Street Targets are defined by the p.u. applied to the model base voltage, 240V.

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

- Tap Stagger BSP[4]: Providing voltage support via reactive power absorption at the BSP level.
    - 100% - Tap Stagger Full: Function Level of 100% implements a transformer pair tap separation of eight whilst maintaining a target voltage. Where one transformer taps up four positions and the other down four positions, to achieve MVAr target.
    - 75% - Tap Stagger Three Quarters: Function Level of 100% implements a transformer pair tap separation of six whilst maintaining a target voltage. Where one transformer taps up three positions and the other down three positions, to achieve MVAr target.
    - 50% - Tap Stagger Reduction Half: Function Level of 100% implements a transformer pair tap separation of four whilst maintaining a target voltage. Where one transformer taps up two positions and the other down two positions, to achieve MVAr target.
    - 25% - Tap Stagger Reduction One Quarter: Function Level of 100% implements a transformer pair tap separation of two whilst maintaining a target voltage. Where one transformer taps up one position and the other down one position, to achieve MVAr target.

All TECHNIQUES that include a voltage target assume a +/-1.25% target envelope to consider the discrete nature of the tap positions, for example a CLASS Primary with a function level set to 100%, resulting in a secondary bus voltage target of 1.05p.u., reporting a measurement of 1.043 p.u. would be considered achieving its Function Level of 100%.

Furthermore, all descriptions are representative of the modelling approach only, derived from their descriptions in [1] and [3] and their exact implementation in the QUEST architecture may differ slightly to achieve delivery of core features within the project time scales.

With the TECHNIQUES and BLENDs described, under NETS Normal, QUEST will achieve its objective by targeting a specific BLEND of TECHNIQUES as configured by their FUNCTIONS, where each TECHNIQUE is prioritised by a TECHNIQUE PRIORITY LIST.

The TECHNIQUE PRIORITY LIST helps QUEST implement a function specification for a voltage methodology whose objective is defined by a BLEND, made up by each TECHNIQUE's FUNCTION LEVELS.

It does this by providing an order for each TECHNIQUE within the BLEND to achieve as close to its FUNCTION LEVEL as possible, before moving on to the next TECHNIQUE , where TECHNIQUES higher in the TECHNIQUE PRIORITY LIST achieve outputs closer to their FUNCTION LEVEL, reducing the solution space for the other TECHNIQUES further down the TECHNIQUE PRIORITY LIST to achieve their own FUNCTION LEVELs- allowing the solution to converge.

Additionally, to enable QUEST's voltage methodology to achieve its objective, it also has overarching control over thermal TECHNIQUEs (ANM), whose primary objectives are managing thermal flows against equipment rating limits that may affect the behaviour of the voltage TECHNIQUES and, therefore, must be integrated into the voltage methodology to ensure the TECHNIQUES achieve their FUNCTION LEVELs as described by the TECHNIQUE PRIORITY LIST.

These thermal TECHNIQUES are

[4] Note that the inclusion of a tap stagger separation of 8 taps has been debated extensively with the conclusion that studies should be carried out with an eight-tap separation and any network operational issues reflected in the model recorded to inform future discussions.

- 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.

These thermal TECHNIQUES are assigned MITAGATION MODES as part of the QUEST algorithm, where QUESTs voltage methodology will alter their operational set points to ensure the BLEND of TECHNIQUES and their FUNCTION LEVELs are not affected by these systems actions.

Thermal TECHNIQUES mitigation modes, regarding the delivered architecture will be applied both pro-actively and reactively and never off, as their impact to all TECHNIQUES must and will be considered by QUEST. However, to simplify certain scenario cases, the modelling regime allows these TECHNIQUES to be switched out.

4.2. National Electricity Transmission System: Emergency

Service provision to the National Electricity Transmission System (NETS) during times of emergency system conditions supersedes QUESTs normal operation. Under these system conditions or SYSCON, QUEST's state changes depending on the emergency identified.

The QUEST states are split into a six level SYSCON hierarchy, where the previously discussed state refers to SYSCON 6.

- SYSCON 6 is the normal operating condition (99%+ of the time), non-emergency condition of the National Electricity Transmission System.
- SYSCON 5 is the first level of emergency condition. Demand reductions are required via means of primary substation voltage reduction at this level (Grid Code OC6.5 stages 1 & 2).
- SYSCON 4 is the second level of emergency condition. Demand reductions are required at this level via means of demand disconnection at primary substations (Grid Code OC6.5 stages 3 to 5).
- SYSCON 3 is the third level of emergency condition. Demand disconnections are required at the GSP level when a Low Frequency (LF) event occurs and the ESO instructs the DNO to perform them manually. This is often referred to as Manual LFDD (Grid Code OC6.7).
- SYSCON 2 is the penultimate level of emergency condition. Automatic Low Frequency Demand Disconnections (LFDD) have occurred at three or more BSP transformers due to a national electricity system LF event (Grid Code OC6.6).
- SYSCON 1 is the maximum level of emergency condition. This is a 'Black Start' or 'System Recovery' condition where all or most of the national electricity system is no longer functioning (Grid Code OC9).

Under levels five to one all voltage TECHNIQUES and thermal TECHNIQUES are mitigated, and the resulting voltage methodology's objectives are altered to support the emergency objectives.

5. MODELLING REGIME

In this document, the modelling regime is used to run scenario analysis which fully tests the QUEST states.

The high-level structure of the modelling regime is presented in Figure 2.

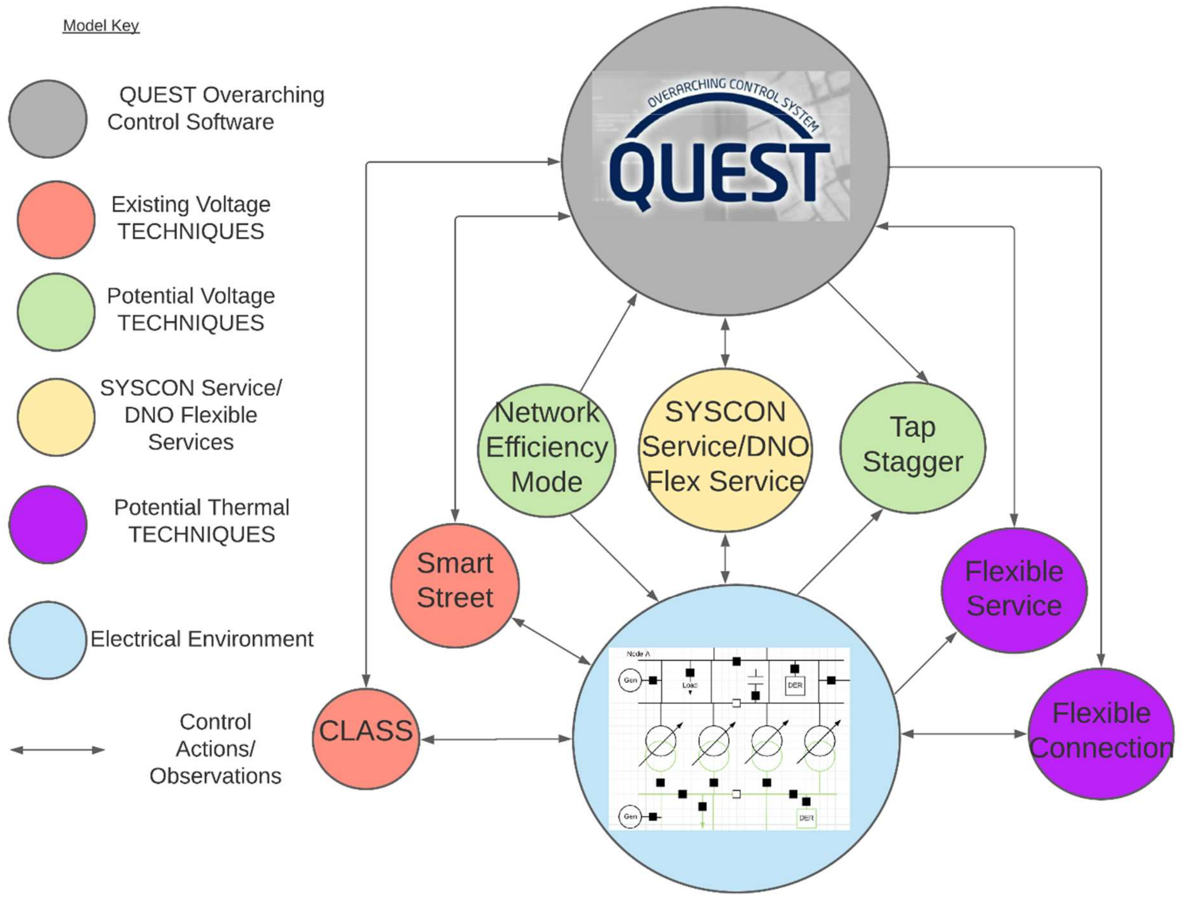

Figure 2: High-Level Modelling Regime

The modelling regime enables:

- Simulation representative of the ENWL electrical distribution system (blue) via network modelling for both time-step and time-series analysis, observing key performance indicators:
    - **Total System Demand:** Since this is a parameter that CLASS and Smart Street seek to reduce, or increase, it must be observed.
    - **33kV System Losses:** Since this is a parameter that Network Efficiency Mode will look to reduce, it must be observed.
    - **External Network Generation:** Since this is a parameter that will alter due to demand changes, it must be observed.
    - **Internal Network Generation:** Since this is a parameter that will alter due to demand changes, it must be observed.
    - **Total System Carbon Intensity:** By converting external generation 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.

- Application of each part of the modelling regime, these are
  - existing voltage TECHNIQUEs (Red):CLASS, Smart Street
  - potential voltage TECHNIQUES (Green): Network Efficiency Mode, Tap Stagger BSP
  - SYSCON Service/DNO Flexible Services (Yellow): Mandatory SYSCON Services such as LFDD and DSO Flexibility Services.
  - Thermal TECHNIQUES: Flexible Connections (Purple).

  These voltage, thermal TECHNIQUES and services, within the modelling regime are then applied upon pertinent network assets within the electrical model and their effects on electrical network parameters observed, for example bus-bar voltages and thermal branch flows and identified key performance indicators.

- Identification of issues within the modelled electrical network, caused by conflicts between voltage TECHNIQUES achieving their objective BLEND FUNCTION LEVEL, to determine how QUEST's voltage control methodology can resolve these issues.
- Analysis of QUEST's overarching voltage control methodology and impacts upon the simulated electrical network; in order to optimise and validate its methodology to shape the TECHNICAL PRIORITY LIST development and how the methodology impacts the key performance indicators associated with the network operation.

The modelling regime is used to implement scenario analysis upon specific QUEST States which are analysed as identified as the most pertinent scenarios, at the current stage of the project, to:

- help our partner Schneider Electric develop the TECHNICAL PRIOTY LIST as part of the operational system architecture, and
- provide operational understanding of the impact the QUEST states have on key performance indicators.

In the future, the modelling regime can also be used to support the trial design, which is outside the scope of this work.

6. TEST BENCH

As part of the modelling regime a test bench[5] has been created to deliver the modelling regime realised in python, where:

- A python method has been created to execute time-series scenario analysis to the IPSA+ simulated electrical network, allowing for operational behaviour from typical load and generation profiles to be applied.
    - Load Models: Exponential Load Models have been integrated into the electrical network model as part of a supplementary work[6] to introduce a more accurate voltage demand behaviour modelling in line with ENWL's usage of this modelling technique as part of their operational CLASS algorithm. Kp values from historical data are used alongside historical voltage measurements, Vb and historical power measurements Pb to induce the correct loaded demand response from the voltage TECHNIQUES applied to the model.

$$P_{EXP} = P_b \cdot (\frac{v}{v_b})^{K_p}$$

    - Generator Models: Simplified P Q generator models have been used in line with the original test bench development.
- Python based representations of Schneider Electric's and SGS's voltage and thermal TECHNIQUES, as well as QUESTs overarching control can be applied to the IPSA+ simulation of the electrical network.
- The time-series scenario analysis enables BLENDS of all voltage and thermal TECHNIQUES to be applied in parallel to identify conflict and examine effects on the network key performance indicators.

Finally, the proposed QUEST software architecture is created as a python representation[7]. Applying a model of an overarching control method to coordinate conflicts TECHNIQUES applied as part of QUESTA fully detailed explanation of the test bench can be found in [1] and the extension of the load models to improve the accuracy of the test bench can be found in [1].

[5] 200952 14B ANM Research (WP4) - Modelling Regime
[6] 201056 01 A Voltage Demand Relationship Research (WP1) - Present Load Model
[7] Python is an interpreted high-level general-purpose programming language.

7. SCENARIO ANALYSIS

The scenario analysis functionality allows the modelling regime to be configured for

- the electrical network input data, and
- QUEST State: BLEND FUNCTION LEVELS,

applied to the electrical network, for specific scenarios under test.

7.1.1. Electrical Network Inputs

The electrical network inputs set the behaviour of the electrical network during the scenario.

The variables which the electrical inputs have control over are:

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

The power flow state is achieved via the power flow solution approach which has two parts:

- the internal power balance equation loop, which produces initial voltage and angle outputs,
- the external voltage control loop, applying the autonomous voltage control heuristics encapsulated in the power-flow solution that alters voltage tap settings and local PV controlled bus bars to achieve their targets, associated with their parameters set points, resulting in the final voltage and angle outputs for the solution.

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.

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 input data is shown in Table 2.

Table 2: 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

The electrical network scenarios will achieve solutions to the power flow state that are a result of generation, demand and the voltage control embedded within the model.

These solutions will provide the baseline result to which QUEST control TECHNIQUES will further correct to achieve the objectives associated with these TECHNIQUES.

7.1.2.QUEST State Inputs

The QUEST State Inputs determines the objective of QUEST for the electrical network scenario. The state is achieved by setting:

- the SYSCON Level,
- the BLEND setting which identifies the TECHNIQUEs enabled,
- the FUNCTION LEVEL associated with each TECHNIQUE that forms the BLEND,
- the TECHNIQUE PRIORITY LIST which determines the order in which each TECHNIQUE that forms the BLEND achieves its FUNCTION LEVEL.

The TECHNIQUES and their FUNCTIONS are tabulated:

Table 3: TECHNIQUES and their FUNCTION LEVELS

TECHNIQUE	FUNCTION	Objective	Acronym
CLASS Demand Reduction	100% - Demand Reduction Full	Function Level implements a voltage target of 0.95 p.u. nominal voltage at secondary busbar at primary substation to achieve CLASS demand MW target.	DRF
	75% - Demand Reduction Three Quarters	Function Level implements a voltage target of 0.9625 p.u. nominal voltage to achieve CLASS demand MW target.	DRTQ
	50% - Demand Reduction Half	Function Level implements a voltage target of 0.975 p.u. nominal voltage to achieve CLASS demand MW target.	DRH
	25% - Demand Reduction One Quarter	Function Level implements a voltage target of 0.9875 p.u. nominal voltage to achieve CLASS demand MW target.	DROQ
	MM- Mitigation Mode	Function altered to facilitate emergency requirement	DRMM
CLASS Demand Boost	100% - Demand Boost Full	Function Level implements a voltage target of 1.05 p.u. nominal voltage to achieve CLASS demand MW target.	DBF
	75% - Demand Boost Three Quarters	Function Level implements a voltage target of 1.0375p.u.	DBTQ

TECHNIQUE	FUNCTION	Objective	Acronym
		nominal voltage to achieve CLASS demand MW target.	
	50% - Demand Reduction Half	Function Level implements a voltage target of 1.025 p.u. nominal voltage to achieve CLASS demand MW target.	DBH
	25% - Demand Reduction One Quarter:	Function Level implements a voltage target of 1.0125 p.u. nominal voltage to achieve CLASS demand MW target.	DBOQ
	MM- Mitigation Mode	Function altered to facilitate emergency requirement	DBMM
Smart Street	100% - Smart Street Full	Function Level implements a voltage target of 0.95 p.u. nominal voltage to achieve max LV efficiency.	SMSTF
	75% - Smart Street Three Quarters	Function Level implements a voltage target of 0.9625 p.u. nominal voltage to achieve reduced, but improved, LV efficiency relative to max.	SMSTTQ
	50% - Smart Street Half	Function Level implements a voltage target of 0.975 p.u. nominal voltage to achieve reduced, but improved, LV efficiency relative to max.	SMSTH
	25% - Smart Street One Quarter	Function Level implements a voltage target of 0.9875 p.u. nominal voltage to achieve	SMSTOQ

TECHNIQUE	FUNCTION	Objective	Acronym
		reduced, but improved, LV efficiency relative to max.	
	MM- Mitigation Mode	Function suspended to facilitate emergency requirement	SMSTMM
Network Efficiency Mode	100% - Network Efficiency Mode Full	Function Level implements a voltage target of 1.05 p.u. nominal voltage at secondary busbar at bulk supply point substation to achieve max 33kV efficiency.	NEMF
	75% - Network Efficiency Mode Three Quarters	Function Level implements a voltage target of 1.0375p.u. nominal voltage at secondary busbar at bulk supply point substation to achieve, reduced, but improved 33kV efficiency relative to maximum.	NEMTQ
	50% - Network Efficiency Mode Half	Function Level implements a voltage target of 1.025 p.u. nominal voltage at secondary busbar at bulk supply point substation to achieve, reduced, but improved 33kV efficiency relative to maximum.	NEMH
	25% - Network Efficiency Mode One Quarter	Function Level implements a voltage target of 1.0125 p.u. nominal voltage at secondary busbar at bulk supply point substation to achieve, reduced, but	NEMOQ

TECHNIQUE	FUNCTION	Objective	Acronym
		improved 33kV efficiency relative to maximum.	
	MM- Mitigation Mode	Function suspended to facilitate emergency requirement	NEMMM
Tap Stagger BSP	100% - Tap Stagger Full	Function Level implements a voltage target of a transformer pair separation of eight whilst maintaining a target voltage. Where one transformer taps up four positions and the other down four positions, to achieve MVAr target.	BSP TSF1
	75% - Tap Stagger Three Quarters	Function Level implements a target of a transformer pair separation of six whilst maintaining a target voltage. Where one transformer taps up three positions and the other down three positions, to achieve to achieve MVAr target.	BSP TSF2
	50% - Tap Stagger Half	Function Level implements a target of a transformer pair separation of four whilst maintaining a target voltage. Where one transformer taps up two positions and the other down two positions, to achieve to achieve MVAr target.	BSP TSF3
	25% - Tap Stagger One Quarter:	Function Level implements a target of a transformer pair separation of two whilst maintaining a target	BSP TSF4

TECHNIQUE	FUNCTION	Objective	Acronym
		voltage. Where one transformer taps up one position and the other down one position, to achieve to achieve MVAr target.	
	MM- Mitigation Mode	Function suspended to facilitate emergency requirement	BSP TSMM
Flexible Connections	MM- Mitigation Mode	ANM system responds to QUEST signals to inhibit voltage TECHNIQUE interference.	FCMM
Flexible Services	MM- Mitigation Mode	ANM system responds to QUEST signals to inhibit voltage TECHNIQUE interference.	FSMM

The QUEST State is a combination of each TECHNIQUE's FUNCTION LEVEL, where the SYSCON, BLEND and TECHNQIUE PRIOITY LIST settings structure the functional specification for the voltage methodology objective and allow this methodology to be solved.

For example, when SYSCON is at level six, any BLEND of TECHNIQUEs can be selected, and any FUNCTION Level, within each TECHNIQUE selected. Then the TECHNIQUE PRIORITY LISTS determines how the BLEND of TECHNIQUEs will prioritise which TECHNIQUE's FUNCTION Level is more important, to resolve conflict in the satisfaction of the voltage methodology objective.

However, when SYSCON is in an Emergency Level, the BLEND is pre-selected, and the TECHNIQUE FUNCTIONs placed into a Mitigation Mode. This is done to ensure the emergency objectives are achieved.

These emergency objectives are not considered as part of the scenario analysis, as they will be rule based in nature and require minimal modelling development. Instead, the QUEST states achieved under SYSCON level six is only considered.

Furthermore, considering there are numerous TECHNIQUE FUNCTIONs Levels that can be selected, and prioritised by a TECHNIQUE PRIORITY LIST, the scenario analysis will only focus on what is considered the most pertinent QUEST states that will aid the development of the QUEST Architecture, that is the focus of this document. In future SYSCON emergency scenarios and the full combination of all TECHNQUE FUNCTIONs and their priority may be explored.

The next section takes the electrical network scenarios and the pertinent QUEST states and combines them, in preparation for application as part of the modelling regime.

7.2. Scenarios

For each test bench scenario, the following can be applied:

- The behaviour of the electrical network, initially based on load and generator input data and embedded autonomous voltage controls, providing a baseline power flow state,
- The behaviour of the control TECHNIQUES, based on their objectives,
- QUEST's overarching control objective to control and coordinate all TECHNIQUES to achieve the BLEND target, as proscribed by the TECHNIQUE PRIORITY LIST.

To achieve these scenario behaviours the following discrete scenario inputs are created:

7.3. Scenario Inputs

- **Analysis Window:** The period of analysis
- **Resolution:** The discretisation of the period of analysis
- **Load Inputs:** The time-series data source for Load Inputs, this includes the historical demand data and the historically calculated Kp values that allows the voltage-demand relationship to be implemented.
- **Firm Generator Inputs:** The time-series data source for Generation Inputs
- **ANM Generator Inputs:** The time-series data source for Generation Inputs
- **Technique Priority List:** The order to which the QUEST algorithm will solve the BLEND of TECHNIQUES as they try and achieve their individual FUNCTION LEVEL
- **Tap Stagger BSP:** Activation/Enablement of Voltage TECHNIQUE
- **Network Efficiency Mode**: Activation/Enablement of Voltage TECHNIQUE
- **CLASS**: Activation/Enablement of Voltage TECHNIQUE
    - CLASS enablement and activation is governed by a time-series schedule.
- **Smart Street**: Activation/Enablement of Voltage TECHNIQUE
- **Flexible Connection**: Activation/Enablement of Thermal TECHNIQUE
- **Flexible Services**: Activation/Enablement of Thermal TECHNIQUE

There are eight scenarios considered pertinent at this stage in the project that will aid QUEST architecture development, as well as provide insight into how QUEST will affect network performance via key performance indicators, since the selected scenarios are also considered as potentially the most frequently applied QUEST States.

Table 4: Voltage Methdology Scenarios

Scenario	Analysis Window	Resolution	Load Inputs	Firm Generator Inputs	ANM Inputs	Technique Priority List	Tap Stagger BSP	NEM	CLASS	Smart Street	Flexible Connection	Flexible Services
1	Max Loading Day	Half Hour	Historical	Historical	Synthesised Technology Data	1.Class	OFF	OFF	DRF	OFF	OFF	OFF
2	Max Loading Day	Half Hour	Historical	Historical	Synthesised Technology Data	1.NEM	OFF	NEMF	OFF	OFF	OFF	OFF
3	Max Loading Day	Half Hour	Historical	Historical	Synthesised Technology Data	1.Tap Stagger (BSP)	BSP TSF1	OFF	OFF	OFF	OFF	OFF
4	Max Loading Day	Half Hour	Historical	Historical	Synthesised Technology Data	1.Smart Street	OFF	OFF	OFF	SSF	OFF	OFF

Scenario	Analysis Window	Resolution	Load Inputs	Firm Generator Inputs	ANM Inputs	Technique Priority List	Tap Stagger BSP	NEM	CLASS	Smart Street	Flexible Connection	Flexible Services
5	Max Loading Day	Half Hour	Historical	Historical	Synthesised Technology Data	1.CLASS 2.SMST	OFF	OFF	DRF	SSF	OFF	OFF
6	Max Loading Day	Half Hour	Historical	Historical	Synthesised Technology Data	1.CLASS 2. SMST 3.NEM	OFF	NEMF	DRF	SSF	OFF	OFF
7	Max Loading Day	Half Hour	Historical	Historical	Synthesised Technology Data	1.NEM 2. SMST 3.CLASS	OFF	NEMF	DRF	SSF	OFF	OFF
8	Max Loading Day	Half Hour	Historical	Historical	Synthesised Technology Data	1.CLASS 2. SMST 3.NEM 4.Tap Stagger 5.Flexible Connection	BSP TSF1	NEMF	DBF	SSF	OFF	MM

7.4. Scenario Outputs

The test bench applies the input data associated with the scenario to the electrical network solution and the control TECHNIQUES and manages the network according to the TECHNIQUEs applied.

There are three main outputs observed for each scenario:

- Voltage Profiles
- QUEST Targets
- Thermal Flow Key Performance Indicators

The behaviours this induces are shown via a voltage and demand profile for a set of candidate sites representing the Royton BSP, this includes:

- BSP Secondary Busbars
- Primary Substation Secondary Busbars
- Distribution Substations Secondary Busbars[8], and
- End of the Distribution Substation Feeder.

Note: Statutory Limits are set as a p.u. of their model base, for example, the statutory limit of the LV network is 6% at 230V (equates to 216V), therefore, regarding the p.u. system this is 0.9 p.u. at a 415/240V(equates to 216V) model base used withing the network models as part of the test bench.

This gives a visualisation of where the voltage/thermal TECHNIQUEs applied are altering behaviour, in relation to a standard solve: where a standard solve is the load flow solution as defined by autonomous control settings applied within the load flow solution itself, for example On Load Tap Changing (OLTC) settings.

The QUEST FUNCTION LEVEL, to determine how close the FUNCTION LEVELs are to their setting

The pertinent KPIs 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

- System Load (MW Average)
- BSP Load (MVAr Average)
- System Generation External (MW Average)
- System Generation Internal (MW Average)
- 33kV Losses (MW Average)
- System Carbon (kgCO2 Average)

7.5. Scenario Limitations:

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 relevance to achieving QUEST's objectives.

[8] Distribution substations are HV/LV substations i.e., 11/0.415kV or 6.6/0.415kV, hence the secondary busbars and feeders are at LV.

- The data available at the time of study allowed for analysis to be applied to the Royton BSP only, any KPI effects, although presented as system wide, are only fully modelled at the Royton BSP and therefore the magnitude of the responses may appear reduced regarding expectation across the whole GSP.
- Furthermore, application of varying schedule-based control methods, namely CLASS, are not considered as part of this scenario analysis, CLASS is applied continuously in scenarios where it is enabled.
- All outputs and conclusions are bounded by the limitations surrounding the network model, data inputs and representation of control TECHNIQUES. The outputs are approximate and are to be used for exploratory analysis and guidance. They do not represent an exact representation of the operational control realties.

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

7.6. Scenario 1: CLASS

Scenario 1 investigates the use of CLASS as a standalone TECHNIQUE with its FUNCTION trying to achieve 95% of nominal voltage to achieve its maximum target demand reduction, the following inputs are applied:

7.6.1.Input Data:

- **Analysis Window:** The 24-hour period is used which identifies the maximum instantaneous demand between 01/04/2020-01/04/2021. This occurs on 04/01/2021.
- **Resolution:** Half-Hour
- **Load Inputs:** ENWL Historical Primary Loading data associated with this day is used.
- **Firm Generator Inputs:** Generators are switched out.
- **ANM Inputs:** Generators are switched out.
- **Technique Priority List:** CLASS
- **Tap Stagger BSP:** Off
- **NEM:** Off
- **CLASS:** On and Set to Demand Reduction Full, fully active in each half hour.
- **Smart Street:** Off
- **Flexible Connection:** Off
- **Flexible Services:** Off

7.6.2.TECHNIQUE FUNCTION LEVELS:

CLASS is trying to achieve a FUNCTION LEVEL of 100% from all primaries to achieve its target maximum demand reduction of 1 MW. Where delivery of this demand reduction target is also presented as a percentage of delivered MW reduction for example, 0.85MW demand reduction represents 85% of the demand reduction target.

7.6.3.QUEST TECHNIQUE PRIORITY LIST Methodology

With CLASS only selected, each CLASS activated primary will attempted to reduce voltage to its FUNCTION LEVE of 100% translating to a target voltage of 0.95 p.u. at the relay without exceeding statutory limits.

7.6.4. Results

In figure 2, the voltage profiles show the depressing of the secondary busbar voltage at Royton Primary to achieve the demand reduction from CLASS. This is confirmed in the time-series plot for demand, showing before the application of the voltage TECHNIQUE and after. Figure 2 also indicates the LV voltage statutory limit of -6% (0.94pu/216V).

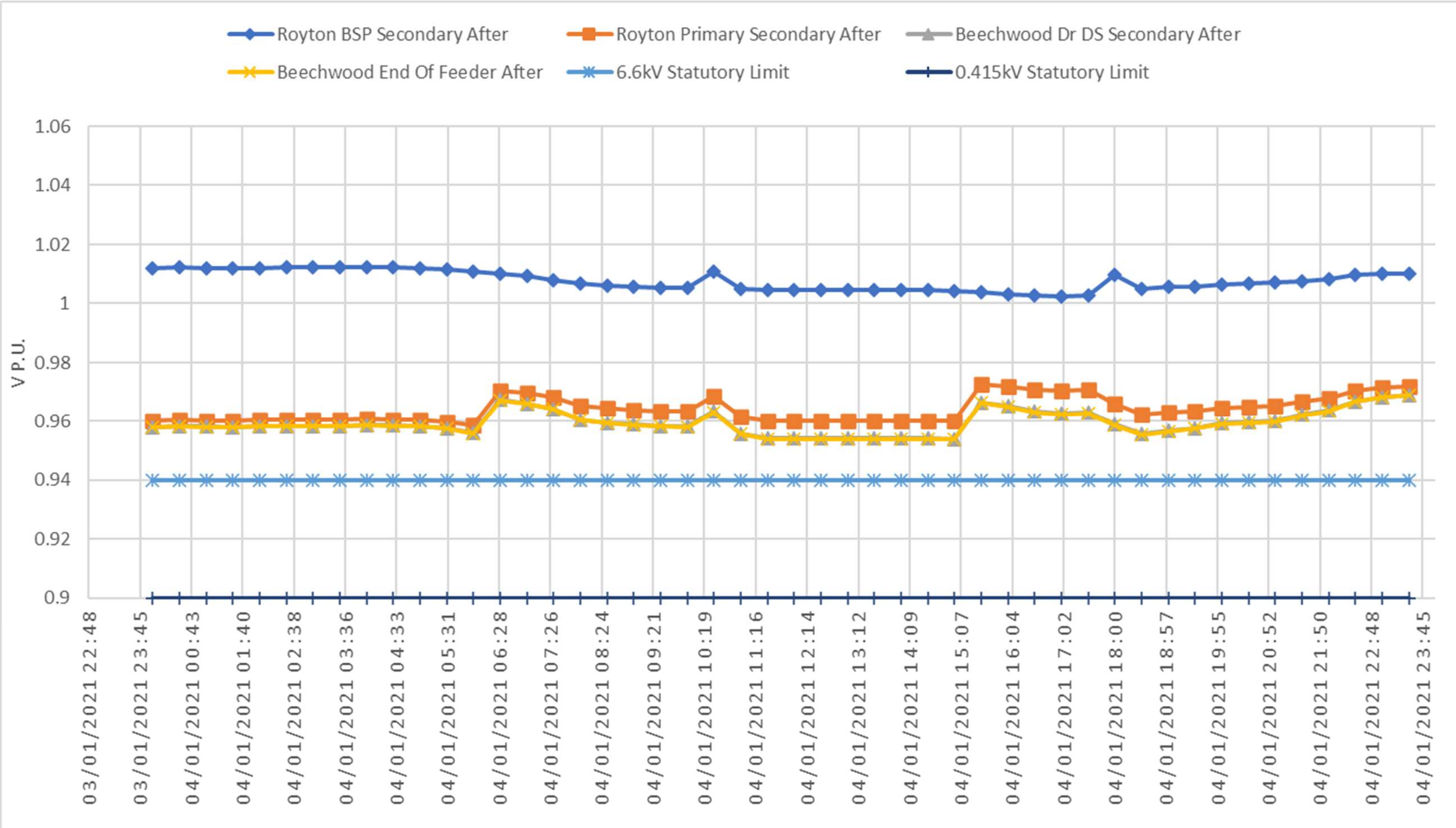

Figure 3: Scenario 1 Voltage Profiles for Selected Buses

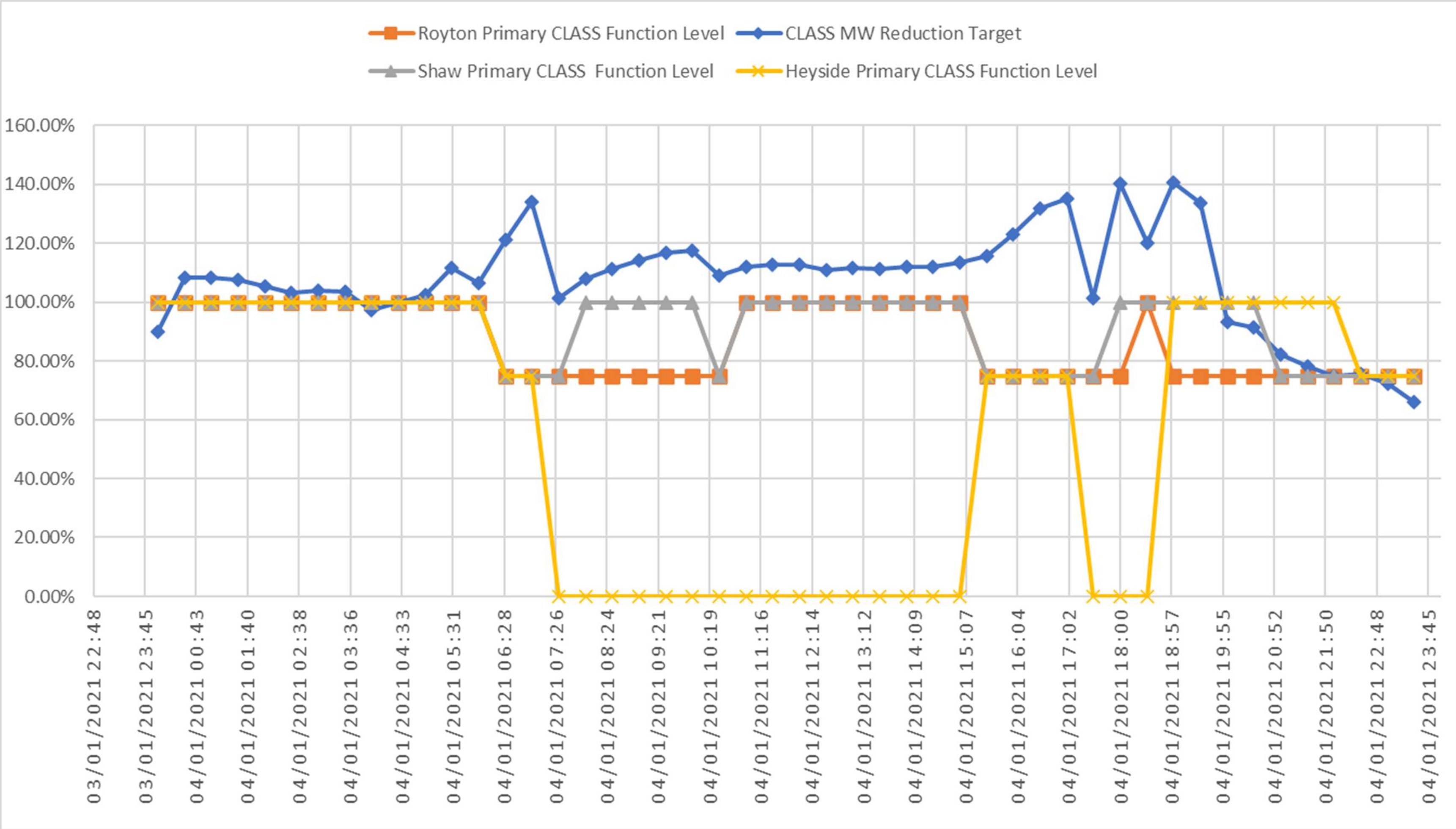

Figure 4: Scenario 1 TECHNIQUE FUNCTION LEVELs and CLASS Target Outputs

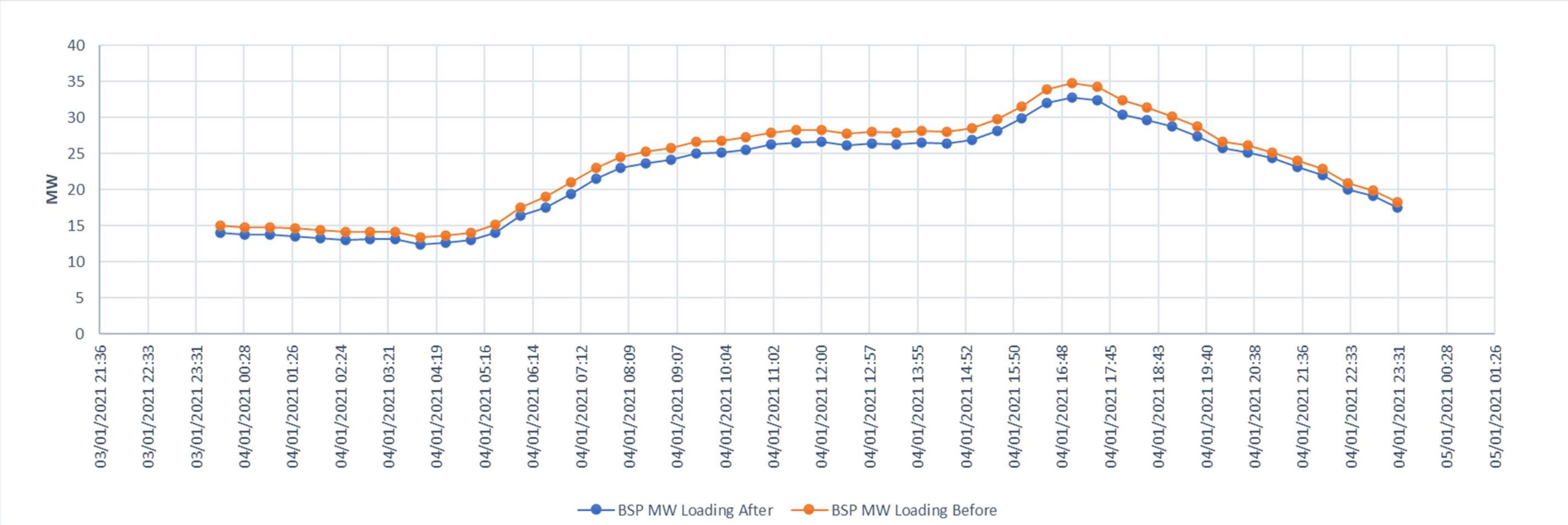

Figure 5: Scenario 1 Loading Profile for Royton BSP

7.6.5. Voltage Profile Observations

- CLASS actions successfully reduce voltage at the secondary busbar of the primary substations within statutory limits.
- The reduction in voltage successfully reduces the demand in the network.
- In some cases, the FUNCTION LEVEL cannot be achieved due to the resulting tap change potentially pushing voltage beyond its lower statutory limit. This issue could be improved by optimising the voltage p.u. target ranges that deliver the function level.

Table 5: Scenario 1: Key Performance Indicators

Key Performance Indicator	Before TECHNIQUE APPLIED	After TECHNIQUE APPLIED	Difference
System Load (MW Average)	79.06	77.983	1.08
System Generation External (MW Average)	113.50	112.42	1.08
System Generation Internal (MW Average)	0.00	0.00	0.00
33kV Losses (MW Average)	0.0753	0.0709	0.00
System Carbon (kgCO2 Average)	7849.18	7742.61	106.57

7.6.6. Thermal Flow Observations

- When the Kp relationship is stronger in the network at specific times i.e., more demand change for the same voltage change, less primary FUNCTION LEVELs need to be met, across all primaries, to achieve the CLASS MW demand reduction target of 1MW, shown as a percentage in Figure 4. When this weakens more primaries need to be used to achieve the MW demand reduction target.
- CLASS actions result in system load demand reduction, due to voltage demand reduction behaviour at the Royton BSP averaging 1.38% on the high loading day analysed. The only system demand that is experiencing a reduction is at the Royton BSP as this was the only BSP fully modelled as part of this scenario.
- If CLASS was applied across the entire operational window, yielding this demand reduction effect, this would result in a demand reduction of 1.36MW on average.
- Where external generation provides this demand, the reduction to Carbon is approximately 133.73 kgCO2 on average

7.7. Scenario 2: Network Efficiency Mode

Scenario 2 investigates the use of Network Efficiency Mode (NEM) as a standalone TECHNIQUE with its FUNCTION LEVEL trying to achieve 100% of nominal voltage increase i.e., a voltage target at the relay of 1.05 p.u to achieve its maximum target 33kV loss reduction, the following inputs are applied:

7.7.1. Input Data:

- **Analysis Window:** The 24-hour period is used which identifies the maximum instantaneous demand between 01/04/2020-01/04/2021. This occurs on 04/01/2021.
- **Resolution:** Half-Hour
- **Load Inputs:** ENWL Historical Primary Loading data associated with this day is used.
- **Firm Generator Inputs:** Generators are switched out.
- **ANM Inputs:** Generators are switched out.
- **Technique Priority List:** NEM
- **Tap Stagger BSP:** Off
- **NEM:** ON and set to 100% Nominal voltage increase target: 1.05 p.u. (Maximum 33kV loss reduction)
- **CLASS:** Off
- **Smart Street:** Off
- **Flexible Connection:** Off
- **Flexible Services:** Off

7.7.2. TECHNIQUE FUNCTION LEVEL:

NEM is trying to achieve 100% of its FUNCTION LEVEL i.e., a voltage target of 1.05 p.u. to achieve its target maximum loss reduction.

7.7.3. QUEST TECHNIQUE PRIORITY LIST Methodology

With NEM only selected, NEM BSPs (Royton only in this scenario) will attempt to raise voltage to its FUNCTION LEVEL of 100% via a voltage target setting of 1.05 p.u.

7.7.4. Results

In Figure 6, the voltage profiles show the increase in the BSP secondary voltage, confirming the correct operation of the TECHNIQUE, the resultant FUNCTION LEVEL is at the target, where the algorithm has calculated it can be achieved, without overshooting its target or statutory limits, the target is not met when either of these constraint are in danger of being violated.

The resulting FUNCTION LEVELs are shown in Figure 7.

The Royton Primary substation secondary busbar voltage sitting at just above 1 p.u due the actions of the primary substation transformer voltage control as expected.

The figure also indicates the 33kV voltage statutory limit of +6% (1.06 p.u.).

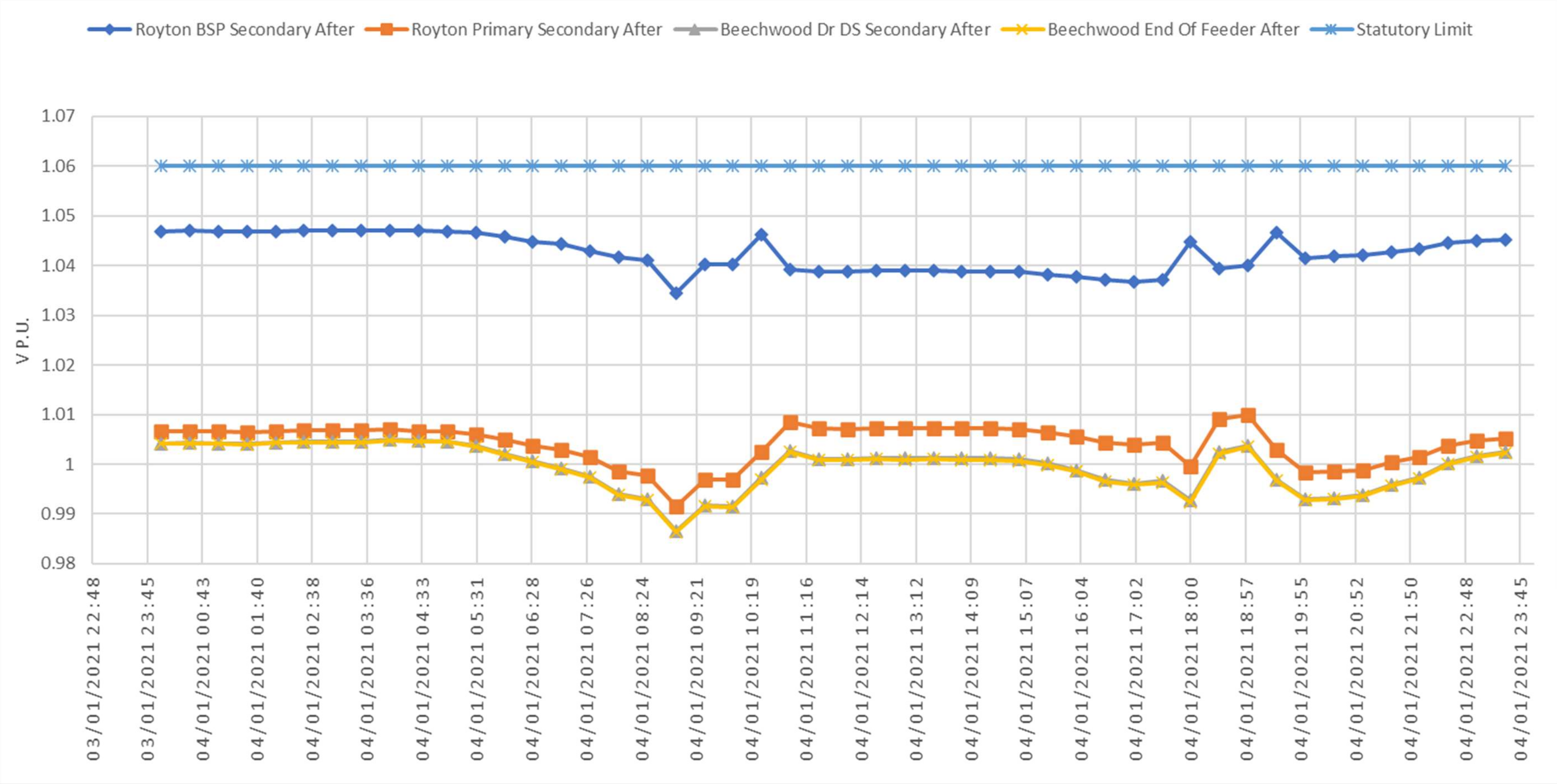

Figure 6: Scenario 2 Voltage Profiles at Selected Busbars

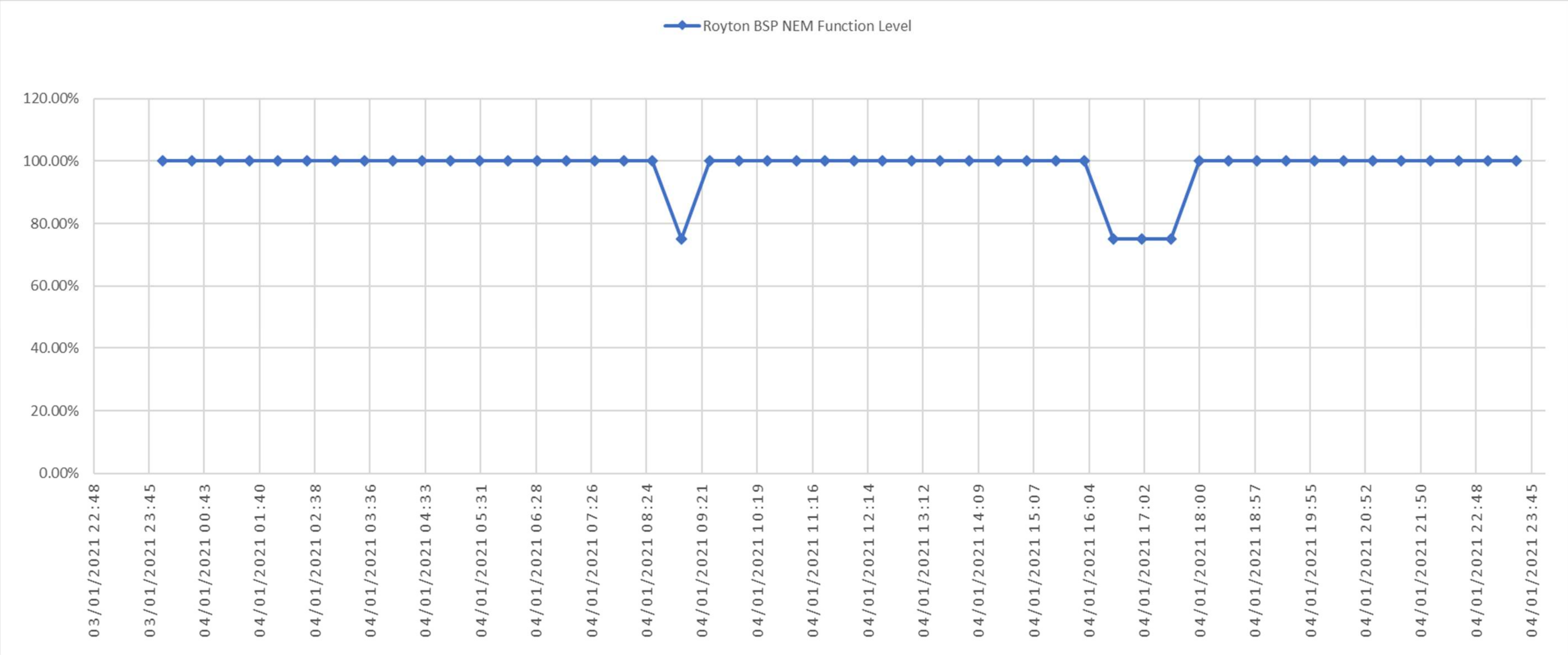

Figure 7:Scenario 2 QUEST TECHNIQUE FUNCTION LEVEL Output

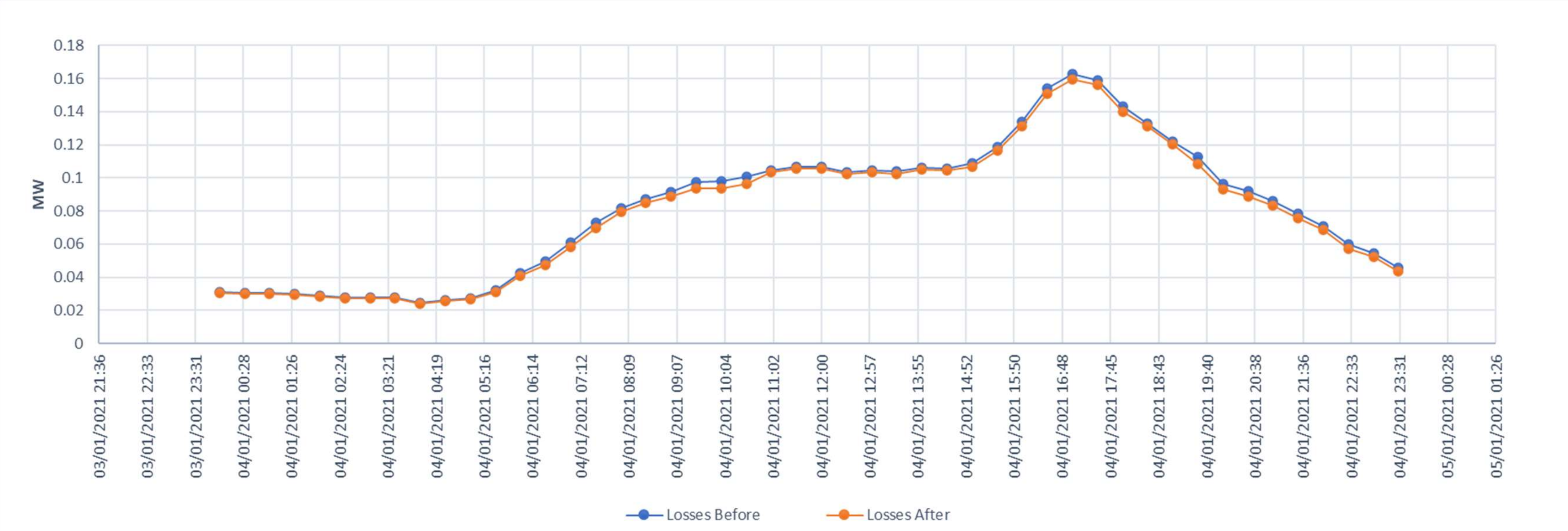

Figure 8: Scenario 2 33kV Losses

7.7.5. Voltage Profile Observations

- NEM actions successfully increase voltage at the secondary busbar of the BSP substation within statutory limits
- The increase in voltage successfully reduces the losses in the 33kV network.
- When CLASS primaries are inactive implement their default OLTC settings.

7.7.6. Thermal Flow Observations

Table 6: Scenario 2: Key Performance Indicators

Key Performance Indicator	Before TECHNIQUE APPLIED	After TECHNIQUE APPLIED	Difference
Royton BSP Load (MW Average)	79.06	79.09	-0.03
System Generation External (MW Average)	113.48	113.51	-0.03
System Generation Internal (MW Average)	0.00	0.00	0.00
33kV Losses (MW Average)	0.0812	0.0793	0.00
System Carbon (kgCO2 Average)	7849.18	7851.61	-2.43

- NEM actions result in a 33kV losses reduction of 2.45% relative to NEM not being applied on the high loading day analysed.
- However, the raising of 33kV voltage has resulted in the slight rise of voltage across the entire BSP fed 11 and 6.6kV and LV network, this has resulted in a small demand increase (0.03%) from voltage dependent loads cancelling out a very small amount of benefit of system loss reduction, noting that -this could be a result of modelling limitations.
- Where external generation provides this increased demand, there is a very small increase in Carbon of approximately 2.43 kgCO2 (0.03%) on average.

7.8. Scenario 3: Tap Stagger

Scenario 3 investigates the use of Tap Stagger (TS) as a standalone TECHNIQUE with its FUNCTION LEVEL trying to achieve 100% MVAr demand increase i.e., a separation of +/- four tap positions off substation voltage target setting, to achieve its MVAr demand increase, the following inputs are applied:

7.8.1. Input Data

- Analysis Window: The 24-hour period is used which identifies the maximum instantaneous demand between 01/04/2020-01/04/2021. This occurs on 04/01/2021.
- Resolution: Half-Hour
- Load Inputs: ENWL Historical Primary Loading data associated with this day is used.
- Firm Generator Inputs: Generators are switched out.
- ANM Inputs: Generators are switched out.
- Technique Priority List: Tap Stagger
- Tap Stagger BSP: On. Set to achieve 100% tap separation.
- NEM: Off
- CLASS: Off
- Smart Street: Off
- Flexible Connection: Off
- Flexible Services: Off

7.8.2. TECHNIQUE FUNCTION LEVEL

Tap Stagger trying to achieve a FUNCTION LEVEL of 100% MVAr demand increase i.e., a separation of +/- 4 tap positions off substation voltage target setting, to achieve its MVAr demand increase

7.8.3. QUEST TECHNIQUE PRIORITY LIST Methodology

With Tap Stagger only selected, each Tap Stagger activated BSP will attempt to provide a separation of tap positions on its pair of taps changing transformers. This tap position separation creates a circulating current between the transformer tap pair which interacts with their leakage reactance, increasing MVAr demand.

7.8.4. Results

In Figure 9, the graph shows the behaviour of the voltage profiles due to OLTC control only, influenced by the effect of Tap Stagger caused by tap separation at the BSP. To achieve this the settings of Royton BSP Grid transformers, sit at 6.68% and -6.68%, an 8-tap step separation .

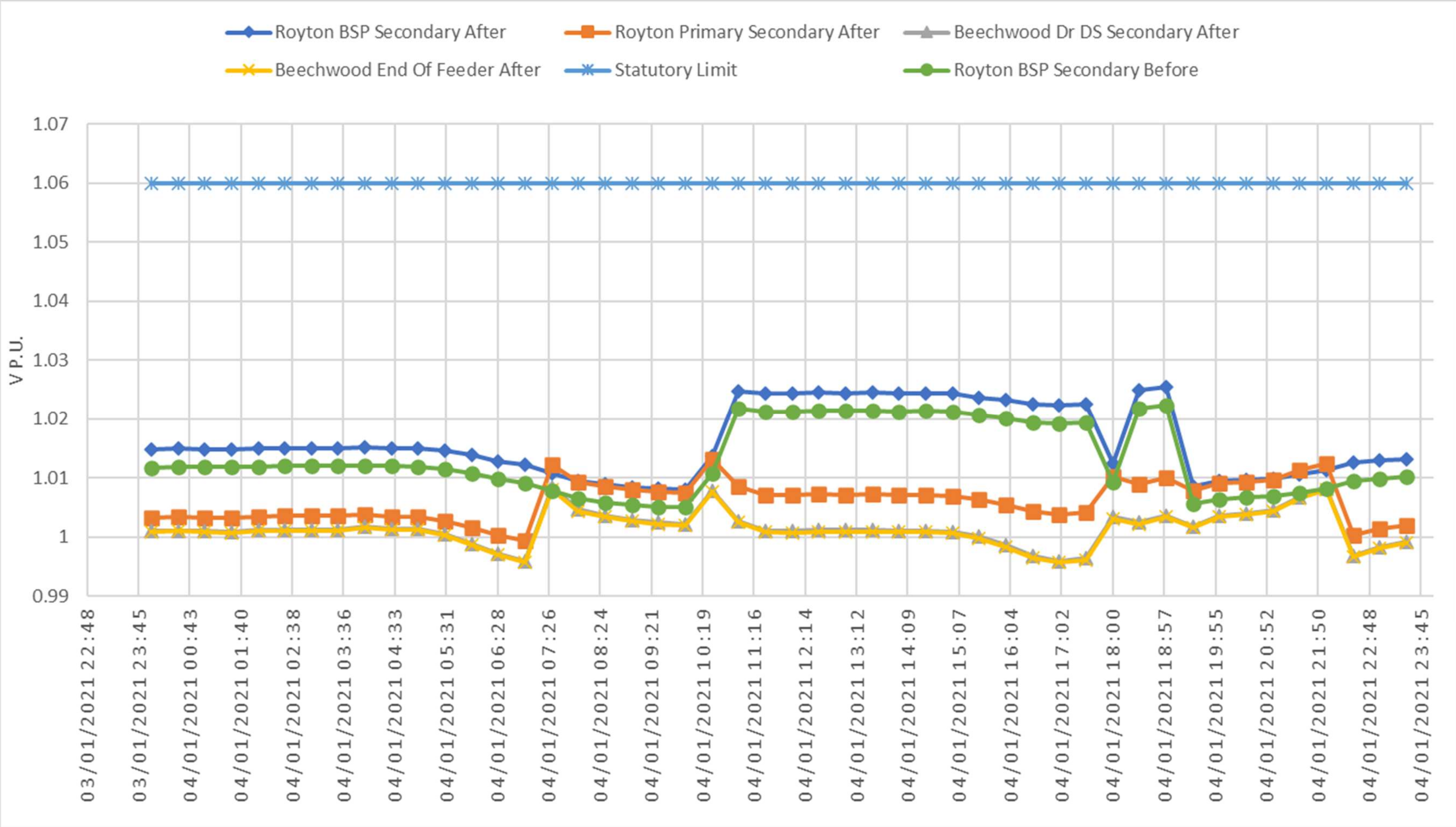

Figure 9: Scenario 3 Voltage Profiles at Selected Busbars

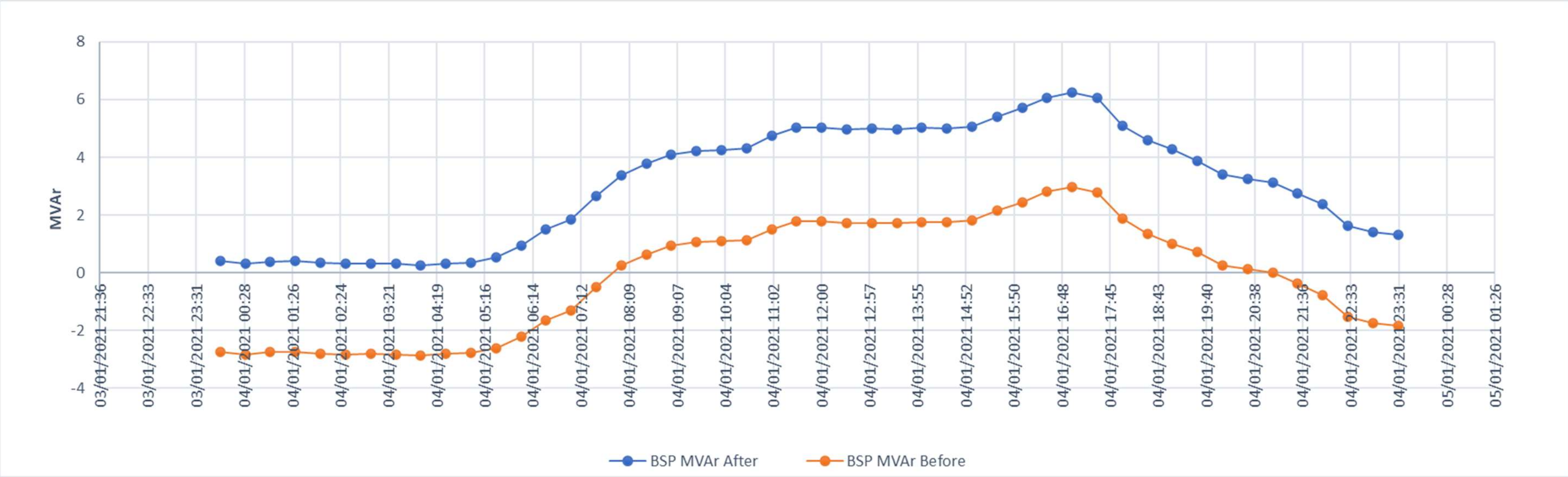

Figure 10: Scenario 3 MVAr Demand Increase at Royton BSP

7.8.5. Voltage Profile Observations

- Tap Stagger actions slightly raise the secondary voltage of the BSP, this will cause a rise in demand due to voltage dependent relationships.
- Tap Stagger creates a circulating current demand that increased MVAr demand at the BSP substation.
- Voltage drops due to demand changes through the day cause the Primary substation OLTC dead band to be exceeded before the BSP, resulting in a minor period where the Primary Secondary Busbar voltage is higher than the BSP secondary voltage in p.u. terms.
- Historical demand show MVAr export is greater in the early hours of the morning for this time of year.

7.8.6. Thermal Flow Observations

Table 7: Scenario 3: Key Performance Indicators

Key Performance Indicator	Before TECHNIQUE APPLIED	After TECHNIQUE APPLIED	Difference
System Load (MW Average)	79.06	79.15	-0.10
BSP Load (MVAr Average)	-0.12	2.99	-3.12
System Generation External (MW Average)	113.48	113.67	-0.18
System Generation Internal (MW Average)	0.00	0.00	0.00
33kV Losses (MW Average)	0.0838	0.1947	-0.11
System Carbon (kgCO2 Average)	7849.18	7859.27	-10.09

- Tap Stagger actions result in average MVAr demand at the BSP increasing by 3.12 MVAr.
- However, the tap stagger causes a slight rise of voltage across the entire BSP, this has resulted in a demand increase from voltage dependent load, shown by the system load increase.
- Furthermore, system losses are increased, coupled with the slight demand increase. The net demand increase results in a marginal increase in carbon emission of 10.09kgCO2.
- Although more carbon emissions have been created, the benefit this service provides to the ESO avoids the need for the addition of new equipment, such as STACOMs.

7.9. Scenario 4: Smart Street

Scenario 4 investigates the use of Smart Street (SMST) as a standalone TECHNIQUE with its FUNCTION LEVEL trying to achieve 100% demand reduction i.e., 0.95 p.u (228V) nominal LV voltage. The following inputs are applied:

7.9.1. Input Data

- Analysis Window: The 24-hour period is used which identifies the maximum instantaneous demand between 01/04/2020-01/04/2021. This occurs on 04/01/2021.
- Resolution: Half-Hour
- Load Inputs: ENWL Historical Primary Loading data associated with this day is used.
- Firm Generator Inputs: Generators are switched out.
- ANM Inputs: Generators are switched out.
- Technique Priority List: Smart Street
- Tap Stagger BSP: Off
- NEM: Off
- CLASS: Off
- Smart Street: Set to 100% demand reduction achieved via a 0.95 p.u. target LV voltage.
- Flexible Connection: Off
- Flexible Services: Off

7.9.2. TECHNIQUE FUNCTION LEVEL

Smart Street trying to achieve 100% its FUNCTION LEVEL to achieve maximum demand decrease this results in a 0.95 nominal (228V) LV voltage target at the relay, to achieve its MW demand reduction.

7.9.3. QUEST TECHNIQUE PRIORITY LIST Methodology

With Smart Street only selected, each Smart Street activated Distribution Substation will attempt to depress voltage of the secondary bus bar, targeting 0.95 p.u. (228V), this will result in demand reducing where a voltage-demand relationship exists.

7.9.4. Results

In the figure, the voltage profiles show the depressing on the secondary busbar at Beechwood Drive to achieve the demand reduction from Smart Street, this is confirmed in the time-series plot for demand, showing before the application of the voltage TECHNIQUE and after. The figure also indicates the LV voltage statutory limit of -6% at 230V which is 0.9 p.u. at 240V base under which the model is constructed.

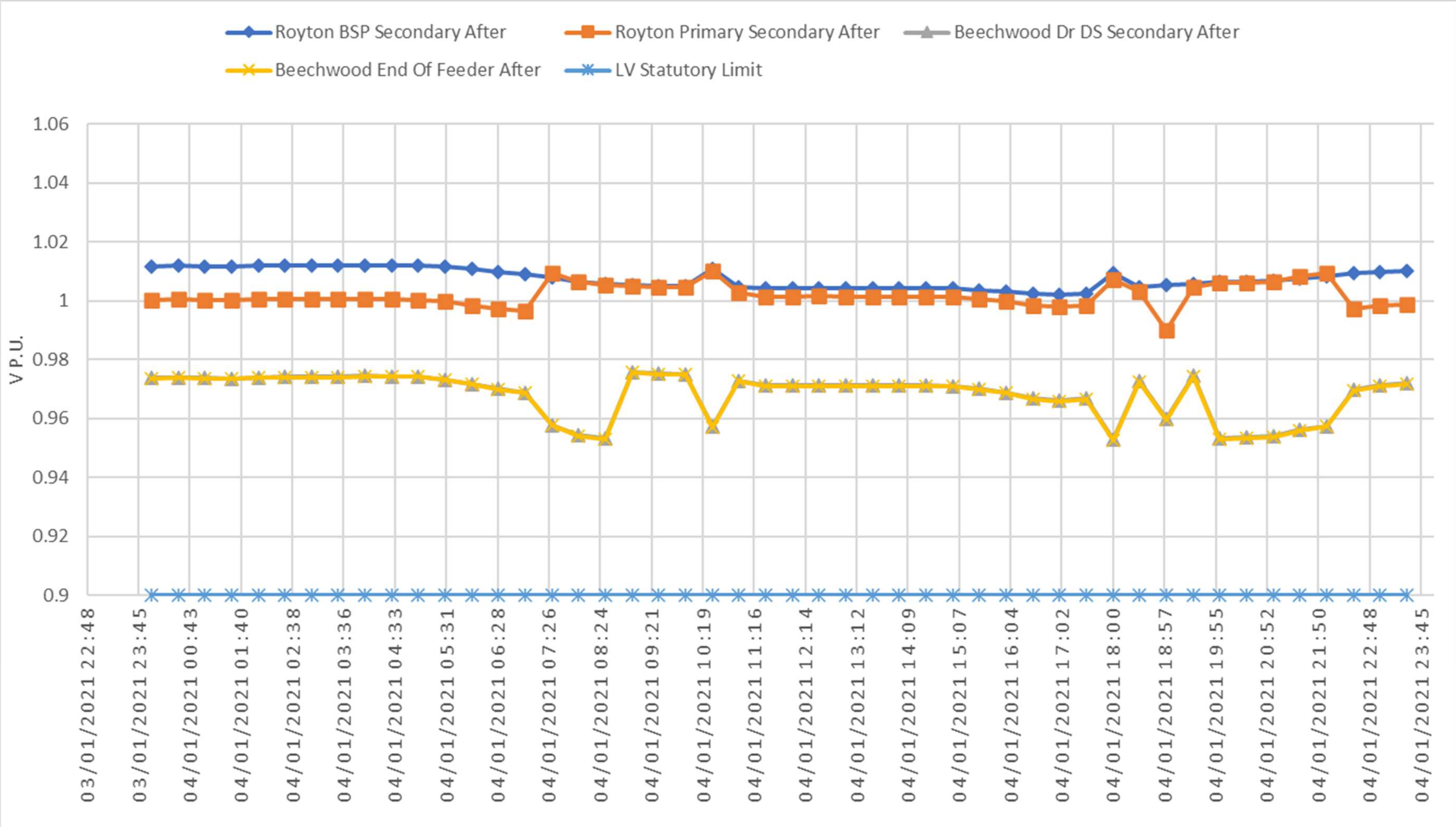

Figure 11: Scenario 4 Voltage Profiles at selected Busbars

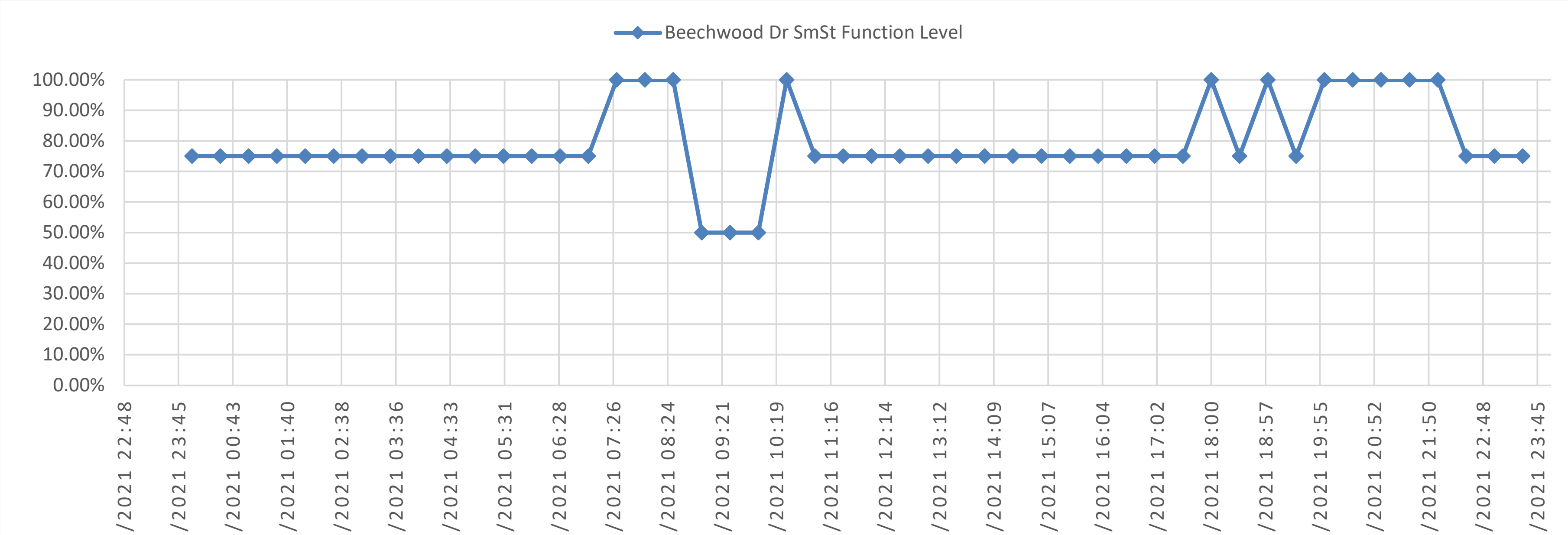

Figure 12: Scenario 4 TECHNIQUE FUNCTION LEVEL Outputs (Beechwood Drive)

Figure 13: Scenario 4 Demand Decrease (Beechwood Dr Distribution Transformer).

7.9.5. Voltage Profile Observations

- Smart Street depresses the voltage (without going out of statutory limits) and causes a reduction in demand due to the voltage demand relationship.
- This is shown in the figure where the demand is reduced due to the voltage depression at the distribution transformers where Smart Street CVR mode is applied.
- Due to the large percentage changes on the Smart Street OLTC 2.5% per tap, exceeding 100% of the target is easily done, therefore, to ensure that does not occur, the result is often far away from the target as illustrated in Figure 12. It is noted that only the influence of changing the Smart Street transformer taps is considered in the Smart Street CVR model, other Smart Street elements such as capacitors and LV meshing are not

modelled. Furthermore, the p.u. target voltage definition used in the model (0.95p.u./228V) could also be lowered, taking due consideration of the statutory voltage limits at this voltage level, to get more from Smart Street.

7.9.6. Thermal Flow Observations

Table 8: Scenario 4 Key Performance Indicators

Key Performance Indicator	Before TECHNIQUE APPLIED	After TECHNIQUE APPLIED	Difference
System Load (MW Average)	79.06	79.00	0.06
System Generation External (MW Average)	113.50	113.44	0.06
System Generation Internal (MW Average)	0.00	0.00	0.00
33kV Losses (MW Average)	0.0847	0.0844	0.00
System Carbon (kgCO2 Average)	7849.18	7842.86	6.32

- In this scenario, Smart Street is applied to 16 distribution substation and has reduced system demand by 0.06MW, however, in this example smart street is only applied to every substation along two primary substation feeders at Royton Primary only, so its effects are relative to the load influenced by Smart Street CVR.
- This output does show that Smart Street reduces demand and carbon, creating a reduction of 6.32kgCO2 for this period of analysis.
- Expanding Smart Street to more feeders would result in a greater impact to demand reduction.

It should be noted that while the Smart Street FUNCTION LEVELs stated in section 4.1 reflected the FUNCTION LEVELs in the QUEST design on delivery of the sub-phase 2 report [3], the reality is that present Smart Street transformers only have three tap steps to reduce voltage below the nominal tap setting, each tap step being 2.5% of nominal voltage-now included in the final functional design specification [4]. This would equate to Smart Street FUNCTION LEVELS of 100% with a 0.925 p.u. voltage target; 66% with a 0.95 p.u. voltage target and 33% with a 0.975 p.u. voltage target. While this does not impact the conclusions of the scenario studies carried out, this issue should be resolved, and any revised studies carried out during the QUEST trial phase to reflect the final agreed Smart Street FUNCTION LEVELS. This applies the other scenarios reported in the following sections that involve Smart Street.

7.10. Scenario 5: CLASS & Smart Street

Scenario 5 investigates the use of CLASS with Smart Street (SMST) as combined TECHNIQUEs with both FUNCTIONs trying to achieve 100% demand reduction i.e., 0.95 p.u nominal voltage (primary substation secondary voltages and LV system voltages). The following inputs are applied:

7.10.1. Input Data:

- Analysis Window: The 24-hour period is used which identifies the maximum instantaneous demand between 01/04/2020-01/04/2021. This occurs on 04/01/2021.
- Resolution: Half-Hour
- Load Inputs: ENWL Historical Primary Loading data associated with this day is used.
- Firm Generator Inputs: Generators are switched out.
- ANM Inputs: Generators are switched out.
- Technique Priority List: CLASS>Smart Street
- Tap Stagger BSP: Off
- NEM: Off
- CLASS: Set to 100% demand reduction achieved via a 0.95 p.u. target voltage.
- Smart Street: Set to 100% demand reduction achieved via a 0.95 p.u. target voltage.
- Flexible Connection: Off
- Flexible Services: Off

7.10.2. TECHNIQUE FUNCTION LEVEL:

CLASS is trying to achieve a MW demand reduction of 1.75MW by applying a FUNCTION LEVEL of 100%, at each primary. Smart Street is trying to maximise conservation of voltage by applying a FUNCTION LEVEL of 100%.

7.10.3. QUEST Control and Coordination Test Bench Regime Methodology

With CLASS taking priority over Smart Street, CLASS FUNCTION LEVELs are set first, then Smart Street achieves what it can without interfering with the CLASS FUNCTION LEVELs delivering the demand reduction target.

7.10.4. Results

In Figure 14, the voltage profiles show the depressing on the secondary busbar at Royton Primary to achieve the demand reduction from CLASS, this is confirmed in the time-series plot for demand, showing the application of the voltage TECHNIQUE and its effect on voltage after its application.

Smart Street depresses voltages across each distribution transformer, the Beechwood Distribution secondary is shown to highlight this, furthermore, the Beechwood End of Feeder voltage is used to confirm compliance of the statutory limit.

The figure also indicates the LV voltage statutory limit of (0.9p.u., 216V on a 240v p.u. base) and the 33kV statutory limit of 1.06 p.u.

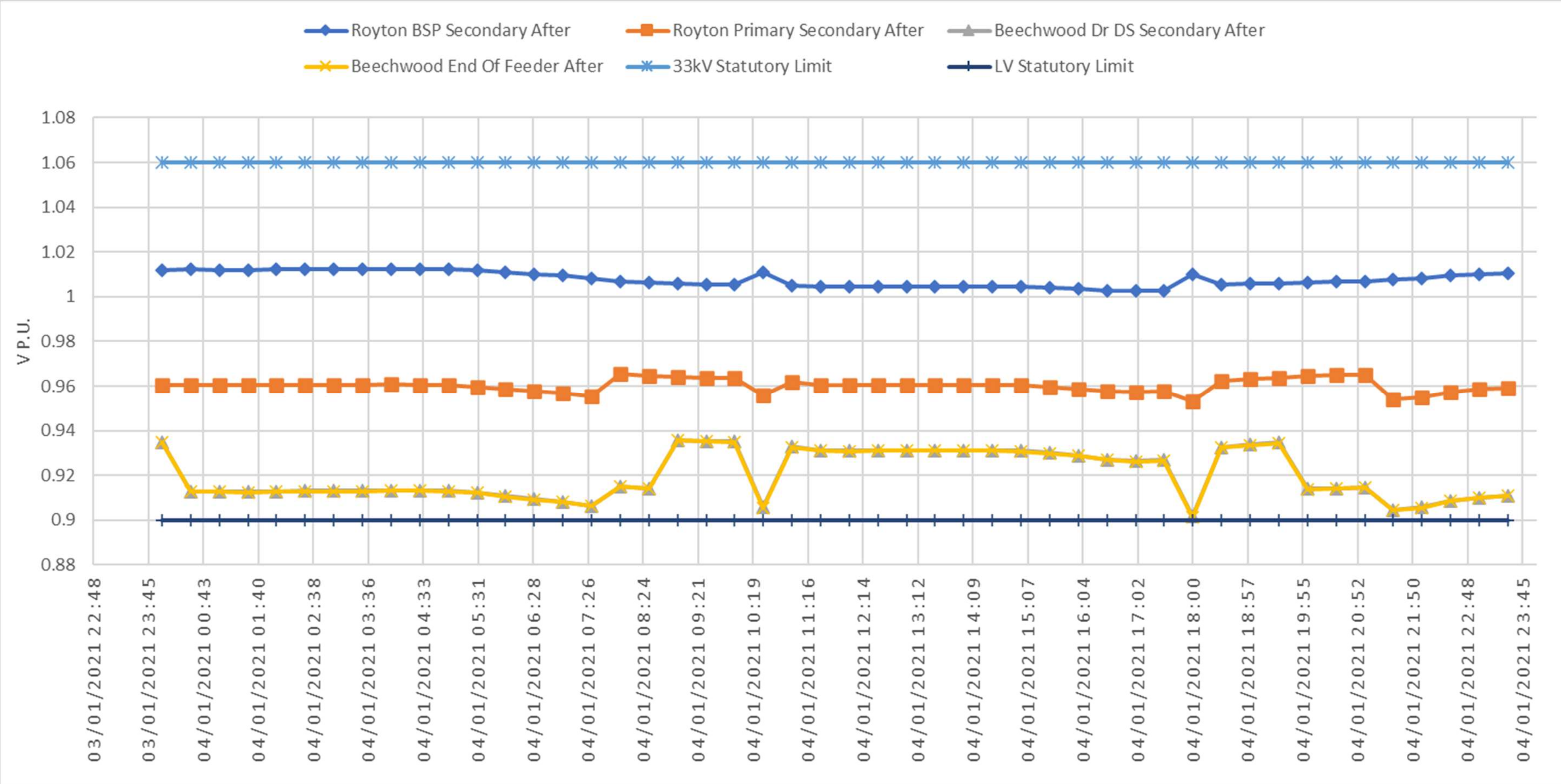

Figure 14: Scenario 5 Voltage Profiles at Selected Busbars

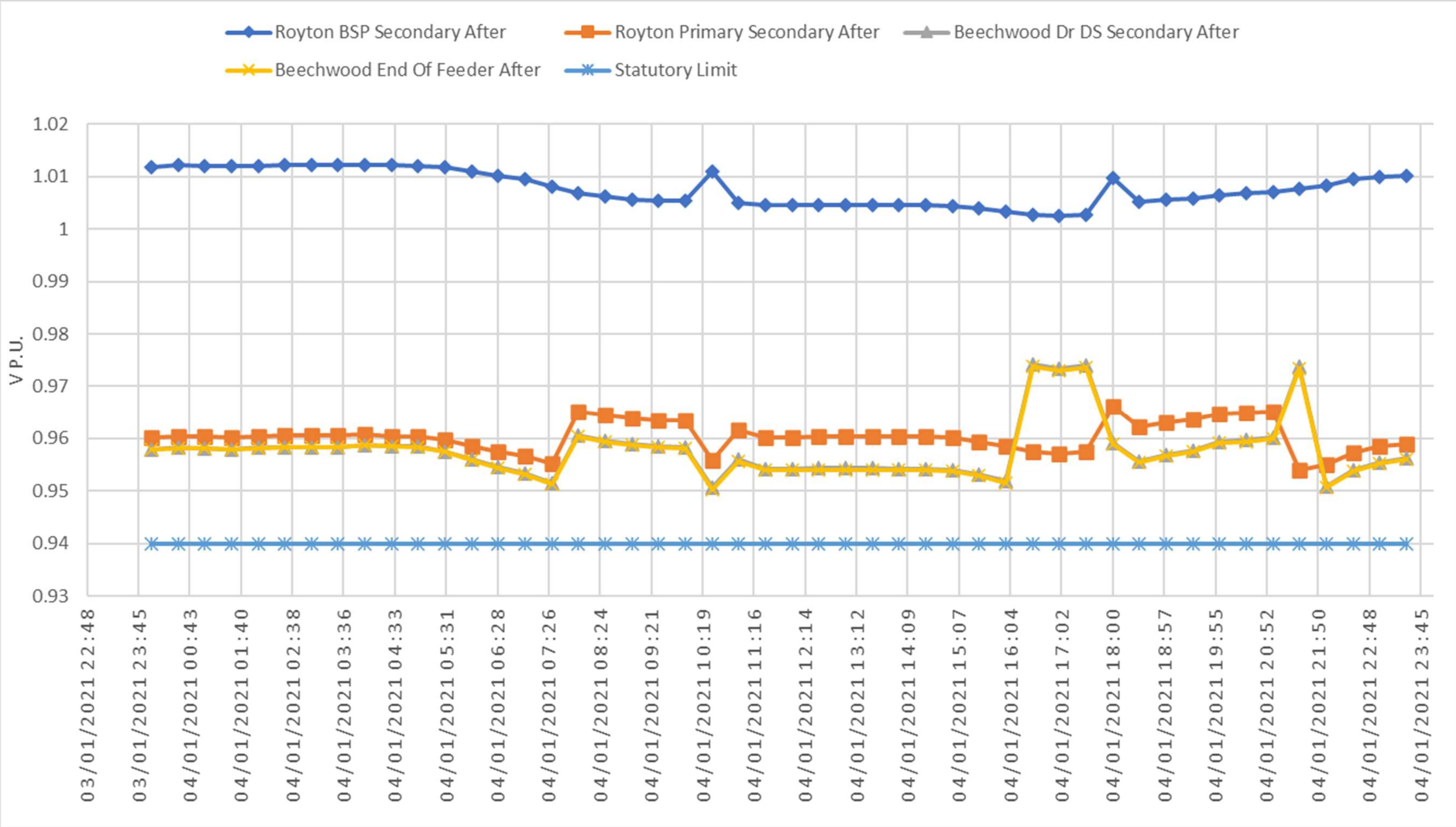

Figure 15: Scenario 5 Voltage Profiles at Selected Busbars

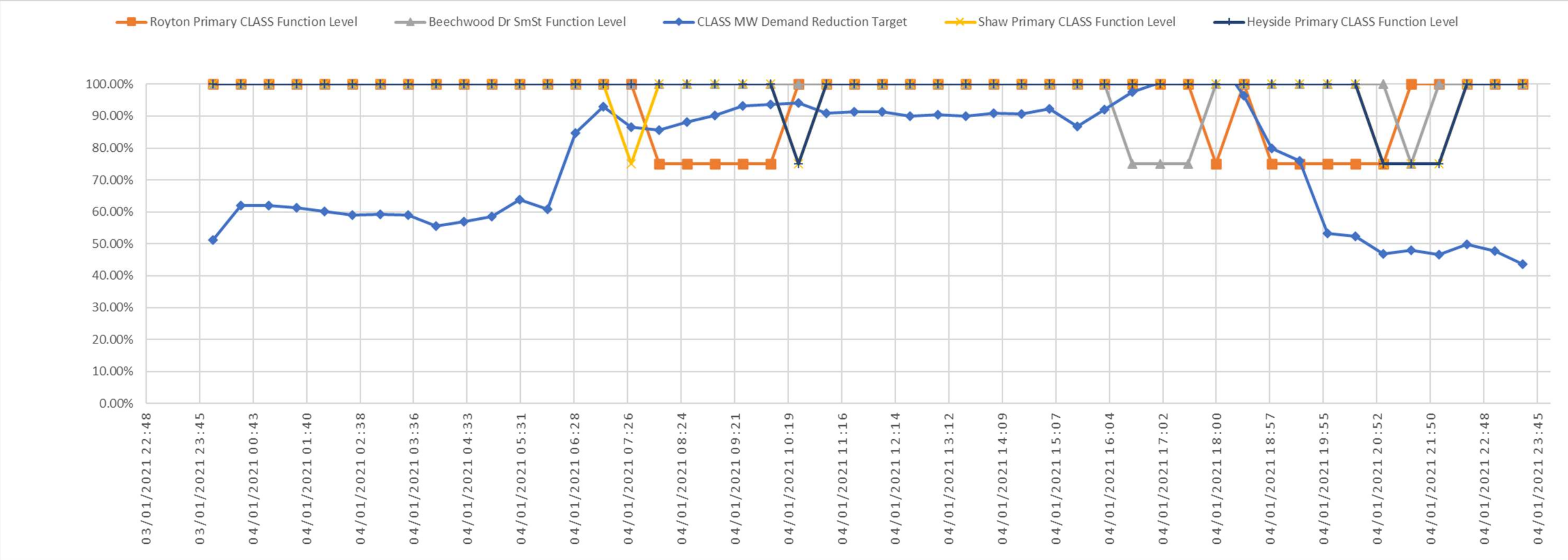

Figure 16: Scenario 5 QUEST TECHNIQUE FUNCTION LEVEL Outputs

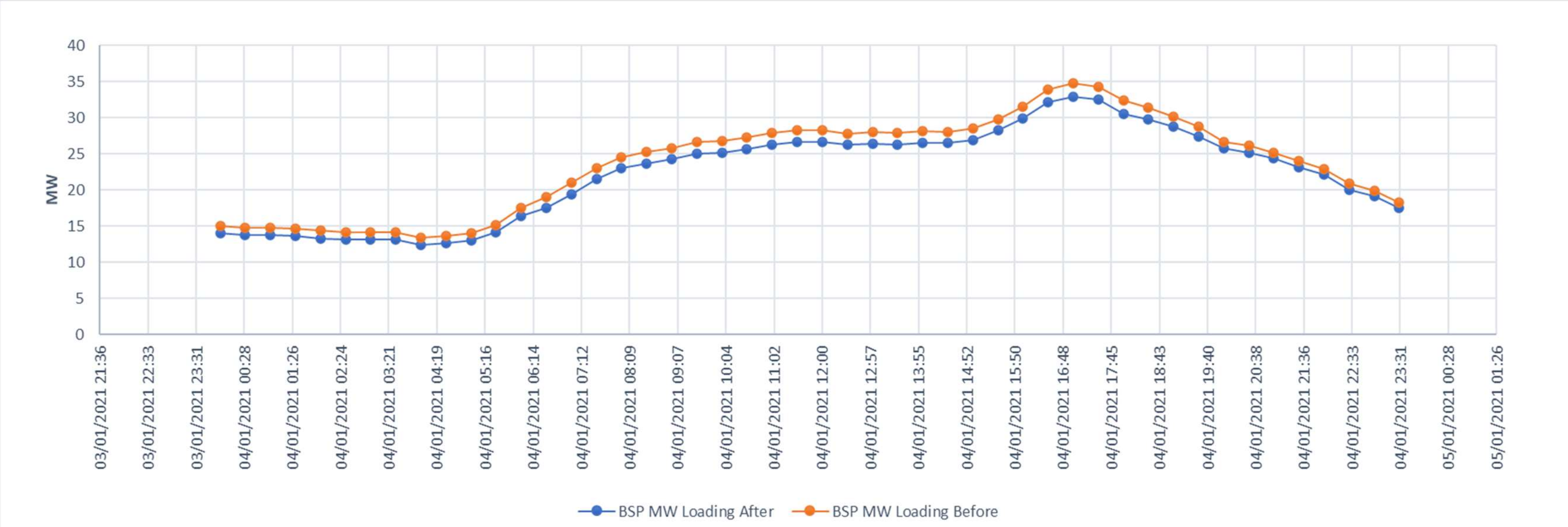

Figure 17: Scenario 5 Demand Decrease Applied (coordinated by QUEST)

7.10.5. Voltage Profile Observations

- In Figure 14, CLASS depresses the voltage (without going out of statutory limits) to cause a reduction in demand due to the voltage demand relationship, at the primary's secondary bus bar. However, this is at a cost of Smart Street potentially going outside statutory limits if CLASS and Smart Street actions are left uncoordinated. The Smart Street controller would recover the voltages in time, but Figure 14 is used here to show that the LV voltage gets too close to a statutory violation for comfort, since this approximates the actual demand and operationally could be in violation, without coordination of CLASS and Smart Street. If a Smart Street 100% Function Level target voltage of 0.925 p.u. was applied (still to be clarified with the QUEST partners as discussed earlier), the statutory LV voltage limit would be violated without QUEST coordination.
- In Figure 15, QUEST makes CLASS and Smart Street aware of each other's objectives, in this case CLASS takes priority to achieve its objectives, moving to tap positions that achieve close to 100% of its target without violating limits, after which QUEST calculates what target Smart Street can achieve within these constraints and moving its taps accordingly. This has resulted in some cases, hours 16:00-18:00 Smart Street moving to

a relatively high tap position, as the discrete nature of the tap, and the relatively low voltage fixed by the primary substation transformers, means this Smart Street target is as close as it can get without risking statutory limit LV voltage violations.

7.10.6. Thermal Flow Observations

Table 9: Scenario 5 Key Performance Indicators

Key Performance Indicator	Before TECHNIQUE APPLIED	After TECHNIQUE APPLIED	Difference
Royton BSP Load (MW Average)	79.06	77.74	1.32
System Generation External (MW Average)	113.50	112.15	1.35
System Generation Internal (MW Average)	0.00	0.00	0.00
33kV Losses (MW Average)	0.0846	0.0787	0.01
System Carbon (kgCO2 Average)	7849.18	7713.96	135.22

- Due to the altering Kp Values, only when the voltage-demand relationship is relatively stronger can CLASS meet its demand reduction target, set to 1.75MW for the scenario, this requires all primaries achieving a FUNCTION LEVEL of 100% where physically possible i.e., a further tap step won't exceed statutory limits.
- CLASS and Smart Street both try and depress voltages to achieve demand reduction while maintaining LV voltages within statutory limits, and this is shown to be achieved while reducing system demand by 1.7%. Due to reduced demand, the 33kV losses have also reduced. Comparing with Scenario 1 (CLASS only) and Scenario 4 (Smart Street only), the majority of demand reduction results from the CLASS action which has priority over Smart Street. However, Smart Street customer benefits will still be delivered but due to the CLASS voltage reduction applied rather than Smart Street actions. Therefore, when CLASS is operating, to ensure the safe operation of Smart Street, it may not be achieving its full potential.
- Both these reductions to demand and losses results in a reduction in external generation reducing carbon, creating a reduction of 135.22kgCO2 for this period of analysis.

7.11. Scenario 6: CLASS & Smart Street & NEM

Scenario 6 investigates the use of CLASS with Smart Street (SMST) and Network Efficiency Mode as a combined TECHNIQUE with all three FUNCTION LEVLES trying to achieve 100% service delivery. CLASS and Smart Street full demand reduction i.e., 0.95 p.u nominal voltage target at its relays and NEM 33kV system voltage increase of 1.05pu. voltage target at its relay. The following inputs are applied:

7.11.1. Input Data

- Analysis Window: The 24-hour period is used which identifies the maximum instantaneous demand between 01/04/2020-01/04/2021. This occurs on 04/01/2021.
- Resolution: Half-Hour
- Load Inputs: ENWL Historical Primary Loading data associated with this day is used.
- Firm Generator Inputs: Generators are switched out.
- ANM Inputs: Generators are switched out.
- Technique Priority List: CLASS>Smart Street>NEM
- Tap Stagger BSP: Off
- NEM: Set to 100% demand reduction achieving a 1.05 p.u. target voltage.
- CLASS: Set to 100% demand reduction achieve via a 0.95 p.u. target voltage.
- Smart Street: Set to 100% demand reduction achieve via a 0.95 p.u. target voltage.
- Flexible Connection: Off
- Flexible Services: Off

7.11.2. TECHNIQUE FUNCTION LEVEL

Both CLASS and Smart Street trying to achieve 100% demand decrease i.e., 0.95 p.u. nominal voltage, to achieve the MW demand decrease. NEM is trying to achieve a 1.05 p.u. nominal 33kV voltage to reduce the 33kV network current flows and hence reduce 33kV system resistive losses.

7.11.3. QUEST Control and Coordination Test Bench Regime Methodology

With CLASS taking priority over Smart Street and NEM, CLASS FUNCTION LEVELs are set first, then Smart Street achieves what it can without interfering with the CLASS FUCNTION LEVELs. Finally, NEM achieves as close to its FUCNTION LEVEL without affecting either CLASS or Smart Street.

7.11.4. Results

In the figure, the voltage profiles show the depressing on the secondary busbar at Royton Primary to achieve the demand reduction from CLASS, this is confirmed in the time-series plot for demand, showing before the application of the voltage TECHNIQUE and after.

Smart Street depresses voltages across each distribution transformer, the Beechwood Distribution secondary is shown to highlight this, furthermore, the Beechwood End of feeder voltage is used to confirm compliance with the statutory LV voltage limit.

Network efficiency mode is raising voltage on the 33kV network to reduce losses.

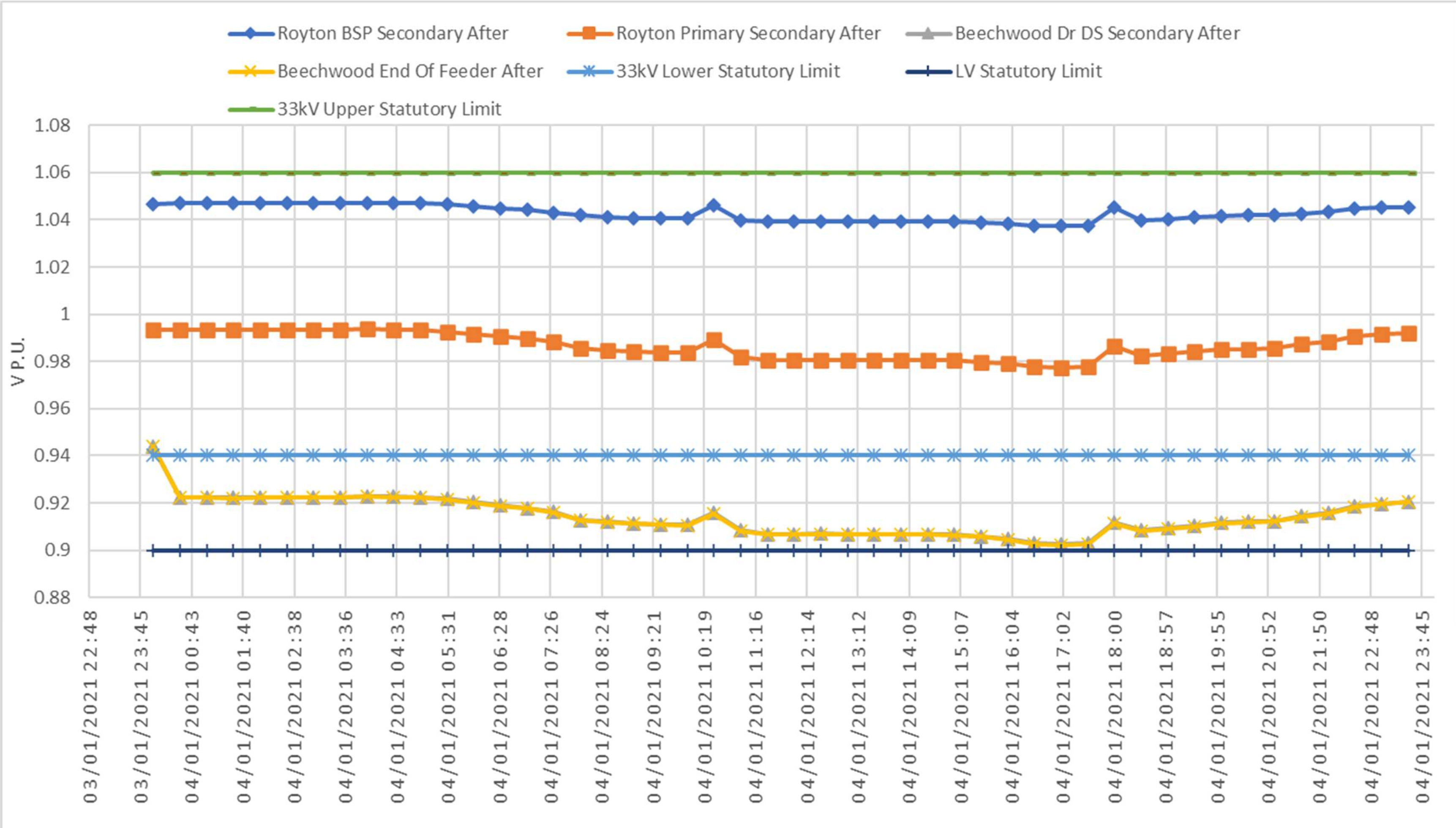

Figure 18: Scenario 6 Voltage Profiles at Selected Bus Bars (Uncoordinated)

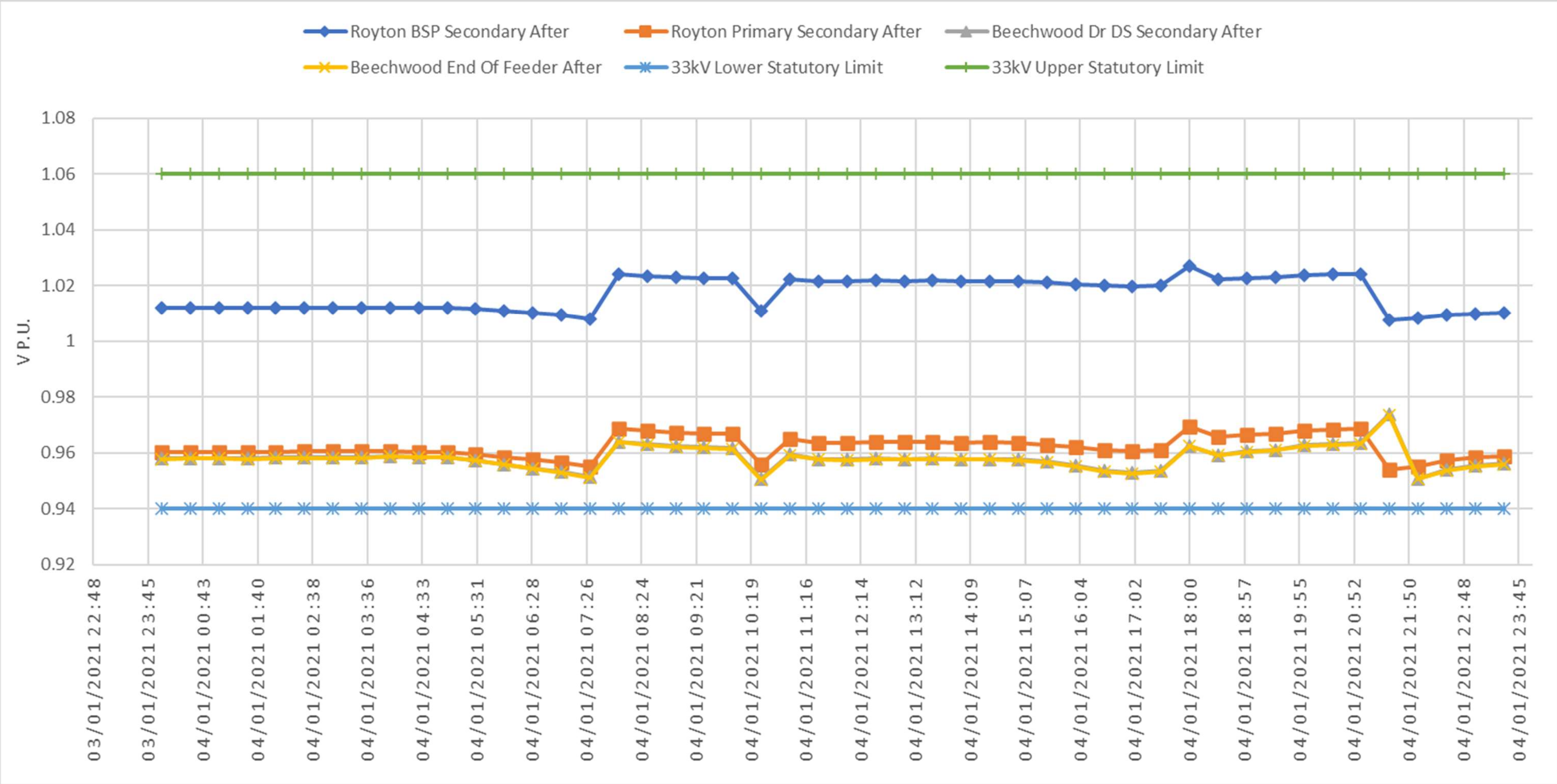

Figure 19: Scenario 6 Voltage Profiles at Selected Bus Bars (Coordinated)

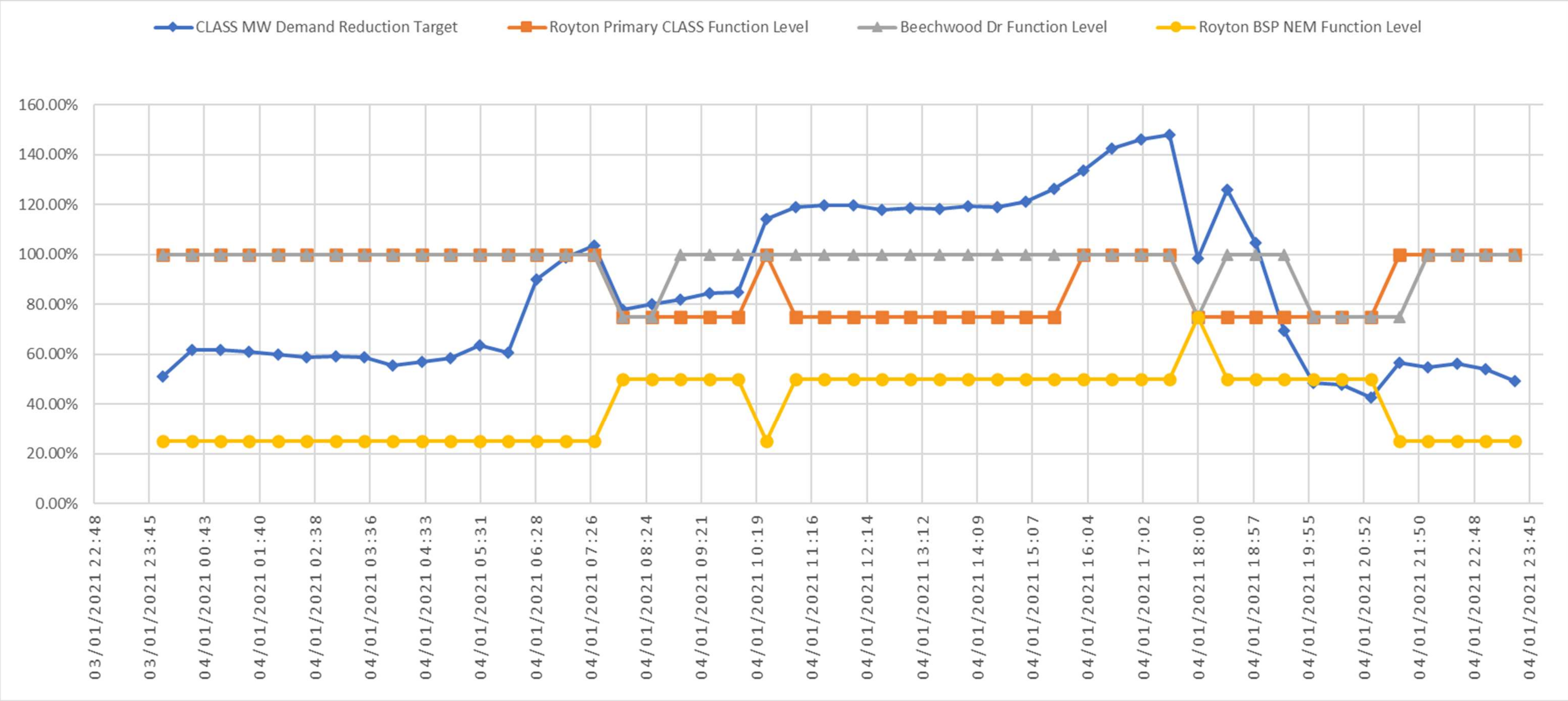

Figure 20: Scenario 6 TECHNIQUE FUNCTION LEVEL Outputs

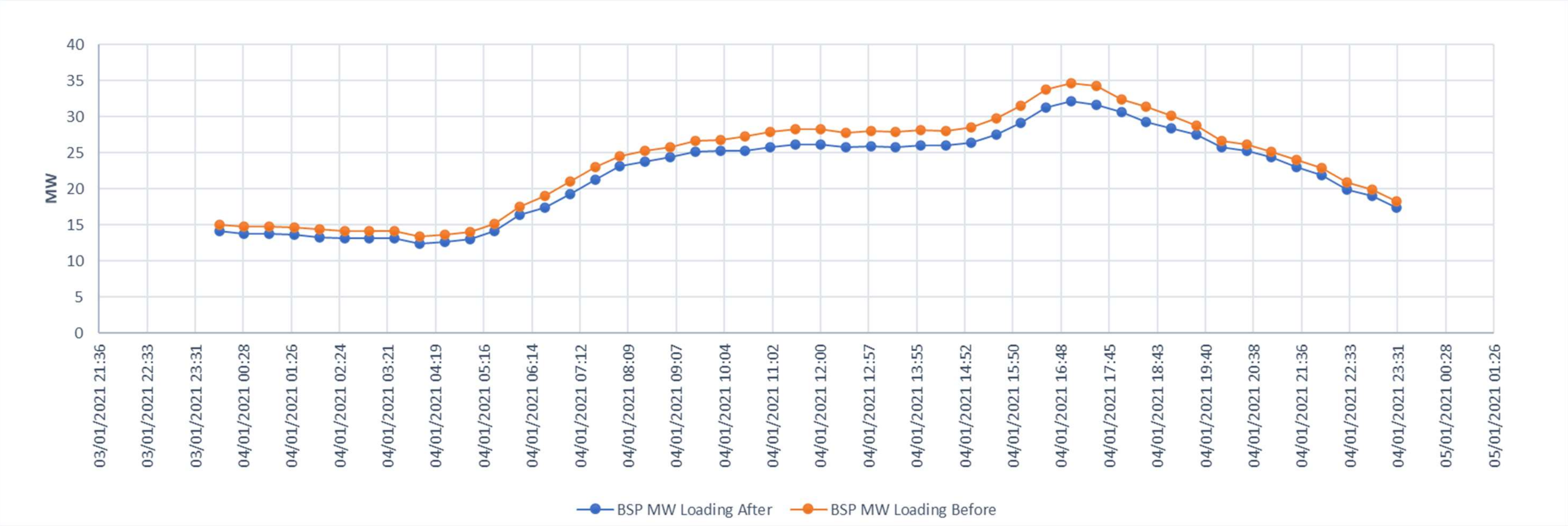

Figure 21: Scenario 6 Demand decrease

7.11.5. Voltage Profile Observations

- In Figure 18, the uncoordinated response of each TECHNIQUE results in multiple issues for each individual technique:
  - The high-voltage technique (NEM) dominates raising voltages for all lower control methodologies
  - CLASS can only respond to this by reducing its voltage to its highest tap position, which leaves it far off its target voltage of 0.95pu.
  - Smart Street's target is applied in advance of CLASS tap adjustments, which results in LV voltages dropping close to the statutory limits when CLASS demand reduction full is applied, until the Smart Street OLTC at the distribution transformer responds (disabled in this example to show the impact of uncoordinated actions).
- In Figure 19 QUEST coordinates the TECHNIQUES as established by the TECHNIQUE PRIORTY LIST (CLASS>Smart Street>NEM):
  - CLASS's FUNCTION LEVEL is achieved, within statutory limits.
  - Smart Street then achieves what is can within the low voltage statutory limits.

- QUEST then determines what NEM can achieve by altering the NEM target to the highest voltage whilst holding CLASS at the lowest target voltage.

- Figure 19 illustrates the percentage level of CLASS, Smart Street and NEM achieved through the QUEST coordination.

7.11.6. Thermal Flow Observations

Table 10: Scenario 6-Key Performance Indicators

Key Performance Indicator	Before TECHNIQUE APPLIED	After TECHNIQUE APPLIED	Difference
System Load (MW Average)	79.06	77.54	1.52
System Generation External (MW Average)	113.48	111.89	1.59
System Generation Internal (MW Average)	0.00	0.00	0.00
33kV Losses (MW Average)	0.0831	0.0761	0.01
System Carbon (kgCO2 Average)	7849.18	7690.87	158.31

- By coordinating all TECHNIQUEs, the total objective benefits from CLASS are experienced, and demand has reduced, furthermore system losses have reduced, achieving the goal of the TECHNIQUES.
- Due to the altering Kp Values, only when the voltage-demand relationship is relatively stronger can CLASS meet its demand reduction target, set to 1.75MW for the scenario, this requires all primaries achieving a FUNCTION LEVEL of 100% where physically possible i.e., a further tap step won't exceed statutory voltage limits.
- Interestingly, the rise of the 33kV network voltage results in more favourable lower voltage targets to be achieved, in some instances, compared with the CLASS (Scenario 1) the CLASS and Smart Street (Scenario 5) example. Hence the increase in demand reduction compared with these examples. This is due to the primary substation and Smart Street tap positions, that would have caused statutory limit violation before now being achievable due to the raised 33kV voltage (while not reflected at Royton Primary substation, this is reflected in the results for other Primary substations with CLASS).
- The reductions to demand and losses, results in a reduction in external generation reducing carbon, creating a reduction of 158.31kgCO2 for this period of analysis.

7.12. Scenario 7: Network Efficiency Mode & Smart Street & CLASS

Scenario 7 investigates the use of Network Efficiency Mode with priority above Smart Street (SMST) and CLASS as a combined TECHNIQUE with each FUNCTIONs trying to achieve 100% demand reduction i.e., 0.95 p.u nominal voltage (CLASS , SMST) and 100% efficiency i.e., 1.05 p.u. on 33kV network (NEM) The following inputs are applied:

7.12.1. Input Data

- Analysis Window: The 24-hour period is used which identifies the maximum instantaneous demand between 01/04/2020-01/04/2021. This occurs on 04/01/2021.
- Resolution: Half-Hour
- Load Inputs: ENWL Historical Primary Loading data associated with this day is used.
- Firm Generator Inputs: Generators are switched out.
- ANM Inputs: Generators are switched out.
- Technique Priority List: NEM>Smart Street>CLASS
- Tap Stagger BSP: Off
- NEM: Set to 100% Efficiency via a 1.05 p.u. target voltage.
- CLASS: Set to 100% demand reduction achieve via a 0.95 p.u. target voltage.
- Smart Street: Set to 100% demand reduction achieve via a 0.95 p.u. target voltage.
- Flexible Connection: Off
- Flexible Services: Off

7.12.2. TECHNIQUE FUNCTION LEVEL

NEM is trying to achieve 100% of its efficiency target. Both CLASS and Smart Street are trying to achieve 100% FUNCTION LEVEL to meet the CLASS demand decrease target and Smart Streets CVR objectives. This resulting in 0.95 p.u. nominal voltage target at the CLASS and Smart Street enabled asset relays, to achieve the MW demand decrease.

7.12.3. Results

In the figure, the voltage profiles show the depressing on the secondary busbar at Royton Primary to achieve the demand reduction from CLASS, this is confirmed in the time-series plot for demand (Figure 24), showing before the application of the voltage TECHNIQUE and after. The figure also indicates the 33kV voltage statutory limit of -6% (0.94pu).

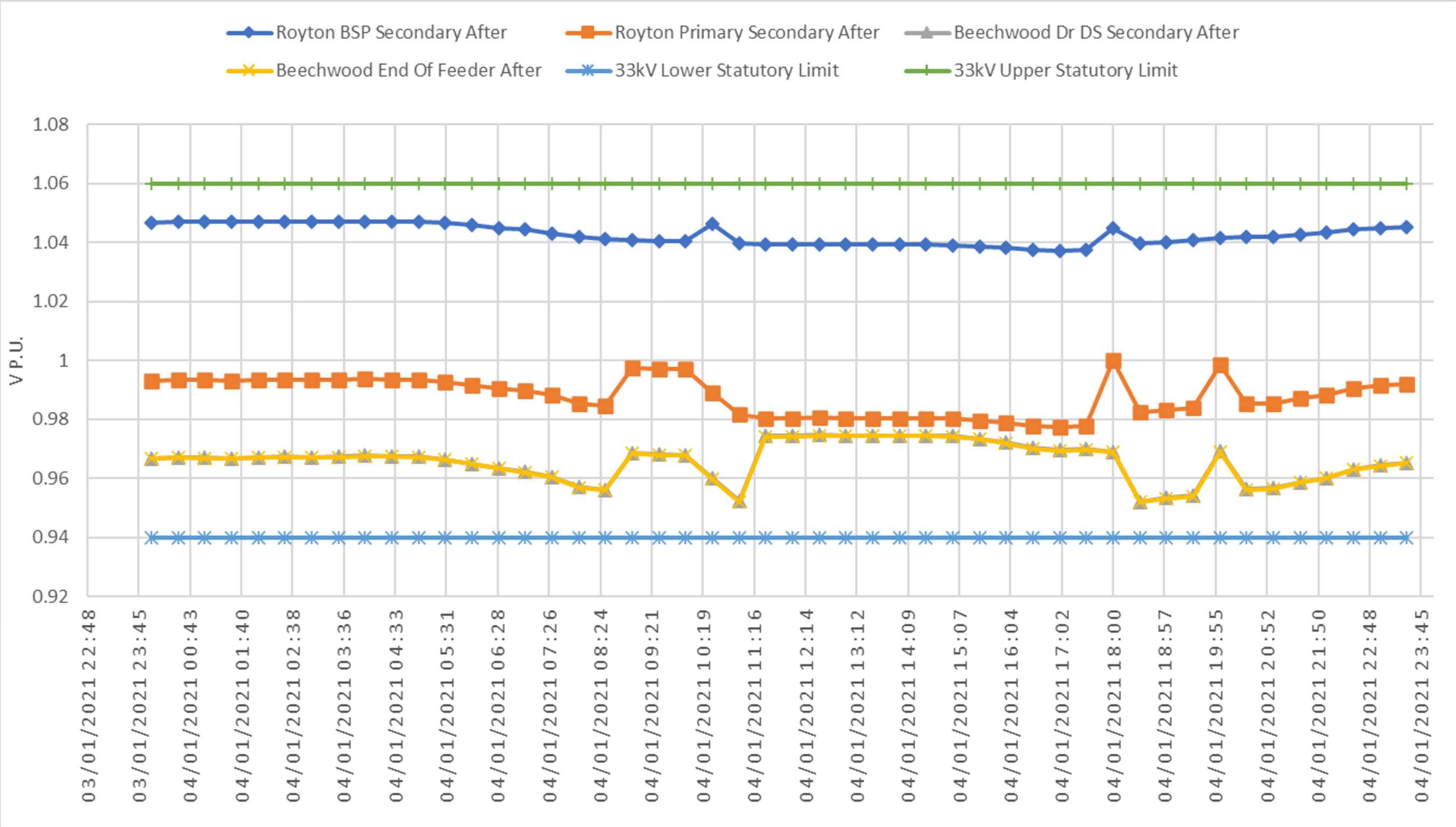

Figure 22: Scenario 7 Voltage Profiles at Selected Busbars

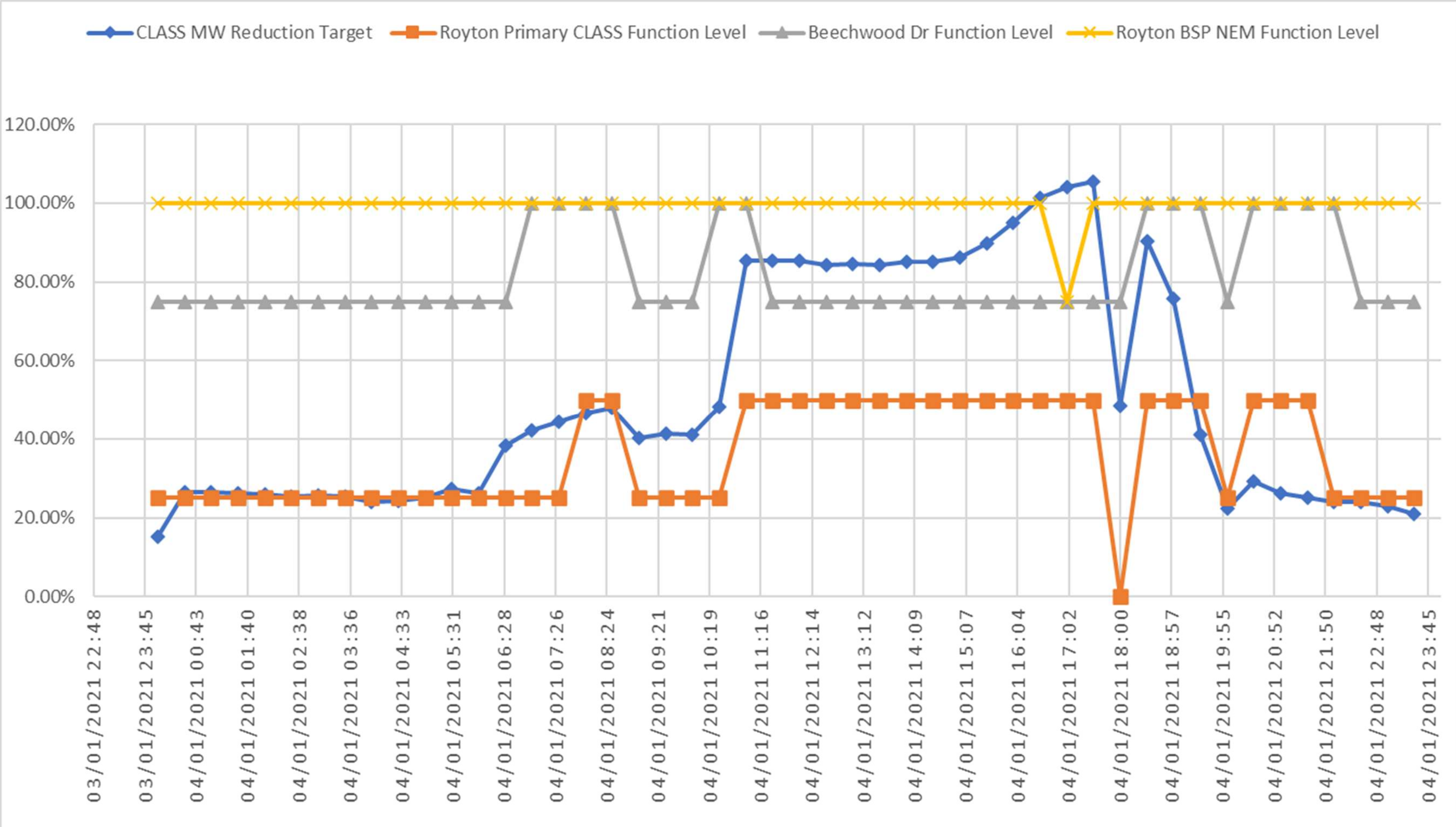

Figure 23: Scenario 7 QUEST TECHNIQUE FUNCTION LEVEL Outputs

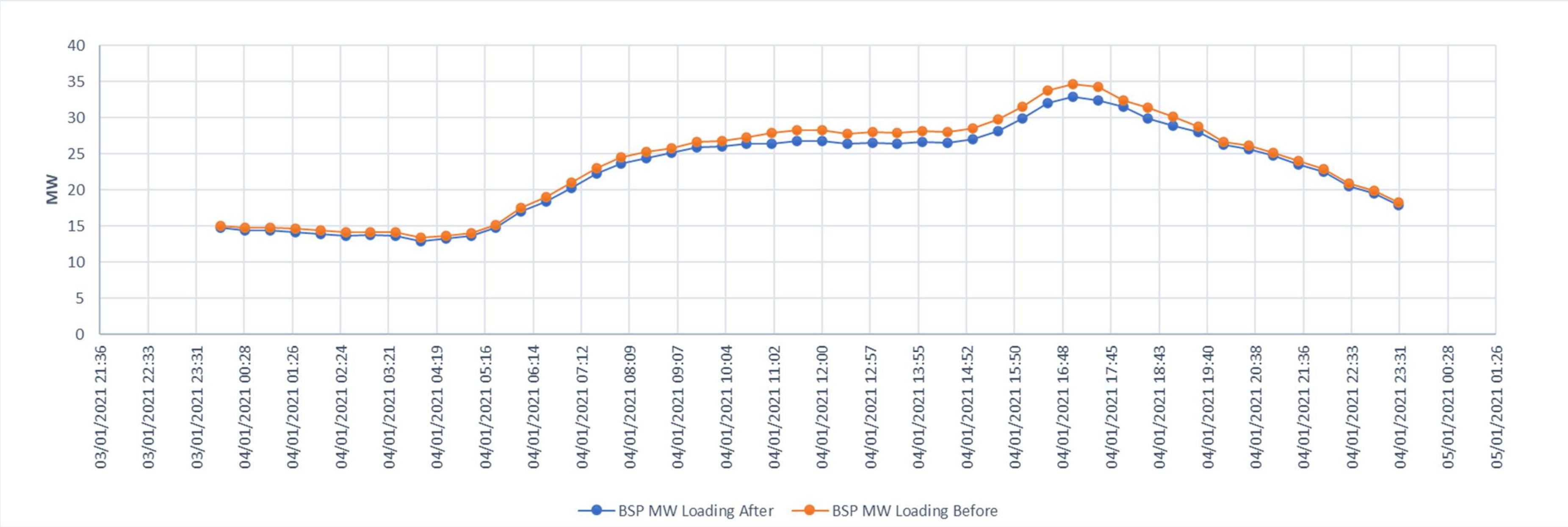

Figure 24: Scenario 7 Royton BSP Loading Changes

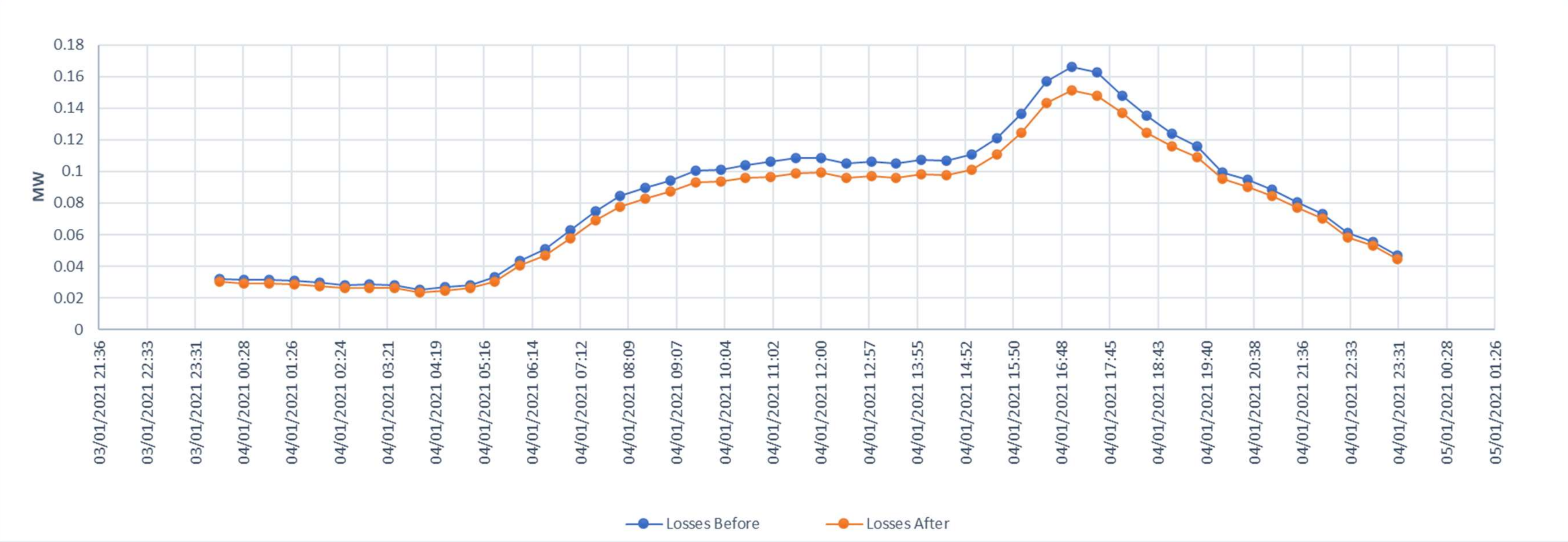

Figure 25: Scenario 7 Royton BSP 33kV Losses

7.12.4. Voltage Profile Observations

- Once prioritised, NEM can achieve higher voltages at the BSP secondary bus bar, within statutory limits to achieve its target.
- Due to higher voltages on the 33kV network, CLASS struggles to achieve its target and can only achieve its highest tap position.
- Even though Smart Street is prioritised ahead of CLASS it is limited by CLASS's voltage position at the primary substation secondary busbars, resulting in its target being restricted sometimes due to the discrete tap positions.

7.12.5. Thermal Flow Observations

Table 11: Scenario 7- Key Performance Indicators

Key Performance Indicator	Before TECHNIQUE APPLIED	After TECHNIQUE APPLIED	Difference	Percentage Change
System Load (MW Average)	79.06	78.17	0.88	1.13%
System Generation External (MW Average)	113.48	112.55	0.93	0.83%
System Generation Internal (MW Average)	0.00	0.00	0.00	0.00%
33kV Losses (MW Average)	0.0831	0.0769	0.01	8.06%
System Carbon (kgCO2 Average)	7849.18	7753.17	96.01	1.24%

- Prioritising NEM does cause a reduction to network losses but at the expense of CLASS achieving its target. However, CLASS not achieving its target results in more losses comparatively to the scenario when CLASS is prioritised over NEM (Scenario 6). The net result is that although NEMs is given priority, the drop in 33kV losses is less than Scenario 6 where NEMS had the lowest priority. This is because the loss improvement from NEMS versus the loss improvement from demand reduction has less influence in Scenarios 6 and 7.
- The overall demand reduction is 1.13%, reducing carbon by 96.01 kgCO2 across this analysis period.

7.13. Scenario 8: CLASS (Demand Boost) & Smart Street & Network Efficiency Mode & Tap Stagger-Flexible Connections

Scenario 8 investigates the use of all voltage TECHNIQUEs plus thermal TECHNIQUEs.

CLASS (Demand Boost) is prioritised which seeks to increase demand in the network by targeting 100% of demand increase i.e., 1.05 p.u voltage on the Primary substation secondary busbars.

Smart Street (SMST) is trying to achieve 100% demand reduction i.e., 0.95 p.u nominal voltage on the LV side of the Smart Street substations. NEM is targeting 100% efficiency i.e., 1.05 p.u voltage on the 33kV network.

Tap Stagger is trying to achieve 100% MVAr demand increase (+/-4 tap separation).

Finally, since constrained generation sensitive to constraints where demand increase would release capacity are present, in order to mitigate these generators from utilising this CLASS demand gain by releasing constrained generation export, QUEST will coordinate thermal TECHNIQUEs to ensure CLASS objectives are not eroded by the release of ANM constrained generation export.

The following inputs are applied:

7.13.1. Input Data

- Analysis Window: The 24-hour period is used which identifies the maximum instantaneous demand between 01/04/2020-01/04/2021. This occurs on 04/01/2021.
- Resolution: Half-Hour
- Load Inputs: ENWL Historical Primary Loading data associated with this day is used.
- Firm Generator Inputs: Generators are switched out.
- ANM Inputs: Generators are switch in. A 30 MW generator flexible connection is applied at the Royton Primary, where a reverse power constraint limit of 10 MW has been applied across the Primary group.
- Technique Priority List: CLASS (Demand Boost)>Smart Street>Network Efficiency Mode> Tap Stagger>Flexible Connections
- Tap Stagger BSP: Set to 100% MVAr demand increase i.e., 8 step separation of transformer group (+4 taps and -4 taps).
- NEM: Set to 100% Efficiency via a 1.05 p.u. target voltage.
- CLASS: Set to 100% demand boost achieve via a 1.05 p.u. target voltage.
- Smart Street: Set to 100% demand reduction achieve via a 0.95 p.u. target voltage.
- Flexible Connection: ANM controlling generators, receiving mitigation instruction from QUEST.
- Flexible Services: Off

7.13.2. TECHNIQUE FUNCTION LEVEL

Both CLASS and Smart Street trying to achieve 100% demand decrease i.e., 0.95 p.u. nominal voltage, to achieve the MW demand decrease. NEM is trying to achieve a 1.05 p.u. nominal 33kV voltage to reduce the 33kV current flows and hence reduce 33kV system resistive losses. Tap Stagger at the BSP aims to achieve 100% of target MVArs demand increase within the available BSP transformer tap range available after NEM is applied.

7.13.3. QUEST Control and Coordination Test Bench Regime Methodology

With CLASS taking priority over Smart Street and NEM, CLASS targets are set first, then Smart Street achieves what it can without interfering with the CLASS target. Then, NEM achieves as close to its target without affecting either CLASS or Smart Street and finally BSP Tap Stagger increases the MVAr demand within the available BSP transformer tap range available after NEM is applied.

7.13.4. Results

The figures below show all voltage TECHNIQUES and thermal TECHNIQUES are applied and coordinated by QUEST to achieve the TECHNIQUE PRIOITY LIS (TPL).

In Figure 26, since CLASS Boost is priority it sets the constraints of all other techniques, and achieves its target voltage of 1.05 p.u. It was shown in a previous example that NEM can interfere with CLASS objectives and would do so again here if it was not for QUEST coordination actions (NEM will be limited by QUEST to prevent 33kV upper voltage limits being exceeded when CLASS Demand Boost is activated).

However, to show the impact of Tap Stagger a variant of this scenario highlighting the effect of coordinated NEM but with not tap stagger is applied. Table 12 shows the scenario where everything is under QUEST control on the left and everything but tap stagger is under QUEST control on the right.

Table 12: Tap Stagger Coordination Issues

Timestep	Royton Primary Secondary After V p.u.	Royton Primary Secondary After (NO TS Coordination) V p.u.
04/01/2021 08:30	1.0497	1.0512
04/01/2021 09:00	1.0491	1.0506
04/01/2021 09:30	1.0487	1.0502
04/01/2021 10:00	1.0486	1.0501

This result shows tap stagger causes a slight creeping up of BSP secondary busbar voltage, which if left uncoordinated would result in the CLASS Demand Boost voltage creeping beyond its target 1.05 p.u as illustrated in Table 12.

Therefore, QUEST must coordinate Tap Staggers tap level (in this example moving from 100% level 4 to 50% level 2) to ensure it doesn't interfere with the CLASS objective, as shown by the orange line in the Figure 26, when this is implemented, CLASS doesn't exceed its target of 1.05 p.u.

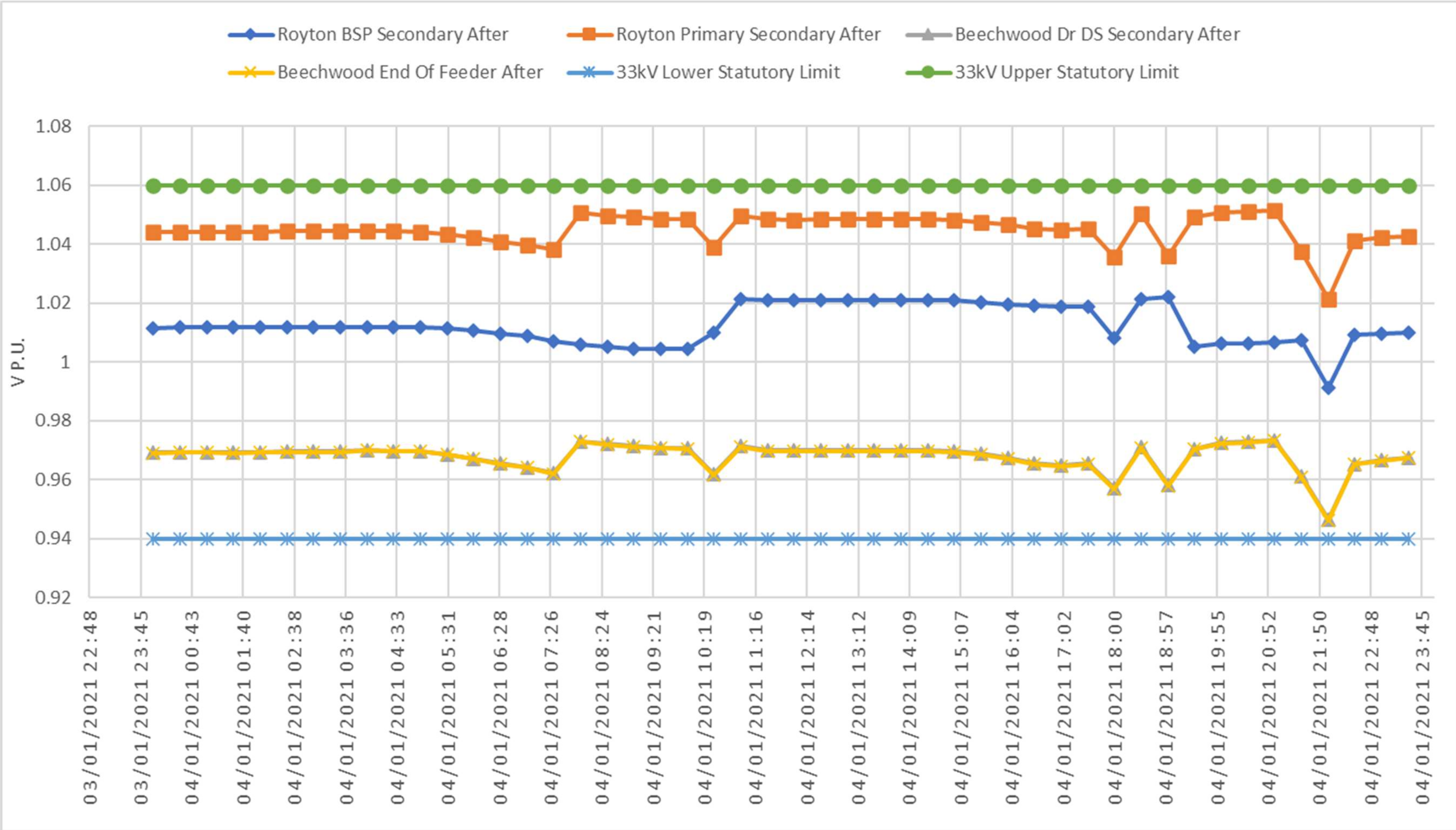

Figure 26: Scenario 8 Voltage Profiles at Selected Busbars

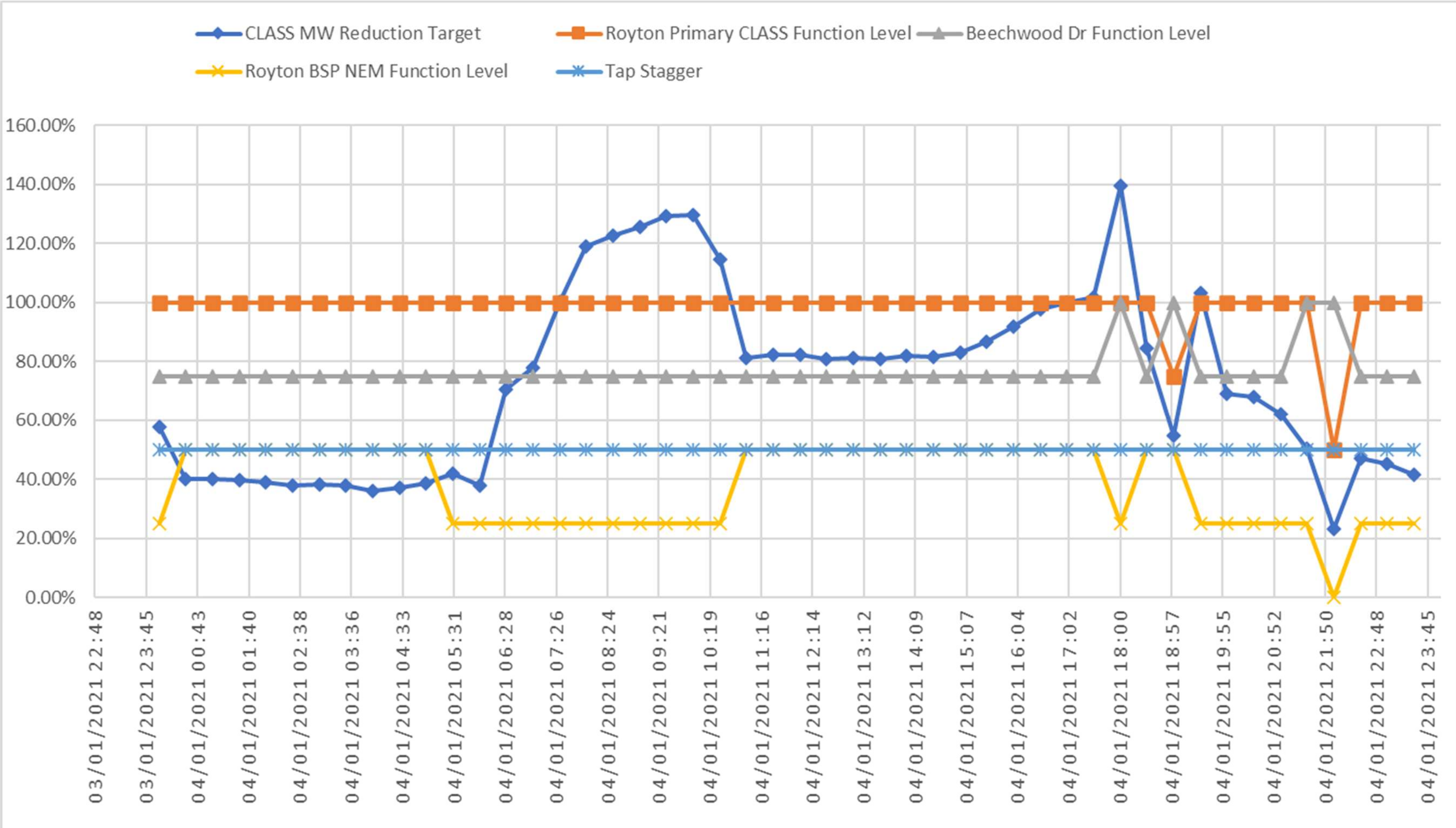

Figure 27: Scenario 8 QUEST TECHNIQUE FUNCTION LEVEL Outputs

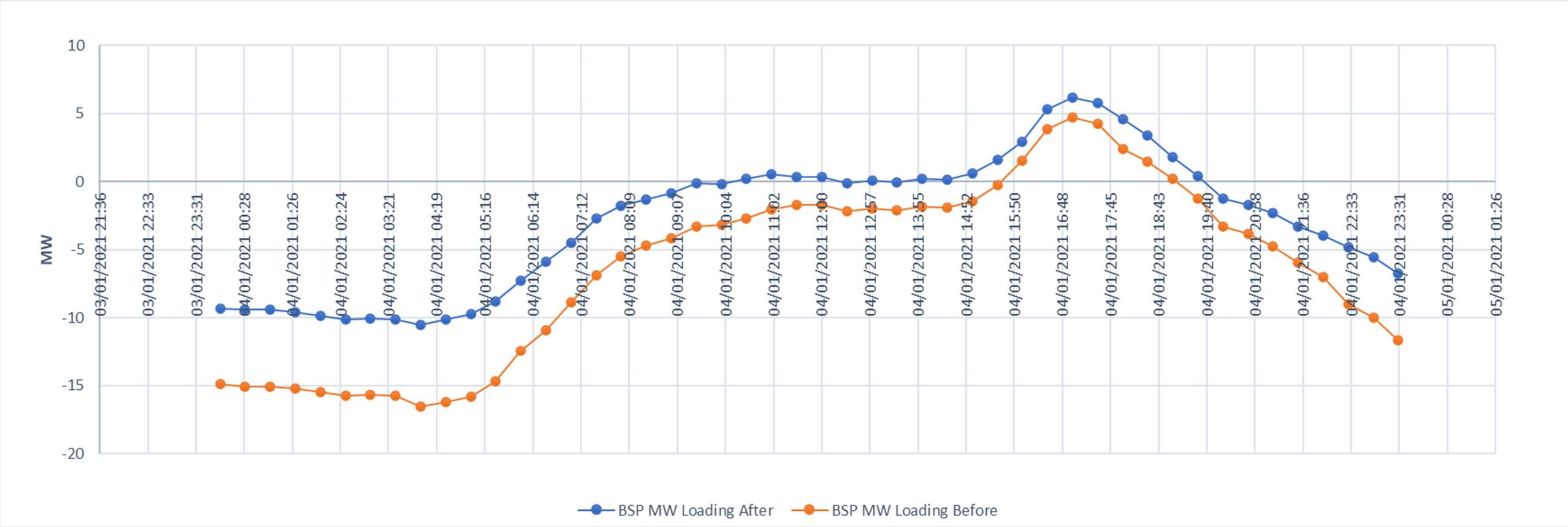

Figure 28: Scenario 8 Royton BSP MW Loading Changes

Figure 29: Scenario 8 MVAr Demand with BSP Tap Stagger (Level 4)

Figure 30: Scenario 8 MVAr Demand with BSP Tap Stagger (Level 2)

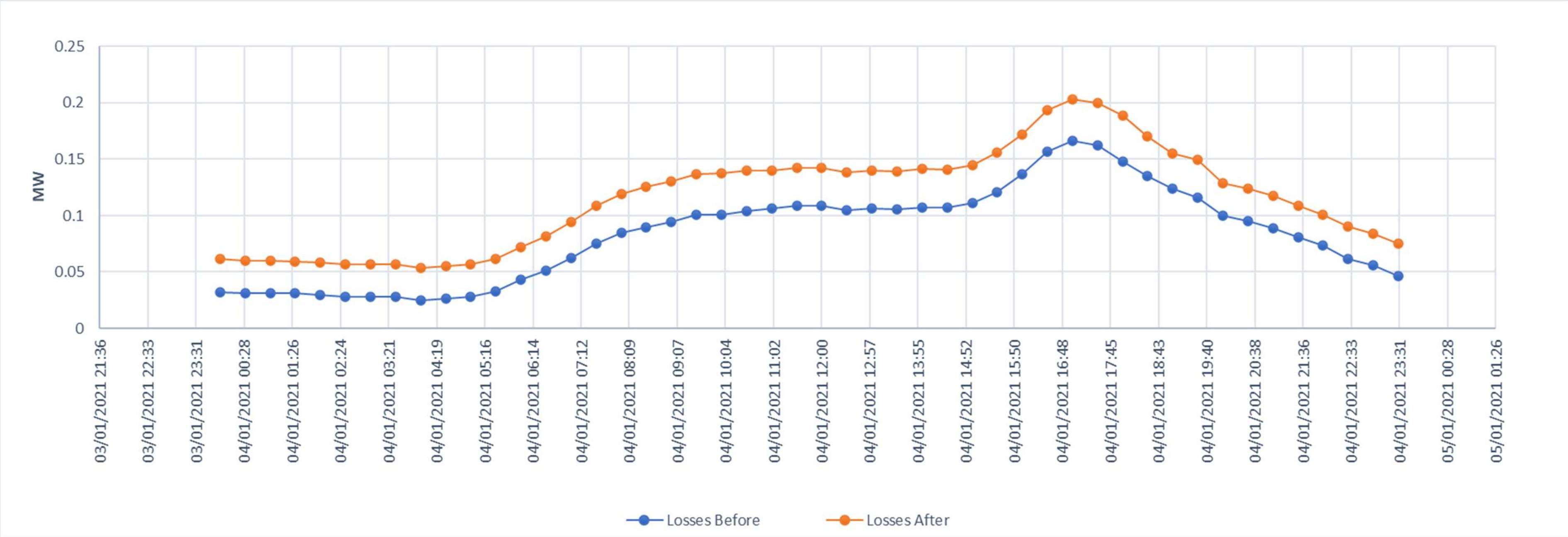

Figure 31: Scenario 8 Royton BSP 33kV Losses

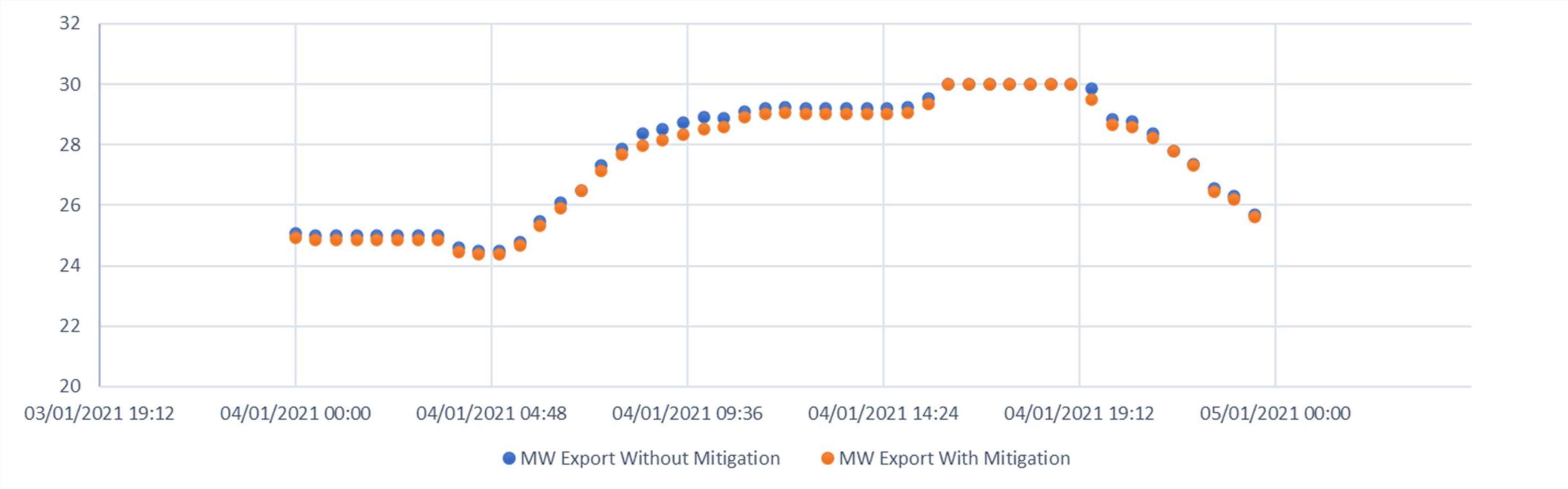

Figure 32: Scenario 8 'Always On' Generator Export connected at Royton Primary

- CLASS demand boost priority limits both Tap Stagger and NEM objectives but not smart street, where discrete taps can achieve targets within statutory limits, illustrated in Figure 27.
- CLASS boosts demand, Figure 28, this demand increase removes any loss reduction due to the increase in voltage, showing an increase in 33kV losses overall Figure 31
- Tap Stagger only achieves 50% tap separation (2 taps separation) because of compliance to CLASS objectives, the MVAr demand for both Level 4 and Level 2 Tap Stagger are shown respectively in Figure 29 and Figure 30.
- The always on generator has an export target of 30MW, due to a 10MVA reverse power limit at Royton Primary this results in generation curtailment. When QUEST is not coordinating the ANM system the generator uses the capacity released from the demand boost caused by CLASS at the Royton primary, which would reduce the demand boost delivery to the wider network. This point is highlighted in greater detail below.

- Coordination is important between NEM and CLASS DB. When CLASS DB moves to its target voltage to achieve its FUNCTION LEVEL, then NEMs actions will cause the primary voltage at the secondary bus bar to rise above statutory limits as it raises voltage across the BSP. Therefore, NEM must temper its FUNCTION LEVEL to ensure this doesn't happen. Although this does not affect CLASS DB from meeting its MW demand boost target, it does affect NEM from achieving its own FUNCTION LEVEL.

7.13.5. Thermal Flow Observations

Table 13: Scenario 8 Key Performance Indicators (QUEST System No ANM Mitigation)

	Before TECHNIQUE applied	After TECHNIQUE applied	Difference	Percentage Change (%)
System Load (MW Average)	79.06	80.106	-1.05	-1.31%
System Generation External (MW Average)	83.40	86.89	-3.48	-4.01%
System Generation Internal (MW Average)	30	24.50	05.5	0.00%
33kV Losses (MW Average)	0.1533	0.2346	-0.08	-34.65%
System Carbon (kgCO2 Average)	7849.18	7960.49	-111.31	-1.40%
BSP Load (MVAr Average)	1.55	3.85	-2.31	-59.88%

Table 14: Scenario 8 Key Performance Indicators (QUEST System ANM Mitigation)

	Before TECHNIQUE applied	After TECHNIQUE applied	Difference	Percentage Change (%)
System Load (MW Average)	79.06	80.106	-1.05	-1.31%
System Generation External (MW Average)	83.40	87.03	-3.63	-4.17%
System Generation Internal (MW Average)	30	24.386	5.614	0.00%
33kV Losses (MW Average)	0.1533	0.2334	-0.08	-34.34%
System Carbon (kgCO2 Average)	7849.18	7960.49	-111.31	-1.40%
BSP Load (MVAr Average)	1.55	3.83	-2.28	-59.59%

- The two tables show QUEST coordinating everything except the ANM system, Table 13 and then mitigating the ANM system generation, Table 14. When CLASS is applied, demand overall is boosted including on the Royton Primary Substation fed network. The 30MW generator is connected to the Royton Primary Substation secondary busbars and is managed by the ANM and where the ANM is not under QUEST coordination, the ANM will release some generator constrained export to meet the higher Royton Primary substation demand caused by the CLASS demand boost. Hence the demand boost at Royton Primary will be met by the 30MW generator and not via the Royton Primary substation transformers which would show as an increase in “System Generation External (MW Average)” in the tables. Table 14 which represents QUEST blocking the release of constrained generation export on CLASS Demand Boost by the ANM therefore shows a larger increase in “System Generation External (MW Average)” and a lower “System Generation Internal (MW Average), After TECHNIQUE applied” compared with the value in Table 13 where the ANM is not being coordinated by QUEST.

8. CONCLUSIONS AND NEXT STEPS

The Scenario Analysis has achieved the following objectives:

- validated the functional specification for the voltage control methodologies defined by the control system architectures, and
- provided the impact of key performance indicators associated with the network operation.

It has achieved this by implementing multiple scenarios using the modelling regime to thoroughly test the functional specification for each voltage methodology in isolation and in concert with one another, with any conflicts between methods regarding either voltage methodology objective conflict or physical network limit compliance conflicts, being resolved by QUEST's overarching control. Additionally showing the benefits and limitations to key performance indicators each combination of voltage control methods will affect.

Furthermore, the outputs of the scenario analysis show that QUEST's overarching control solution is fit for purpose, and the functional specification for voltage methodology once applied as part of a real-time platform architecture, being delivered by Schneider Electric, fundamentally, will achieve the wider QUEST objectives upon ENWL's network.

Although, overall, the outputs from the scenario analysis have achieved the objectives above, it has also provided confirmations and insights into previous speculated benefits and limitations identified in the projects original use cases, these outputs can now be fed into the development of QUEST to improve the delivery of the solution, both now and in the future.

Voltage TECHNIQUE Conclusions

CLASS: Delivering the CLASS demand reduction target will be affected by availability of assets and the voltage-demand relationship that exists in the model. Scenario 1 highlighted that to deliver the CLASS target, when it is achievable it might not need all assets. However, when the voltage-demand relationship is weaker at certain parts of the day, more assets need to be included to achieve the target- and in some cases not meet the target at all (albeit constrained by the scenario bounds). This means ENWL must be aware of the variance surrounding the delivery of the demand reduction target, and not to commercially offer what cannot be achieved.

Network Efficiency Mode (NEM): NEM can provide benefit to the network by reducing system losses in the 33kV network, however, the magnitude of these benefits can be small regarding the loss reduction associated with reduced 33kV current. Therefore, it is suggested from the scenarios that NEM is best suited to support the likes of CLASS and Smart Street demand reduction targets, rather than as a priority in of itself. This is the position concluded by SE in their design work.

Smart Street: Smart Street provides a demand reduction benefit, but, that benefit could be increased further by broadening the voltage targets associated with its function levels used in the scenario studies reported here. In the scenario analysis, the settings were kept in line with CLASS voltage targets, however, due to the p.u. statutory limits being lower at LV (400V), changes to the configuration of FUNCTION LEVEL would allow greater benefits to be unlocked. It has been noted that while the Smart Street FUNCTION LEVELs used reflected the present FUNCTION LEVELs in the QUEST design at the sub-phase 2 stage [3], the reality is that present Smart Street transformers only have three tap steps to reduce voltage below the nominal tap setting, each tap step being 2.5% of nominal voltage- now updated within the final QUEST functional design specification [4]. This would equate to Smart Street FUNCTION LEVELS of 100% with a 0.925 p.u. voltage target; 66% with a 0.95 p.u. voltage target and 33% with a 0.975 p.u. voltage target. While this does not impact the conclusions of the scenario studies carried out, this issue should be resolved, and any revised studies carried out during the QUEST trial phase to reflect the final agreed Smart Street FUNCTION LEVELS. This applies to the scenarios reported here that involve Smart Street. This will be investigated as part of the QUEST Trials.

Tap Stagger: Tap stagger can provide a MVAr absorption service to the DNO and ESO, instead of the construction and installation of alternate voltage control systems such as a STATCOM. However, since this behaviour is induced by taking advantages of increased system losses there is an impact to carbon intensity when operating, therefore, a balance in benefits must be struck. Furthermore, tap stagger operations cause a slight voltage rise on the secondary bus bar of the BSP, which needs to be monitored by QUEST to ensure this does not interfere with delivering other TECHNIQUE FUNCTION LEVELs.

QUEST Conclusions

Conflict satisfaction and coordination applied by QUEST allowed for all TECHNIQUEs to be applied in concert with one another, some important observations were:

In certain cases, uncoordinated responses would result in "known voltage excursions", therefore, setting Smart Street to its FUNCTION LEVEL voltage target before CLASS has achieved its own, would cause a double impact to voltage reduction at LV. Therefore, QUEST must allow CLASS to achieve its FUNCTION LEVEL and associated voltage target first, then calculate the resulting FUNCTION LEVEL and subsequent voltage target for Smart Street to utilise post CLASS action.

This behaviour will be investigated, as part of the QUEST trials, to determine the worst-case impacts to uncoordinated actions across a year to allow proactive setting of Smart Street, where the activation of CLASS may potentially occur and cause an LV excursion. This option is only required if a fast tap solution does not exist and cannot be applied, where this solution exists it would allow QUEST to place Smart Street into a safe mode instantaneously following CLASS activation, then QUEST would calculate the FUNCTION LEVEL due to the constraints applied under the CLASS activation.

Tap Stagger: Due to Tap Stagger slightly raising the secondary busbar voltage, if this voltage rise is not considered by QUEST, it can result in slight impacts to FUNCTION LEVEL delivery.

Flexible Connections: CLASS demand boost was shown to provide greater demand in the network. To be satisfied by the higher voltage network as a service, however, previously curtailed generation was quick to utilise this released demand, cancelling our any CLASS boost service. QUEST must mitigate in this circumstance by holding DERMS/ANM managed DER setpoints to their pre-CLASS Boost calculated positions, in order to ensure this service can be delivered. Noted that all DER will not be under DERMS/ANM managed control at present.

CLASS: CLASS objective delivery suffered in some cases from not being able to achieve voltage targets associated with its FUNCTION LEVEL due to discrete transformer tap limits. Since QUEST offers much more observability of voltages across the network, it is possible that voltage targets associated with CLASS FUNCTION LEVEL can also be optimised, since these targets are conservative in nature to consider unobserved voltage drop across the network. This update would facilitate the delivery of CLASS targets and aid the delivery of FUNCTION LEVELs as part of being associated within a TECHNIQUE PRIORITY LIST.

Overall, QUEST offers benefit in not only delivering each individual TECHNIQUE but also in concert with one another, providing the actions to achieve over-arching control. The impact of this control is shown not only in the delivery of the objectives associated with each voltage TECHNIQUE but also the key performance indicators associated with the network.

For the most part each TECHNIQUE will improve these key performance indicators, such as demand reduction and system loss reduction reducing carbon emissions. However, certain TECHNIQUE objective fulfilment can reduce the overall impact of benefits and in some case reverse them, therefore, these benefits must be weighed against the limitations on a case-by-case bases. The importance being that visibility to make these decisions is required and provided by QUEST.

Next Steps

The next steps will focus on the two developments identified within the conclusions; these are:

- Defining the proactive FUNCTION LEVELS Smart Street can achieve to ensure safe operation of CLASS and Smart Street, upon CLASS activation.
- Defining the FUNCTION LEVEL voltage targets associated with Smart Street to optimise CVR impact.

Both these points can be addressed as part of the QUEST Trials work.