The University of Manchester

*Title:* **Final Profile Modelling Study**

*Synopsis:* This document presents demand profiles through modelling and validation using high-resolution field measurement data. Load models have been developed and network demand responses have been estimated from voltage increment and decrement while analysing actual ENWL measurement data at 60 selected substations across entire annual cycle from June 2014 to May 2015. Representative features of load models for three types of substations (industrial/domestic/mix-type) are presented. The key outputs from this study are the methodology for characterising the demand profile with appropriate load models along with load model parameters from the primary substations depending on the customers connected. Developed voltage-demand relationship matrix across entire annual cycle considers seasonal, weekly and daily variation of demand and presented in every half-an-hour interval (i. e. 48x½ hr format), which is suitable to be used in the CLASS dashboard.

*Document ID:* Final Profile Modelling Study_UoM-ENWL CLASS WP1

*Date:* 31st August 2015

*Prepared For:*
Mr. Andy Howard, CLASS project manager
Mr. Steve Stott, CLASS technical engineer
Mr. Paul Turner, Future networks delivery manager
Mr. Kieran Bailey, Future networks engineer
Electricity North West Limited, UK

*Prepared By:*
Dr. Kazi N Hasan
Dr. Xiaoqing Tang
Prof. Jovica V Milanovic
The University of Manchester
Sackville Street, Manchester M13 9PL, UK

*Contact:*
Prof. Jovica V Milanovic
+44 (0)161 306 8724
jovica.milanovic@manchester.ac.uk

*The results and discussions provided in this report are outcomes of analyses and 'proof of concept' validation performed at selected subset of substations of a particular electricity distribution network under specific operating conditions and is not guaranteed to be the same for other sites or other networks. The readers should use this document as guidance and at their own responsibility. Any omissions or errors, if identified, should be reported to the authors.*

# Executive Summary

This report provides detail study, results and analysis of WP1 of the UoM-ENWL CLASS project which particularly deals with the demand profiles through modelling and validation using trial-1 data. The CLASS (Customer Load Active System Services) project revolves around a basic principle of electricity network which is "the demand of certain loads can change with voltage". Load modelling (WP1) of the CLASS project is intended to develop an accurate voltage-demand relationship matrix for different load compositions at representative substations of the ENWL distribution network. Actual load responses following initiated voltage disturbances have been measured and analysed for the development of suitable load models and estimation of load model parameters. Thus a prolonged sustained response of a load has been modelled through a voltage-demand matrix.

## Key Milestones

There are three key milestones and deliverables of WP1, which have been promised and agreed upon, are as follows:

- **Load Model Development:** Developing load models for representative set of 60 primary substations selected for the CLASS trials based on actual measurement data.
- **Load Model Validation:** Refinement and validation of load models based on field measurement data collected across entire annual cycle.
- **Voltage-Demand Relationship Matrix:** A voltage-demand relationship matrix which describe mathematically the voltage-demand relationship for every half-an-hour of a day (48 x ½ hr) of each season during the year for each characteristic demand profile.

## Key Outputs

The load modelling part (WP1) of the CLASS project interactively imports and processes measured load data; captures required load characteristics, develops appropriate load models and provides a voltage-demand relationship matrix.

WP1 has accomplished all the tasks, provided Project Progress Reports (PPR) and met CLASS Successful Delivery Reward Criteria (SDRC) which have been promised in the UoM-ENWL CLASS project outline report. Key outputs of the WP1 are as follows:

- **Load Model Development:** Appropriate tools and techniques (software codes and programs) have been developed for data processing, filtering and load modelling (at trial hours at trial-1 substations, at non-trial hours at trial substations, and at other monitored substations where trials have not been carried out).
  - ❖ Statistical analysis of ENWL load measurement data has been presented in detail in the report, while some key results are as summarised below:
    - *Static load model is found to be the most appropriate load model for CLASS (load) measurement data as it captures the prolonged sustained response of the load following a voltage disturbance which is of interest in the CLASS project.*
    - *Static exponential load model is chosen for load modelling at all substations due to its simplicity and clear coherence in defining voltage-demand matrix.*
    - *It has been found that the load model parameters describing weekday load behaviour are more consistent, i.e., less variable. Differences in the weekdays and weekend parameters are influenced by both the changing load-mix of the substations and by changes in consumption pattern during weekend.*

- Estimated load model parameter values have been presented in Table ES.1 and ES.2, and can be summarized as follows:
  - *For domestic substations, average value of real power exponent for weekday is about 1.30 and reactive power exponent is about 6.06;*
  - *For industrial and commercial substations, average value of real power exponent for a weekday is close to 1.48 and reactive power exponent is close to 5.58;*
  - *For mixed-type substations, average value of real power exponent for a weekday is about 1.22 and reactive power exponent is about 5.90.*

**Table ES.1 Statistics of Kp values on weekdays (all 60 substations)**

| | **Mainly domestic** | | | **Industrial/commercial** | | | **Mixed** | | |
|---|---|---|---|---|---|---|---|---|---|
| | Min | Avg | Max | Min | Avg | Max | Min | Avg | Max |
| **Winter** | 0.87 | 1.33 | 1.93 | 0.86 | 1.47 | 1.85 | 0.70 | 1.23 | 1.91 |
| **Spring** | 0.83 | 1.32 | 1.86 | 1.02 | 1.39 | 1.80 | 0.80 | 1.20 | 1.68 |
| **Summer** | 0.72 | 1.25 | 2.11 | 1.02 | 1.52 | 1.97 | 0.70 | 1.20 | 1.58 |
| **Autumn** | 0.67 | 1.31 | 1.91 | 0.95 | 1.53 | 1.98 | 0.71 | 1.23 | 1.80 |

**Table ES.2 Statistics of Kq values on weekdays (all 60 substations)**

| | **Mainly domestic** | | | **Industrial/commercial** | | | **Mixed** | | |
|---|---|---|---|---|---|---|---|---|---|
| | Min | Avg | Max | Min | Avg | Max | Min | Avg | Max |
| **Winter** | 3.98 | 5.96 | 7.98 | 3.79 | 5.62 | 6.86 | 4.36 | 5.92 | 6.93 |
| **Spring** | 4.58 | 6.14 | 8.05 | 4.30 | 5.56 | 6.75 | 3.82 | 5.82 | 7.52 |
| **Summer** | 3.25 | 5.98 | 7.62 | 3.96 | 5.65 | 7.26 | 4.52 | 5.75 | 6.95 |
| **Autumn** | 4.41 | 6.16 | 8.06 | 2.41 | 5.49 | 6.79 | 4.26 | 6.10 | 7.58 |

- **Load Model Validation:** Developed voltage-demand matrices for every half-an-hour intervals for all 15 trial-1 substations have been validated with trial-1 data.
  - Sensitivity/robustness analyses of the developed load model have been performed by outlier removal, application of different filtering techniques, and assessment of the lengths of fitting data window.
    - *The load model developed by the trail data from June 2014 to March 2015 is compared with the WP1 seasonal load model developed by non-trial data.*
    - *The two models have fitted well with each other validated WP1 seasonal load model development methodology.*
- **Voltage-Demand Relationship Matrix:** Seasonal voltage-demand relationship matrices for every half-an-hour intervals for 15 trial-1 substations as well as for all remaining 45 non-trial-1 buses have been developed. (*This is an extension of the originally planned work as voltage-demand relationship matrices have been developed for all trial and non-trial substations (all 60) instead for only a subset of non-trial substations*).
  - Developed methodologies have been tested and applied to CLASS measurement data from 15 trial-1 and 45 non-trial-1 substations, which provides a full 24hr (48 x ½ hr) load matrix covering 4 seasons for 3 defined customer profile classes (domestic, industrial and commercial, and mixed), divided between weekdays and weekends.

In summary, the results and analyses presented include a detailed yearly, seasonal, weekly and daily 24 hour (48 x ½ hr) voltage-demand relationship matrix for all 60 monitored substations (15 trial-1 and 45 non-trial-1 substations) of the ENWL distribution network associated with the CLASS project.

# Table of Contents

# 1 Introduction

Load modelling plays a lead role in power system planning and operation. Detailed understanding of the actual load response to the actions of dynamic voltage control (and/or system disturbances) can provide flexibility to the network operators for efficient and reliable system operation. In contrast to the constant power and constant impedance based load models which are mostly used by the network operators, this work attempts to develop actual measurement based load models and corresponding parameters for selected ENWL network points under the CLASS (Customer Load Active System Services) project.

## 1.1 Load Modelling from the CLASS Perspective [1]

The CLASS project inherits a basic principle of electricity network which is “the demand of certain loads can change with voltage”. Hence, an active voltage management can lead to a mechanism of demand management in the network.

Load modelling research of the CLASS project is intended to develop accurate voltage-demand relationship for different load compositions existing in the network. Developed load models can provide a guideline in the decision making process that facilitates the following purposes.

- The requirement and time span/delay of network reinforcement deferral by manipulating the active voltage-demand management.
- Provision of voltage support to the transmission grid from this active voltage control mechanism by estimating accurate load responses.
- Flexibility of accommodating more intermittent renewable generation into the network, which if necessary, can be maintained by controlling the distribution-level voltage.

Appropriate load models will facilitate these services to the DNOs (Distribution Network Operator) and subsequently to the national electricity grid once this ‘proof of concept’ is rolled-out all over the country.

Actual load responses following initiated voltage disturbances will be measured and analysed for the development of suitable load models and for the estimation of load model parameters. This measurement-based load modelling approach can capture the stochastic nature of the variation in load and can reflect the actual load behaviour during disturbances [2]. Load models, developed through this approach, can be validated through measured data and can be modified accordingly.

## 1.2 Tasks, Delivery and Dissemination of WP1 Studies

The load modelling part (WP1) of the CLASS project interactively imports and processes measured load data; captures required load characteristics, develops appropriate load models and provides a voltage-demand relationship matrix.

Key milestones and scopes of WP1 have been agreed as follows:

- Task 1. Assisting with and review of CLASS Trials design and associated test regimes.
- Task 2. Developing demand composition at monitored buses throughout the day/week based on data provided by ENWL.
- Task 3. Data collection and pre-processing for load model development.
- Task 4. Developing appropriate static or/and dynamic load model structures and corresponding parameters for a reprehensive set of trial substations.
- Task 5. Sensitivity/robustness analysis of developed load models for monitored buses to cover other operating regimes and voltage disturbances.

- Task 6. Developing appropriate load models for a representative set of non-trial buses in the network based on similarity of their demand profile with the demand profile at monitored buses.

Key outputs delivered by WP1 are as follows:

- **Load Model Development:** Load models for *all* 60 primary substations selected for the CLASS trials based on actual measurement data. This is more than what was originally planned as the original task was to develop appropriate load models for a representative set of non-trial buses only, i.e., load models were planned to be developed for 15 trail buses and for a sub-set of remaining 45 buses.
- **Load Model Validation:** Refinement and validation of load models based on field measurement data collected across entire annual cycle.
- **Voltage-Demand Relationship Matrix:** A voltage-demand relationship matrix which describe mathematically the voltage-demand relationship for every half-an-hour (of a day) of each season during the year for each characteristic demand profile and for *all* 60 primary substations.

UoM WP1 not only performed all agreed tasks and disseminated results as planned but also exceeded originally set objectives. All CLASS Successful Delivery Reward Criteria (SDRCs) have been achieved timely throughout the project. The most significant SDRCs are listed in Table 1.1 below.

**Table 1.1 Accomplishment of key Successful Delivery Reward Criteria (SDRCs)**

| SDRC | Planned Date | Completion Date |
|---|---|---|
| 1st six-monthly project progress report (PPR) of WP1 | April 2014 | April 2014 |
| 2nd six-monthly project progress report (PPR) of WP1 | November 2014 | November 2014 |
| Interim Profile Modelling Study | January 2015 | January 2015 |
| | Available in CLASS website [2]. http://www.enwl.co.uk/docs/default-source/class-documents/university-of-manchester-interim-report-wp1.pdf?sfvrsn=4 | |
| Final Profile Modelling Study | September 2015 | September 2015 |

The findings of the project have also been presented at two leading international conferences [3, 4] and attracted very high interest.

The detailed methodology for accomplishing all of the tasks, analyses and dissemination will be given in this report along with key findings. Following sub-section describes an outline of the report.

## 1.3 Outline of the Report

Section 1 describes the objectives, tasks and deliveries of the project and an outline of the report.

Section 2 presents a description of the CLASS trails and data acquisition approaches.

Section 3 reports detail load modelling procedure used in this study.

Section 4 illustrates the sensitivity/robustness analyses of developed load models.

Section 5 discusses voltage-demand matrix development and validation based on trial – 1 field measurements.

Section 6 summarizes major outcomes and learnings from the project.

# 2 Description of CLASS Trials and Data Collection

The objective of CLASS (Customer Load Active System Services) trials and field measurements is to demonstrate the CLASS solution to reduce peak network demand, voltage control and frequency management support to the Transmission System Operator (TSO). 4 types of trials have been designed to conduct in 60 selected substations. High resolution measurement devices and data acquisition systems have been deployed to record field measurements. Following subsections describes details of the CLASS trials, measurement sites and data acquisition.

## 2.1 Description of CLASS Trials

Having 4 specific objectives, 4 types of CLASS trials have been designed to conduct in 60 selected substations. Details of the CLASS trials have been presented in Table 2.1 below [1]. As can be seen from Table 2.1 that trail 1, 2, 3 and 4 have been designed to assess and analyse load modelling, peak demand reduction, frequency response and reactive power absorption, respectively. The focus of WP1, and hence the trial-1, is load modelling. The tap position of the transformers have been raised or lowered to establish the voltage-demand relationship.Trial-1 has been conducted in 15 selected substations across 3 load categories (i.e. industrial, domestic and mixed) over the entire annual cycle from June 2014 to May 2015.

**Table 2.1 Descriptions of the CLASS trials**

| Trials | Objective | Technique | Location | Trial Period |
|---|---|---|---|---|
| Trial – 1 | Load modelling | Raise and lower tap position | 15 *SS across 3 load categories | Across entire annual cycle |
| Trial – 2 | Peak demand reduction | Lower tap position | 14 SS | Peak demand |
| Trial – 3 | Frequency response | Switch out Transformer | All 60 SS | Anytime |
| Trial – 4 | Reactive power absorption | Stagger tap position | *GSP, regional and ENWL area | Minimum demand |

*SS – Substation, *GSP – Grid Supply Point

## 2.2 The Way of Conducting Trial – 1

The objective of this trial is to develop a voltage-demand matrix that will mathematically quantify the relationship for every half-an-hour across the annual cycle, for different types of connected load. A more detailed description of the CLASS Trial design methodology is documented in the CLASS Full Submission document [4]. Fig. 2.1 presents a schematic of tap changer operation of trial – 1.

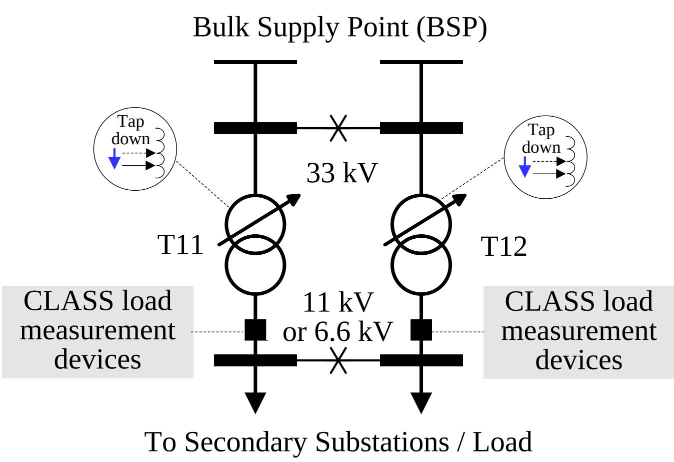



**Figure 2.1. Schematic of tap change at primary substations**

Typically, tap changer operation at a primary substation may occur between 2 and 20 times a day with each operation changing the secondary voltage by approximately 1.5%. This normal operation could provide sufficient data for the purposes of developing seasonal voltage-demand matrix to be used in the dashboard. However, to ensure that the development of seasonal load model can be validated and the full dynamics of the voltage regulation is captured, tests have been carried out at specific periods as outlined in the trial/test schedule for each primary substation.

During this trial period, both parallel primary transformers have been tapped by one tap position, which has changed the voltage depending on tap changer type and position by approximately 1.5%. The new tap position has been held for 15 minutes to capture any recovery phase of the demand. In order to capture any discernible effects caused by any initial dynamic response of the load following a change in voltage, high resolution monitoring has been deployed.

## 2.3 Trial – 1 CLASS (15) Measurement Sites

The CLASS measurement sites have been selected through a step-by-step analytical approach which has been documented in the “Trial Substation Selection Methodology” [3]. The steps include the consideration of demand zone, loading level and practical implications of the substations. The measurement sites have been chosen from different GSPs (Grid Supply Point) and at different voltage levels. There is also diversity in customer profile classes and peak load consumption.

15 representative trail-1 substations have been selected from the ENWL network for data analysis and load modelling. Trial-1 sites have different classes of customers connected to the corresponding substations. 15 selected substations fall into three categories, (a) large industrial and commercial, (b) largely domestic and (c) mixed. Table 2.2 shows the general descriptions of the selected 15 trial-1 primary substations.

**Table 2.2 Descriptions of the 15 selected CLASS trial-1 sites**

| | Primary | Primary Name | Substation Type | Grid Supply Point | Transformer Voltage | Total Customers | Peak Load (MW) |
|---|---|---|---|---|---|---|---|
| 1 | 100633 | Trafford Park North | Industrial | Carrington | 33/6.6 | 107 | 8.45 |
| 2 | 400402 | Avenham | Industrial | Penwortham East | 33/6.6 | 3366 | 13.31 |
| 3 | 100502 | Dickinson Street | Mixed | South Manchester | 33/6.6 | 2078 | 23.78 |
| 4 | 100508 | Central Manchester | Mixed | Stalybridge | 33/6.6 | 2261 | 14.09 |
| 5 | 302529 | Wilmslow | Mixed | South Manchester | 33/11 | 6217 | 13.52 |
| 6 | 100140 | Victoria Park | Mixed | Bredbury | 33/6.6 | 992 | 17.1 |
| 7 | 400013 | Hyndburn Road | Mixed | Padiham | 33/6.6 | 4270 | 11.32 |
| 8 | 400212 | Buckshaw | Mixed | Penwortham West | 33/11 | 1894 | 5.9 |
| 9 | 200406 | Kitt Green | Domestic | Washway Farm | 33/6.6 | 4405 | 19.42 |
| 10 | 100114 | Fallowfield | Domestic | Bredbury | 33/6.6 | 9981 | 14.03 |
| 11 | 302963 | Romiley | Domestic | Bredbury | 33/11 | 11997 | 14.52 |
| 12 | 609351 | Egremont | Domestic | Harker/Hutton | 33/11 | 10168 | 12.27 |
| 13 | 205308 | Ashton (Golborne) | Domestic | Bold | 33/11 | 14358 | 27.25 |
| 14 | 100639 | Blackfriars | Domestic | Agecroft | 33/6.6 | 4856 | 11.64 |
| 15 | 100642 | Bridgewater | Domestic | South Manchester | 33/6.6 | 2960 | 13.38 |

## 2.4 All CLASS (60) Measurements Sites

Above-mentioned 15 sites have been selected for trial-1, based on which load model should be developed and validated. Further, load models will be estimated for 45 other CLASS substations based on the similarity of their demand profile with the trial-1 substations. Altogether load models will be provided for 60 substations which have been selected for CLASS project. The list of 60 CLASS substations is given in Table 2.3.

**Table 2.3 Descriptions of the 60 selected CLASS sites**

| # | Substation | ID | Category | # | Substation | ID | Category |
|---|---|---|---|---|---|---|---|
| 1 | Avenham | 400402 | Industrial | 31 | Bollington | 301435 | Domestic |
| 2 | Blackpool | 400113 | Industrial | 32 | Winifred Road | 301304 | Domestic |
| 3 | Kingsway | 305100 | Industrial | 33 | Belgrave | 300832 | Domestic |
| 4 | Trafford PN | 100633 | Industrial | 34 | Middleton junction | 300015 | Domestic |
| 5 | Kirkby stephen | 609660 | Mixed | 35 | Golborne | 205308 | Domestic |
| 6 | Annie Pit | 609303 | Mixed | 36 | Carr Street | 205306 | Domestic |
| 7 | Chatsworth street | 609003 | Mixed | 37 | Skelmersdale | 200417 | Domestic |
| 8 | Douglas street | 400406 | Mixed | 38 | Ashton | 200414 | Domestic |
| 9 | Moss side | 400221 | Mixed | 39 | Kitt Green | 200406 | Domestic |
| 10 | Tarleton | 400213 | Mixed | 40 | Upholland | 200404 | Domestic |
| 11 | Buckshaw | 400212 | Mixed | 41 | Heady Hill | 200211 | Domestic |
| 12 | Bamber Bridge | 400201 | Mixed | 42 | Lostock | 200113 | Domestic |
| 13 | Cleveleys | 400104 | Mixed | 43 | Harwood | 200107 | Domestic |
| 14 | Hyndburn Road | 400013 | Mixed | 44 | Campbell Street | 200103 | Domestic |
| 15 | Wilmslow | 302529 | Mixed | 45 | Trinity | 100645 | Domestic |
| 16 | Hyde | 300061 | Mixed | 46 | Bridgewater | 100642 | Domestic |
| 17 | Chmamber Hall | 200205 | Mixed | 47 | Blackfriars | 100639 | Domestic |
| 18 | Central Manchester | 100508 | Mixed | 48 | Irlam | 100615 | Domestic |
| 19 | Dickinson Street | 100502 | Mixed | 49 | Chassen Road | 100608 | Domestic |
| 20 | Victoria Park | 100140 | Mixed | 50 | Longsight | 100135 | Domestic |
| 21 | Burrow Beck | 609910 | Domestic | 51 | Withington | 100131 | Domestic |
| 22 | Westgate | 609907 | Domestic | 52 | Stuart street | 100128 | Domestic |
| 23 | Egremont | 609351 | Domestic | 53 | Openshaw | 100125 | Domestic |
| 24 | Cecil Street | 400103 | Domestic | 54 | Didsbury | 100122 | Domestic |
| 25 | Griffin | 400006 | Domestic | 55 | Levenshulme | 100119 | Domestic |
| 26 | Littleborough | 304884 | Domestic | 56 | Green Lane | 100117 | Domestic |
| 27 | Romiley | 302963 | Domestic | 57 | Fallowfield | 100114 | Domestic |
| 28 | South west Macclesfield | 302660 | Domestic | 58 | Denton east | 100110 | Domestic |
| 29 | Willowbank | 302292 | Domestic | 59 | Droylsden east | 100107 | Domestic |
| 30 | Gowhole | 301671 | Domestic | 60 | Baguley | 100103 | Domestic |

## 2.5 Test Schedule of CLASS Trial-1

For assessing a wide range of operating conditions, there are voltage step-up and step-down by changing transformer tap position in different time-periods of the day (late night, morning, day and evening), in high-demand and low-demand days of the week, and in two seasons – summer (April to November) and winter (December to March). Test schedules have been chosen to replicate representative periods within a day. Time intervals have been chosen so that the static and changing load patterns can be captured at 1:00 to 6:00, 6:00 to 9:00, 9:00 to 17:00 and 17:00 to 1:00 time-periods. A large number (71 tests/trials) of suitable disturbances per bus have been analysed for load model development.

Sample trail-1 schedule has been presented in Table 2.4 which includes trial-1 from May to July 2014. These trials have been conducted over the entire annual cycle. Full list of the CLASS trial-1 (and other trials) are available in the Appendix A (Test Schedule) of the ENWL document "CLASS Trial design and associated test schedule" [1]. WP1 collected and analysed field measurement data from June 2014 to May 2015 to develop load models. Further, load models have been validated against trial-1 events.

**Table 2.4 Trail-1 at 15 selected substations, May – July, 2014**

| Substations | Date | Time | Date | Time | Date | Time | Date | Time | Date | Time |
|---|---|---|---|---|---|---|---|---|---|---|
| Trafford Park North | May18 | 9-9:30 | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 |
| Dickinson Street | June10 | 7-9 | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 |
| Kitt Green | June17 | 7-9 | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 |
| Avenham | June03 | 7-9 | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 |
| Central Manchester | June10 | 7-9 | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 |
| Fallowfield | May09 | 9-9:30 | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 |
| Romiley | | | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 |
| Wilmslow | | | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 |
| Egremont | May18 | 13-15 | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 |
| Ashton (Golborne) | May09 | 7-9 | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 |
| Buckshaw | June03 | 7-9 | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 |
| Victoria Park | | | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 |
| Hyndburn Road | June10 | 7-9 | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 |
| Blackfriars | May09 | 7-9 | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 |
| Bridgewater | | | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 |

## 2.6 CLASS Data Collection

Measurement data has been processed and/or normalized and/or scaled in at least three stages before it has been passed for load modelling. Fig. 2.2 depicts the architecture of data collection procedure.

In this series cascaded system, load monitoring, data transfer and database interfaces are connected together for collecting measurement data. Following devices are in operation in the CLASS data acquisition system,

- iStat i5MT (of Alstom) – Load monitoring device [5]
- Envoy device – Data transfer interface
- iHost - Database server

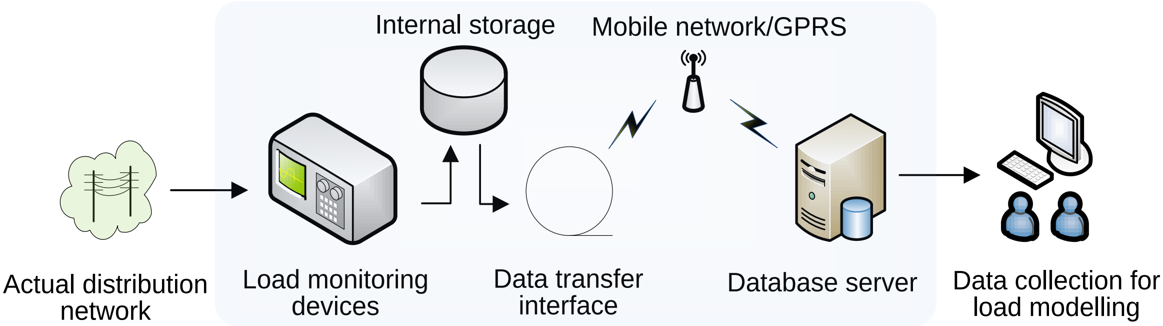



**Figure 2.2. Architecture of data collection and importing procedure [5]**

**Data Acquisition**

- iStat i5MT is installed at the bus bar of primary substations. iStat unit measures the parameters (time, voltage, real and reactive power and frequency) of each transformer. There are two iStat devices per substation for two transformers. The sampling rate of i5MT is 1Hz.
- iStat units have around 4GB of local storage. iStat transfer data to Envoy devices for further processing and updating to the iHost server
- The communication interface between Envoy and iHost is mostly 3G mobile network (roughly 90%) and GPRS (approximately 10%)
- Envoy devices capture sampled data every 5 seconds (sampling rates might go to 1 second). Updates of data at iHost are every hour.

CLASS is designed to be a low cost, rapidly deployable solution providing demand response and voltage regulation effects over minutes and hours. Data collection, quality and measurement systems installed reflect these aims and are not intended to be used for load model development for dynamic studies, i.e., for time frames shorter than several tens of seconds. Data quality for developing load models reflects the aim of CLASS project considering sustained response of load over half-an-hour interval after a disturbance in the network.

The following Chapter will discuss load model development approach based on CLASS trial data.

# 3 Load Modelling based on Trial Data

## 3.1 Load Modelling Approach

This section briefly describes the data processing procedure and load model development technique. The methodology has been applied to actual measurement data and a step-by-step procedure determines the appropriate load models and associated parameters. A step-by-step load modelling procedure has been presented in Fig. 3.1, which processes measurement data. This methodology divides the load modelling technique into four steps:

- **Recorded Measurements Extraction and Processing:** Actual measurement data is imported to the MATLAB software where the filtering and further processing of the data are carried out.
- **Data Filtering:** A range of filters, along with design parameters of different filters, have been tested to filter measured data and performances of different filters have been compared.
- **Load Model Selection:** Extensive literature review has identified traditional and advanced load modelling techniques which have been used to perform measurement-based load modelling.
- **Parameter Estimation and Validation:** Corresponding load model parameters have been estimated and parameters have been tested against trial-1 data for validation.

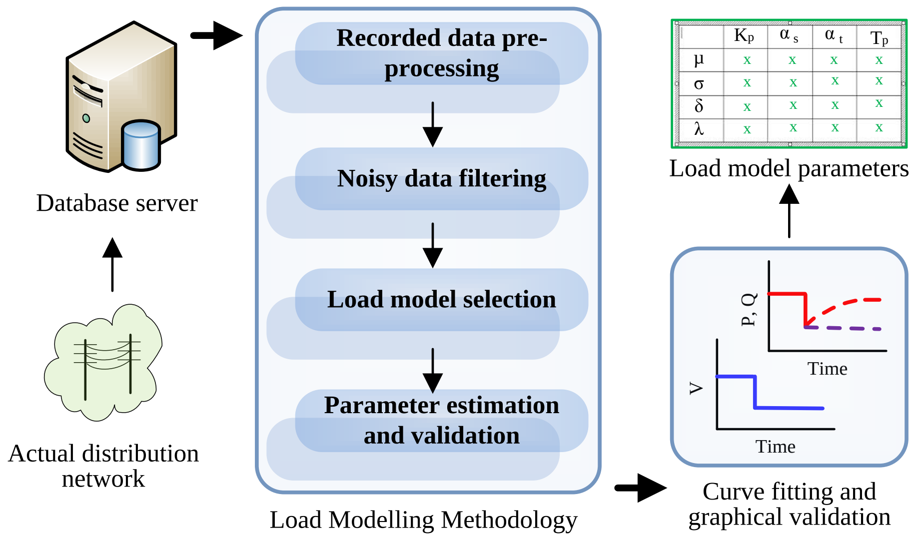



**Figure 3.1. Step-by-step workflow for CLASS data acquisition, load modelling and parameter estimation [3]**

## 3.2 Data Processing

Measurement data needs further processing and analysis for load model development. The first stage of this processing is filtering. Recorded signal contains naturally occurring noise in the measurements. Appropriate filtering of the recorded data is needed to eliminate unwanted natural disturbance. A range of filters has been tested to filter measured data and corresponding program/code has been developed. Design parameters of different filters have been investigated in this project and performances of different filters have been compared. A detail description and analysis of filtering techniques, design parameters and comparative performances of different filters have been provided in the "Interim Profile Modelling Study", which provides open access and is available online [2].

## 3.3 Load Model Selection

The purpose of load model development is to obtain a mathematical representation, which depicts the actual load behaviour. Load model can be developed through component-based or measurement-based approach, while the prior method models each individual load (component) and the latter one considers aggregate load (measurement) at substations. The load is finally represented in mathematical formulation with corresponding load model parameters. This subsection describes different load modelling approaches and load model parameters.

### 3.3.1 Different Load Models

Load model can be categorized into two basic groups – static and dynamic. A static load model determines the relationship among load model parameters irrespective of time. A dynamic load model includes the response of changing load behaviour with time. Fig 3.2 shows the classification of load models into static and dynamic along different approaches.

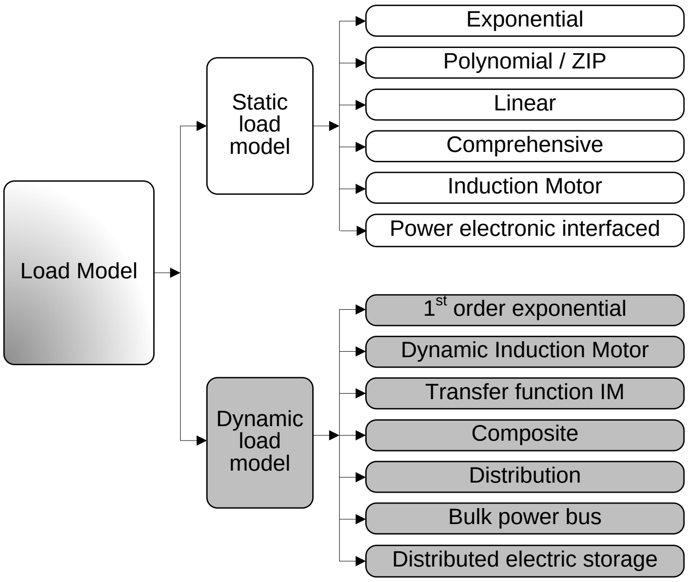



**Figure 3.2. Different load modelling techniques [6]**

Static load models include exponential, polynomial, linear, comprehensive, static induction motor and power electronic-interfaced models. Dynamic load models include exponential dynamic load model, dynamic induction motor (IM) models, transfer function IM model, composite, distribution, bulk power bus load and distributed energy storage system (DESS) models [8].

### 3.3.2 Candidate Load Models

Among different load models, candidate models have been selected based on the study purpose and available recorded measurements. The purpose of the CLASS load modelling is to demonstrate that voltage reductions (or rises) are followed by the demand reduction (or increase) at those substations at different loading conditions. The developed load models will be rolled-over through the whole ENWL network and (further) nationwide. Such intended applications of a load model require less complex models without sacrificing accuracy.

- Simplicity and general acceptability of the load model is required to implement and roll-over on a wide scale. Simplified models with less parameter can provide a general applicability of the model and high flexibility in the use [2]. Hence, widely used models such as (static) exponential, polynomial ZIP, (dynamic) 1st order exponential and induction motor model have been primarily selected.
- A further selection criterion of the candidate load model is resolution of data. As the data resolution is 1 second, induction motor (IM) model cannot be developed with reasonable accuracy as the load dynamics cannot be captured with this data resolution. The

recommended sampling rate for identification of dynamic load models at bulk supply buses is of the order of 1ms (1kHz) up to 100ms (10Hz) [8]. IM model, therefore, has not been considered as a candidate model.

**Static Exponential Load Model**

One of the most frequently used load models, which is the exponential model can be represented as follows,

$$P = P_0\left(\frac{V}{V_0}\right)^{K_p}, \; Q = Q_0\left(\frac{V}{V_0}\right)^{K_q} \tag{3.1}$$

The $K_p$ and $K_q$ represents the voltage exponents of real and reactive power for a static exponential load model [7].

**Static Polynomial / ZIP Load Model**

Another static load model frequently used is the second order polynomial model. The model can be represented as follows:

$$P = P_0 \times \left[Z_P\left(\frac{V}{V_0}\right)^2 + I_P\left(\frac{V}{V_0}\right) + P_P\right], \; Q = Q_0 \times \left[Z_Q\left(\frac{V}{V_0}\right)^2 + I_Q\left(\frac{V}{V_0}\right) + P_Q\right] \tag{3.2}$$

where, $Z_P, Z_Q$ represent the relative participation of constant impedance load, $I_P, I_Q$ are the relative participation of constant current load, and $P_P, P_Q$ are the relative participation of constant power load. This model is known as "ZIP model", as it contains constant impedance (Z), constant current (I) and constant power (P) loads components.

**Dynamic 1st Order Exponential Load Model**

A dynamic load model with exponential recovery can be presented by following equation [6],

$$P = P_0 \times \left[V^{\alpha_s} - V^{\alpha_t}\right]\left(e^{-\frac{t}{T_p}}\right), \; Q = Q_0 \times \left[V^{\beta_s} - V^{\beta_t}\right]\left(e^{-\frac{t}{T_q}}\right) \tag{3.3}$$

where, $\alpha_s$ and $\beta_s$ are steady-state voltage exponents, $\alpha_t$ and $\beta_t$ are transient voltage exponents and, $T_p$ and $T_q$ are load recovery time constant for real and reactive power, respectively.

## 3.4 Load Model Parameter Estimation

Load model parameter estimation fits the measured data with a selected mathematical model. Load model parameters represent the response of the load according to a corresponding model. This Section presents adopted technique for this study and illustration of the selected technique.

### 3.4.1 Selected Technique

Considering the general applicability and simplicity of the model, a least square optimization procedure has been chosen for parameter estimation.

### 3.4.2 Illustration of the Technique

The optimization procedure matches the measurement data with a mathematical model. The mathematical model can be represented through a standard curve, where measurement points are fitted to align with the curve. This approach is also known as the curve fitting technique.

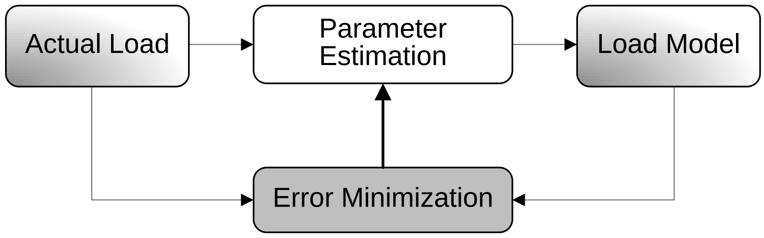



**Figure 3.3. Flowchart of the parameter estimation technique [8]**

**Curve Fitting Technique**

Curve fitting is the process of finding a mathematical form of relationship that most closely indicates relationship between dependent and independent variables. The "curve" defined by the mathematical equation is said to "fit" the observed data. The process of curve fitting is also called "regression". Once the regression equation is obtained, it can be used to predict the output variable. Mathematically, least-squared function is:

$$\min \sum_{i=1}^{n} \left(Y_i - \hat{Y}_i\right)^2 \tag{3.4}$$

For the sake of simplicity, only one explanatory variable is considered. This type of regression equation is referred to as simple linear regression. However, in most of the applications, there are more than one explanatory variables involved. This type of regression is called multiple linear regressions (MLR). The general form of MLR is given by:

$$Y_i = b_0 + b_1 X_{1i} + b_2 X_{2i} \ldots + b_n X_{ni} \tag{3.5}$$

## 3.5 Load Models Based on Trial Data at Trial – 1 Substations

Load models have been developed from field measurements for 15 selected (trial-1) substations. Based on the actual response of the load, static load models and corresponding load model parameters have been calculated.

- **Selection of Dynamic vs. Static Load Models**

Data collection, quality and measurement systems installed reflect these aims and are not intended to be used for load model development for dynamic studies, i.e., for time frames shorter than several tens of seconds. Data quality for developing load models reflects the aim of CLASS project considering sustained response of load over half-an-hour interval after a disturbance in the network.

Static load model is found to be the most appropriate load model for CLASS (load) measurement data as it captures the prolonged sustained response of the load following a voltage disturbance which is of interest in CLASS project.

- **Selection of ZIP vs. Exponential Load Models**

Polynomial (ZIP) model parameters have been derived for selected events following a voltage step-change. The 2nd order polynomial is in the form of, $P = P_0\left[Z_p\left(\frac{V}{V_0}\right)^2 + I_p\left(\frac{V}{V_0}\right) + P_p\right]$ represents the ZIP model. Filtered voltage and real (reactive) power has been used for parameter derivation. Curve fitting technique has been used considering the least square method. Table 3.1 presents ZIP and exponential model parameters for 3 substations. All parameters presented in Table 3.1 have been derived for 1st July 2014 at certain hours of the day following a voltage step-change. An individual coefficient of ZIP model does not have any particular physical meaning. All three terms together can model a load appropriately [7]. While analysing the obtained ZIP parameter values and looking at the requirement of the project, several issues have been considered to select an appropriate load model as discussed below,

**Table 3.1 ZIP model parameters for 3 substations**

| Substation | Type | ZIP Model Parameters | Exponential Model Parameters |
|---|---|---|---|
| **Trafford Park North** | Industrial | $Z_p = 0.11, I_p = 0.22, P_p = -708$<br>$Z_Q = 0.41, I_Q = 0.83, P_Q = -0.42$ | $K_p = 1.63$<br>$K_q = 3.67$ |
| **Fallowfield** | Domestic | $Z_p = 0.46, I_p = -0.91, P_p = -3040$<br>$Z_Q = 0.29, I_Q = -0.58, P_Q = -0.29$ | $K_p = 1.55$<br>$K_q = 5.88$ |
| **Victoria Park** | Mixed | $Z_p = 0.22, I_p = -0.44, P_p = -1483$<br>$Z_Q = 0.36, I_Q = -0.73\, P_Q = -0.37$ | $K_p = 0.83$<br>$K_q = 5.32$ |

- **Reasons for Selecting Static Exponential Model**

*Simplicity*: Exponential model requires a single parameter to describe voltage-demand (P-V or Q-V) relationship. It is a simple model, easily implementable and requires less computational burden. ZIP model requires three parameters to represent one P-V relationship.

*Coherence*: The voltage exponent value is self-explanatory and clearly represents the voltage-demand dependency (i.e. how much % voltage change will result how much % change in power). This coherence in voltage-demand cannot be observed in ZIP parameters, where 3 parameters are involved to describe P-V (or Q-V) relationship.

*Persistence:* The ranges of variation in ZIP model parameters are higher as can be seen from the values presented in tables above than the exponential parameters. The values obtained from polynomial curve fitting vary widely, which means these are more sensitive to any change in system.

*Large-scale application*: From the CLASS perspective, voltage-demand matrix will be used for half-an-hour interval for selected substations. Also, the CLASS concept will roll over throughout the whole UK. Exponential (single parameter) model will be easily deployable and less computationally intensive than ZIP model for such a large-scale application.

Therefore, static exponential load model is chosen for load modelling and parameter estimation at all substations in defining voltage-demand matrix.

# 4 Robustness Analysis of the Developed Load Model

A rigorous analysis of the actually measured data conditioning and pre-processing has been performed in this research. This Section presents these aspects of the study which involve impacts of filtering techniques, usable data extraction, influence of a selected window, different voltage variation threshold and outlier removal techniques.

## 4.1 Impact of Filtering Techniques

Filtering techniques can have a very high influence on measurement-based load modelling. The measured data are subject to measurement errors/noise and is needed to be filtered. There are several filtering techniques, which have been investigated in this research, such as SG (Savitzky-Golay) methods, fast Fourier transform, moving average, and adjacent average techniques. A comparison of the performances among these filters have been investigated and presented in detail in the "Interim Profile Modelling Study" [2].

It should be noted that the filtering techniques have a very high influence on individual load modelling based on trial data. However, for the seasonal load model development, which employs yearly field measurement, and statistical means are used to derive half-hourly load model, the impact of filtering techniques are mitigated.

## 4.2 Extracting Required Information

After filtering the voltage/power data, extracting usable voltage/power signals from the recorded data stream is an important aspect of load modelling. For instance, Fig. 4.1 identifies 4 voltage/power windows from a snapshot of actually measured data.

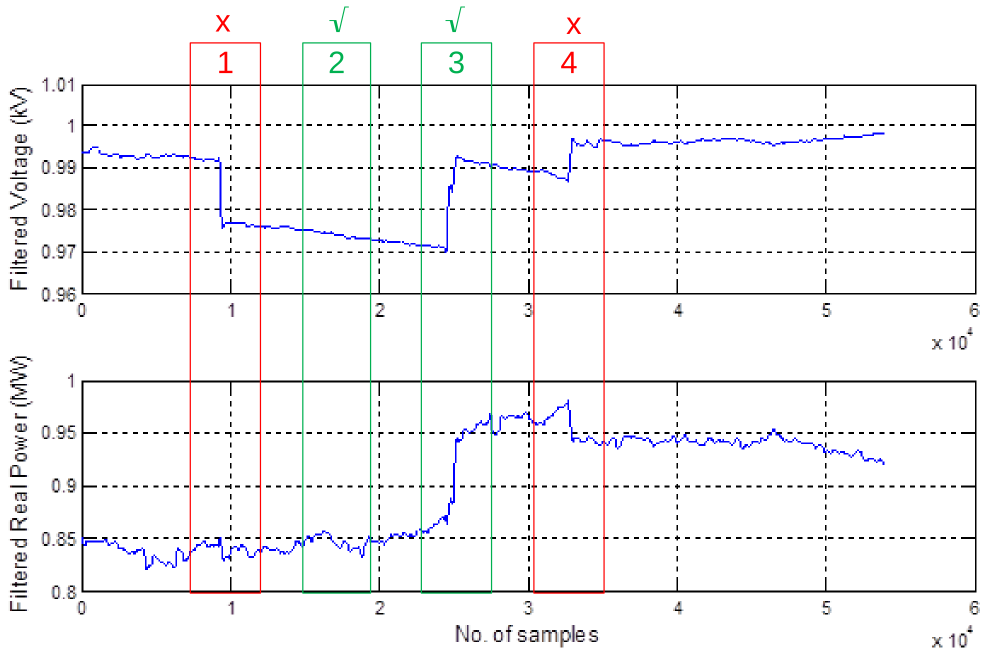



**Figure 4.1. Extracting required (initiated/unintended load/system) response and static/dynamic information from real measurement data**

Window 1 is not usable as this is not capturing a real power response appropriately following a voltage disturbance. This doesn't seem to be the load response rather represents dominant system response (that might be influenced by other devices in the network). Windows 2 and 3 can be used for modelling steady-state and dynamic responses respectively, as these windows capture consistent and realistic load behaviours. On the other hand, window 4 doesn't capture the natural change in real power following the voltage disturbance (it shows voltage increase followed by real power reduction which ultimately could be consequence of load disconnection, i.e., change in load composition), and hence it can't be used for load modelling purposes.

## 4.3 Influence of Window Size

Smoothing a voltage/power signal to avoid spontaneous load changes is important for proper identification of load responses. There is a possibility that some loads might be connected / disconnected from the system at the instant of initiated voltage disturbance, which is needed to be avoided [9].

Therefore, while extracting a voltage/power window for load modelling, selection of the window size is a decisive factor. Load model parameters could be different for a short term and/or a long term observation. A study suggests that it generally takes about 30 minutes of data to determine the steady-state characteristics (assuming an absence of other voltage regulation devices in the network) while it takes about 30 seconds to determine transient characteristics of most mixed loads at higher voltage buses [7]. This time can be significantly shorter and of the order of a few seconds in case of single type of load (e.g., 100% industrial load dominated by induction motors) connected at a certain bus [10, 11].

In this study, different window sizes of 2 minutes, 5 minutes and 9 minutes are tested. To illustrate a clear view of the influence of different window sizes on seasonal load model development, a 2% voltage variation, which has less load model data, are presented in Fig. 4.2. As statistical means are used to derive half-hourly load model, the impact of different window sizes are mitigated. Therefore, to reduce the impact of spontaneous load changes and signal noise, 9 minutes of fitting window are selected in this study for seasonal voltage-demand matrix development.

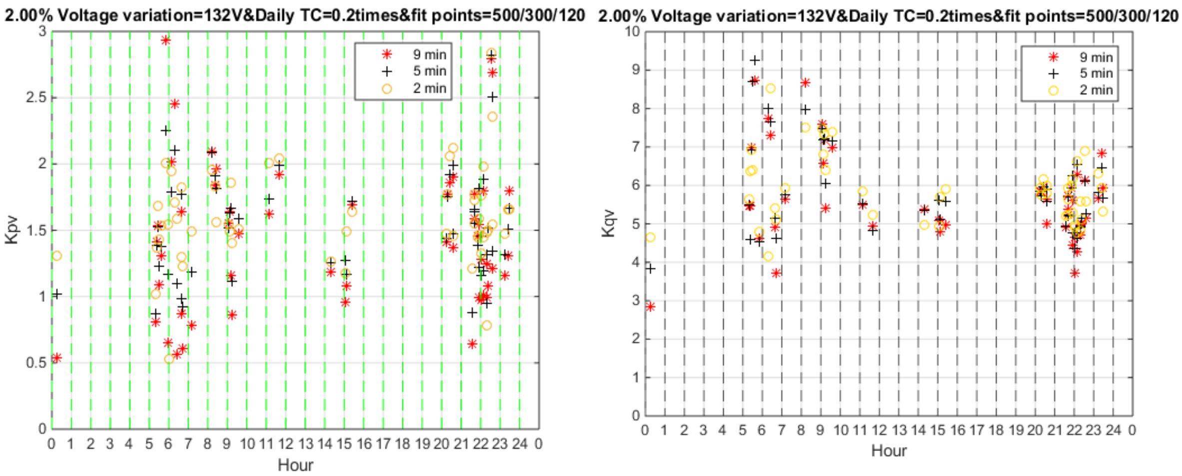



**Figure 4.2. Different lengths of fitting window**

## 4.4 Different Thresholds of Voltage Disturbances

Impacts of different voltage threshold in the selection of events have been presented in Fig. 4.3. Voltage variation threshold have been considered as 0.76%, 1%, 1.44% and 2% and the number of events, are 1900, 550, 250 and 100, respectively.

The data points used for seasonal load model development for $K_p$ and $K_q$ under different voltage variation thresholds are investigated in this study. 1.44% corresponds to the voltage variation caused by 1 tap change, however, due to the impact of natural load/voltage variation and field measurement noise, the actual voltage variation is less than 1.44%, therefore, 1% voltage variation is used for seasonal load model development.

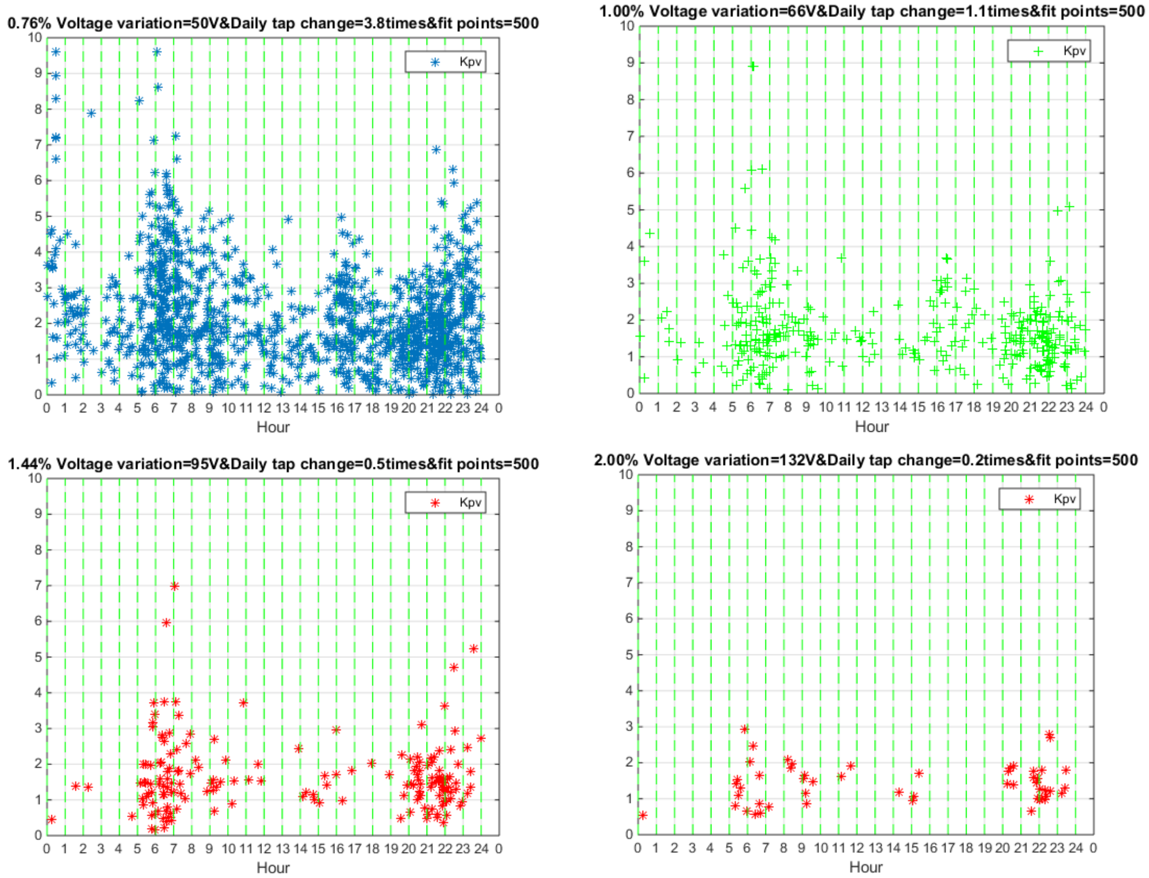



**Figure 4.3. $K_p$ and $K_q$ under different voltage variation threshold**

## 4.5 Outlier Removal

The load models calculated directly from each voltage variation greater than 1% inevitably contain inappropriate points, as shown in the black circles in Fig. 4.4. Outlier removal techniques are applied to remove these points. However, as statistical means are used to derive half-hourly load model, outlier removal makes very negligible impact on the values of load models.

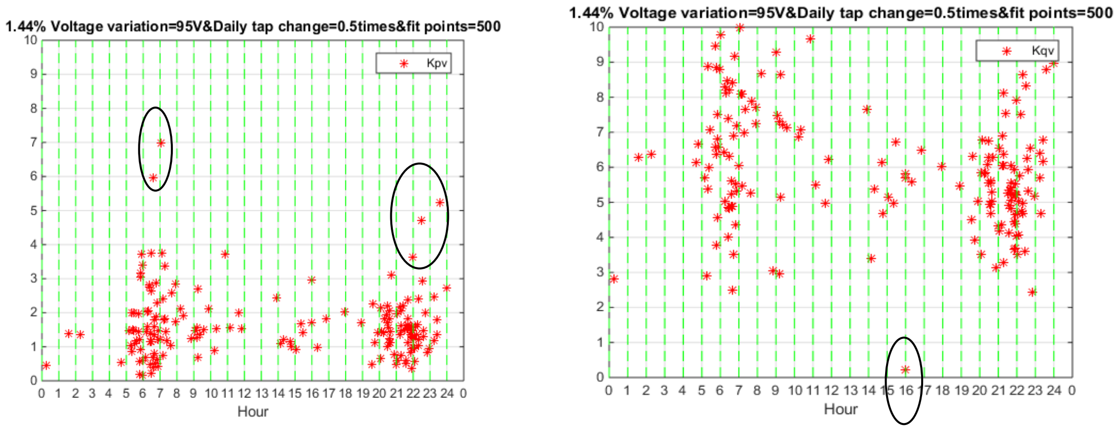



**Figure 4.4. Outliers' removal from $K_p$ and $K_q$**

# 5 Voltage-Demand Matrix: Development and Validation

Appropriate tools and techniques have been developed for automatic development of load models based on field measurements. Seasonal voltage-demand relationship matrices for every half-an-hour intervals for 15 trial-1 substations as well as for all remaining 45 non-trial-1 buses have been developed using a yearly data from 1st June 2014 to 29th May 2015, a full 24hr (48 x ½ hr) load matrix covering 4 seasons for 3 defined customer profile classes (domestic, industrial and commercial, and mixed), divided between weekdays and weekends have been presented.

## 5.1 Capturing Voltage Disturbance

Typically, tap changer operation at a primary substation may occur between 2-20 times per day with each operation changing the secondary voltage by approximately 1.5% [1]. This normal operation should provide sufficient data for the development of seasonal voltage-demand matrix. In the CLASS project, all 60 selected primary substations are deployed with high resolution monitoring devices (1 Hz), where the secondary voltage, active power, reactive power and other parameters are measured. Therefore, the data sets of secondary voltage, active and reactive power are saved when the voltage variation is greater than 1% (9-minute samples before and after the variation, respectively). The search for voltage variation greater than 1% is run throughout a year from June 2014 to May 2015. The saved data are used to develop seasonal/daily/half-hourly load models.

Fig. 5.1 presented 10 voltage changes which are greater than 1%. It can be seen that reactive power is less variable compared to active power. Outlier removal techniques are used to ignore inappropriate voltage step changes, for example, voltage is increasing followed by a decrement in power.

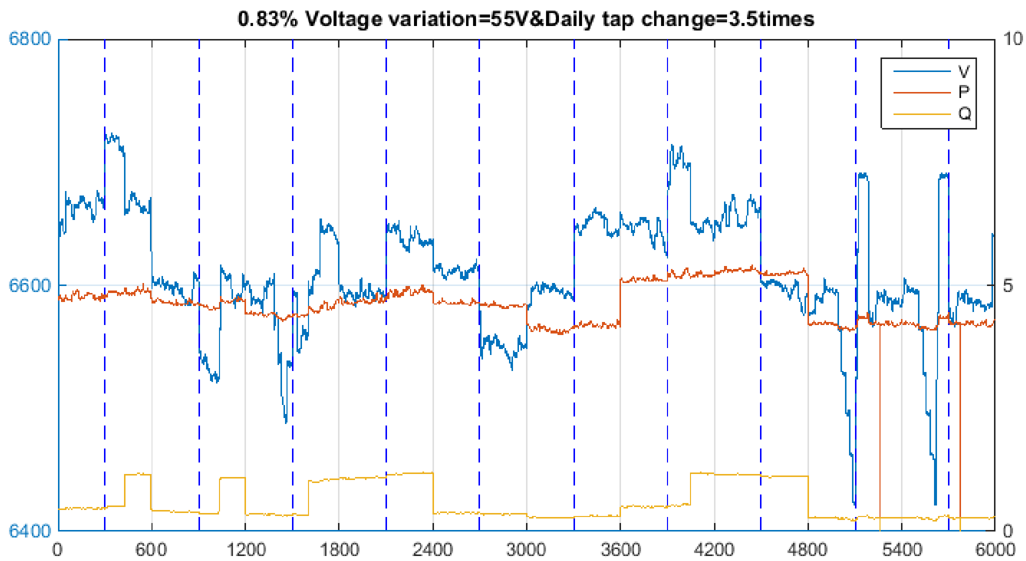



**Figure 5.1. Identified 10 events of voltage change >1%**

## 5.2 Development of Automatic 24 hr (48 x ½ hr) Voltage-Demand Matrix

A full 24hr (48 x ½ hr) matrix for every day over 4 seasons for each profile class, split between weekdays and weekends have been developed, where the seasonal splits are as follows,

- Winter – December, January and February
- Spring – March, April and May
- Summer – June, July and August
- Autumn – September, October and November

As mentioned in the previous section, saved voltage variations greater than 1% will be used for seasonal load modelling. Taking 'Romiley' primary substation as an example, as presented in Fig. 5.1,

- Totally 480 voltage variations are identified from one year of field measurement.
- An exponential load model is calculated for each identified voltage variation, then 480 pairs of Kp and Kq values are obtained.
- According to the types of seasons and days, obtained $K_p$ and $K_q$ values are divided into 8 groups, i.e. winter weekday/weekend, spring weekday/weekend, summer weekday/weekend, and autumn weekday/weekend, which are plotted in Fig. 5.2.

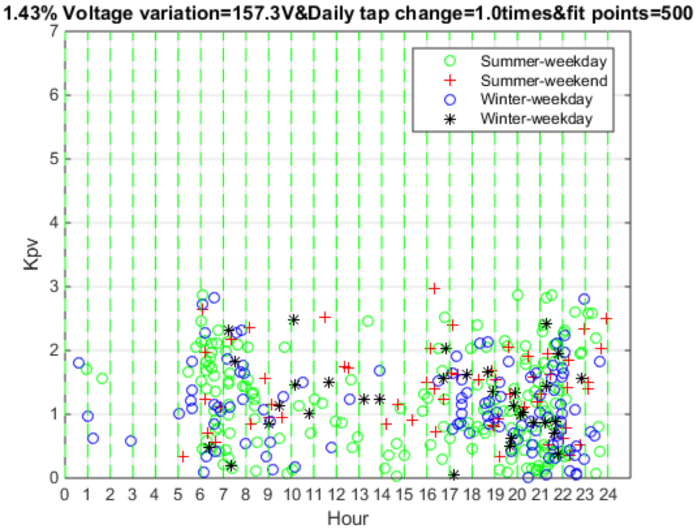



**Figure 5.2. Scatter plot of all yearly points**

### 5.2.1 Obtaining Half-Hourly Load Models from Field Measurements

To produce a full 24hr (48x½ hr) matrix, the following procedure is adopted:

- Looking at the blue dots only in Fig. 5.2, i.e. all the points for winter weekday.
- For each time stamp, the average values of voltage exponent are generated using time frame from 0.5 hour to 24 hours, with a step size of 0.5 hour to 24 hours.
    - For example, at 4:30am, its 0.5 hour window size is from 4:15-4:45am. As there is no blue points in this time period, the average value of this time period is empty, so In Matlab, it is marked as $Kp_{4:30,\ 0.5}$=[ ];
    - Then the window size increases to 1 hour, that is from 4:00-5:00am, one blue dot (1.02) at 5am is in this time period. So the average value for 4:30am with 1 hour time period is 1.02. it is marked as $Kp_{4:30,\ 1}$=1.02;
    - Further the window size increases to 1.5 hours, that is from 3:45-5:15am, only one blue dot (say 1.02) at 5am is in this time period. So the average value for 4:30am with 1.5 hour time period is 1.02, as $Kp_{4:30,\ 1.5=}$1.02;
    - Then the window size increases to 2 hours, that is from 3:30-5:30am, one blue dot (say 1.02) at 5am is in this time period, and the blue dot at 3am (say 0.6) is also in. So the average value for 4:30am with 2 hour time period is 0.81=(1.02+0.6)/2, marked as $Kp_{4:30,\ 2.0=}$0.81;
    - By repeating the process as described in step a-to-d, the window size increases to 24 hours with a step size of 0.5 hour. Then a vector has been obtained for the time stamp of 4:30am, which is 1x48.
- Then the process of 4:30am has been repeated for each time from 00:00, 00:30,..., 23:00, 23:30, with a step size of 30 minutes, and a matrix of $K_p$ has been obtained, which is 48x48

(some elements could be empty). Each column representing the time stamp from 00:00-23:30, each row represents the average of different window size from 0.5 hour to 24 hours, as shown in Fig. 4.3.

- From Fig.5.3, a box plot has been obtained as shown in Fig. 5.4. Boxplot (X) produces a box plot of the data in X. If X is a matrix, there is one box per column; if X is a vector, there is just one box. In each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually (as red +).
- As each column of the 48x48 $K_p$ matrix represents a half-hourly time stamp, a boxplot includes all the data of each column, and hence there is 48 boxplots, each represents each half-an-hour, as shown in Fig. 5.4.

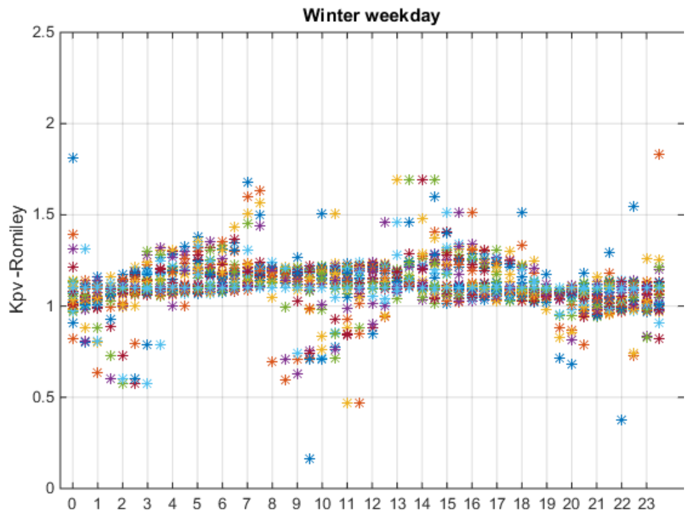



**Figure 5.3. Half-hourly Kp generated by average value of different window size**

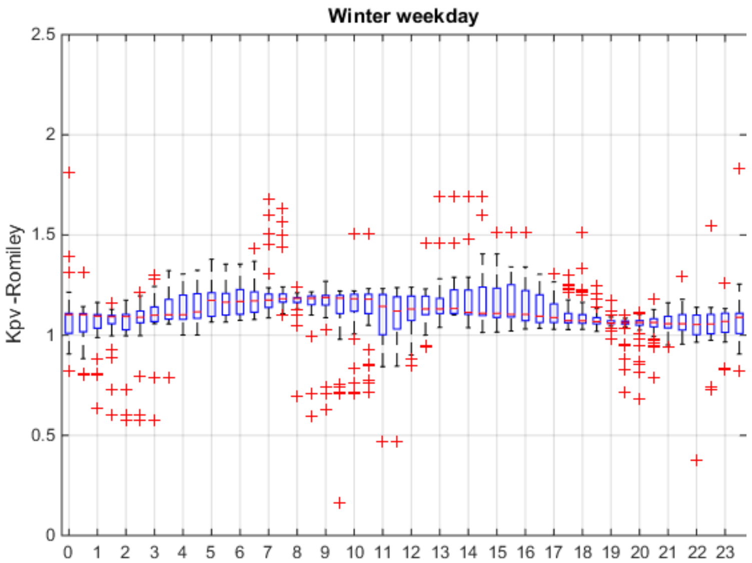



**Figure 5.4. Boxplot for the data points of each half-an-hour as presented in Fig. 5.3**

By repeating the above process for the remaining 7 data sets (winter weekend, spring weekday/weekend, summer weekday/weekend, and autumn weekday/weekend), 7 more boxplot sets for $K_p$ have been obtained. In summary, there are 8 sets of boxplots for $K_p$ (active power) and 8 sets for $K_q$ (reactive power) for each substation.

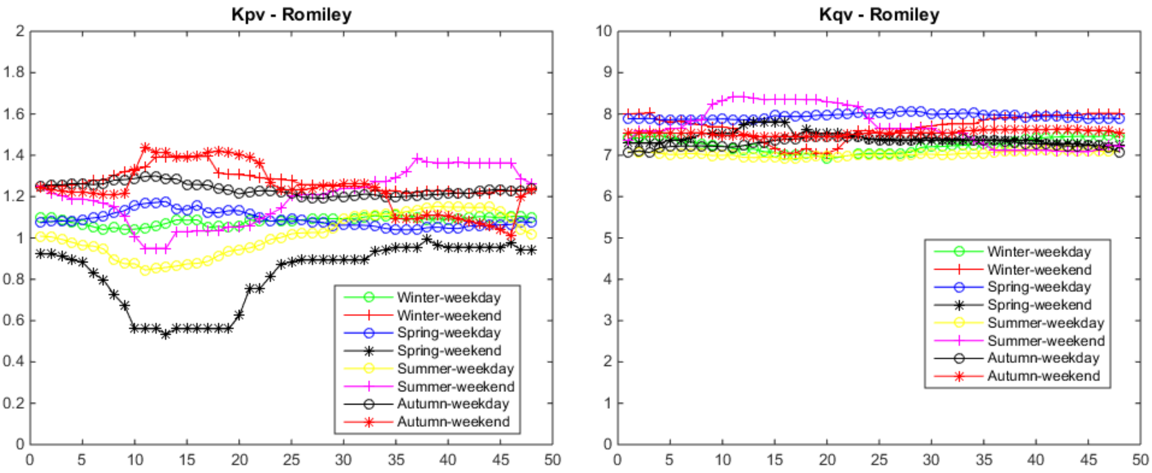
## 5.3 Voltage-Demand Matrix Format: Example of a Substation for One Day

The load parameters varies with seasons and types of days (weekdays/weekends), it also changes with the time of a day influenced by the changing load-mix and consumption pattern of the substations. To account for the uncertainty of load consumption pattern, voltage-demand matrix has been derived with mean, upper bound, lower bound, 75th percentile and 25th percentile. A typical seasonal voltage-demand matrix for $K_p$ values for winter weekday for the substation of 'Romiley' is presented in Table 5.1. For each substation, there will be 8 such tables for $K_p$ values providing above 5 parameters for 4 seasons and 2 types of day, and 8 tables for $K_q$ values.

**Table 5.1 (48x½ hr) 24hr load matrix for Kp values for Romiley for winter weekday**

| No. | Time stamp | Mean | Upper bound | Lower bound | 75th percentile | 25th percentile |
|---|---|---|---|---|---|---|
| **1** | 00:00 | 1.10 | 1.15 | 0.96 | 1.13 | 0.96 |
| **2** | 00:30 | 1.10 | 1.20 | 0.97 | 1.12 | 0.97 |
| **3** | 01:00 | 1.09 | 1.15 | 0.99 | 1.10 | 0.99 |
| **4** | 01:30 | 1.07 | 1.12 | 1.03 | 1.09 | 1.03 |
| **5** | 02:00 | 1.07 | 1.15 | 0.98 | 1.09 | 0.98 |
| **6** | 02:30 | 1.05 | 1.19 | 0.88 | 1.10 | 0.88 |
| **7** | 03:00 | 1.04 | 1.24 | 0.88 | 1.11 | 0.88 |
| **8** | 03:30 | 1.05 | 1.24 | 0.88 | 1.10 | 0.88 |
| **9** | 04:00 | 1.04 | 1.27 | 0.85 | 1.13 | 0.85 |
| **10** | 04:30 | 1.04 | 1.27 | 0.87 | 1.13 | 0.87 |
| **11** | 05:00 | 1.05 | 1.20 | 0.94 | 1.11 | 0.94 |
| **12** | 05:30 | 1.06 | 1.16 | 1.01 | 1.09 | 1.01 |
| **13** | 06:00 | 1.07 | 1.21 | 1.01 | 1.12 | 1.01 |
| **14** | 06:30 | 1.09 | 1.30 | 1.01 | 1.14 | 1.01 |
| **15** | 07:00 | 1.09 | 1.29 | 1.01 | 1.14 | 1.01 |
| **16** | 07:30 | 1.09 | 1.24 | 1.01 | 1.15 | 1.01 |
| **17** | 08:00 | 1.05 | 1.29 | 0.94 | 1.13 | 0.94 |
| **18** | 08:30 | 1.06 | 1.18 | 0.86 | 1.12 | 0.86 |
| **19** | 09:00 | 1.05 | 1.17 | 0.99 | 1.11 | 0.99 |
| **20** | 09:30 | 1.06 | 1.17 | 0.97 | 1.11 | 0.97 |
| **21** | 10:00 | 1.09 | 1.18 | 0.96 | 1.11 | 0.96 |
| **22** | 10:30 | 1.08 | 1.18 | 0.48 | 1.11 | 0.48 |
| **23** | 11:00 | 1.08 | 1.19 | 0.39 | 1.12 | 0.39 |
| **24** | 11:30 | 1.08 | 1.23 | 0.54 | 1.12 | 0.54 |
| **25** | 12:00 | 1.08 | 1.24 | 0.68 | 1.10 | 0.68 |
| **26** | 12:30 | 1.09 | 1.20 | 1.00 | 1.12 | 1.00 |
| **27** | 13:00 | 1.09 | 1.19 | 1.07 | 1.13 | 1.07 |
| **28** | 13:30 | 1.09 | 1.29 | 1.06 | 1.17 | 1.06 |
| **29** | 14:00 | 1.09 | 1.23 | 1.05 | 1.16 | 1.05 |
| **30** | 14:30 | 1.09 | 1.35 | 0.98 | 1.21 | 0.98 |
| **31** | 15:00 | 1.09 | 1.49 | 1.04 | 1.26 | 1.04 |
| **32** | 15:30 | 1.10 | 1.38 | 1.04 | 1.21 | 1.04 |
| **33** | 16:00 | 1.11 | 1.29 | 1.05 | 1.20 | 1.05 |
| **34** | 16:30 | 1.10 | 1.30 | 1.06 | 1.18 | 1.06 |
| **35** | 17:00 | 1.11 | 1.22 | 1.06 | 1.15 | 1.06 |
| **36** | 17:30 | 1.11 | 1.19 | 1.05 | 1.13 | 1.05 |
| **37** | 18:00 | 1.10 | 1.16 | 1.04 | 1.12 | 1.04 |
| **38** | 18:30 | 1.09 | 1.16 | 0.97 | 1.13 | 0.97 |
| **39** | 19:00 | 1.09 | 1.14 | 0.98 | 1.13 | 0.98 |
| **40** | 19:30 | 1.09 | 1.14 | 0.92 | 1.13 | 0.92 |
| **41** | 20:00 | 1.09 | 1.14 | 0.88 | 1.13 | 0.88 |
| **42** | 20:30 | 1.10 | 1.14 | 0.79 | 1.13 | 0.79 |
| **43** | 21:00 | 1.10 | 1.28 | 0.89 | 1.13 | 0.89 |
| **44** | 21:30 | 1.10 | 1.14 | 0.98 | 1.13 | 0.98 |
| **45** | 22:00 | 1.10 | 1.15 | 0.99 | 1.12 | 0.99 |
| **46** | 22:30 | 1.10 | 1.17 | 0.92 | 1.13 | 0.92 |
| **47** | 23:00 | 1.10 | 1.26 | 0.98 | 1.14 | 0.98 |
| **48** | 23:30 | 1.10 | 1.19 | 0.98 | 1.13 | 0.98 |

The mean values of $K_p$ for 'Romiley' substation is presented in Fig. 5.5. There is one such curve for each season and each type of days, describing 24 hr (48x½ hr) load parameters, totally 8 curves in each subfigure.

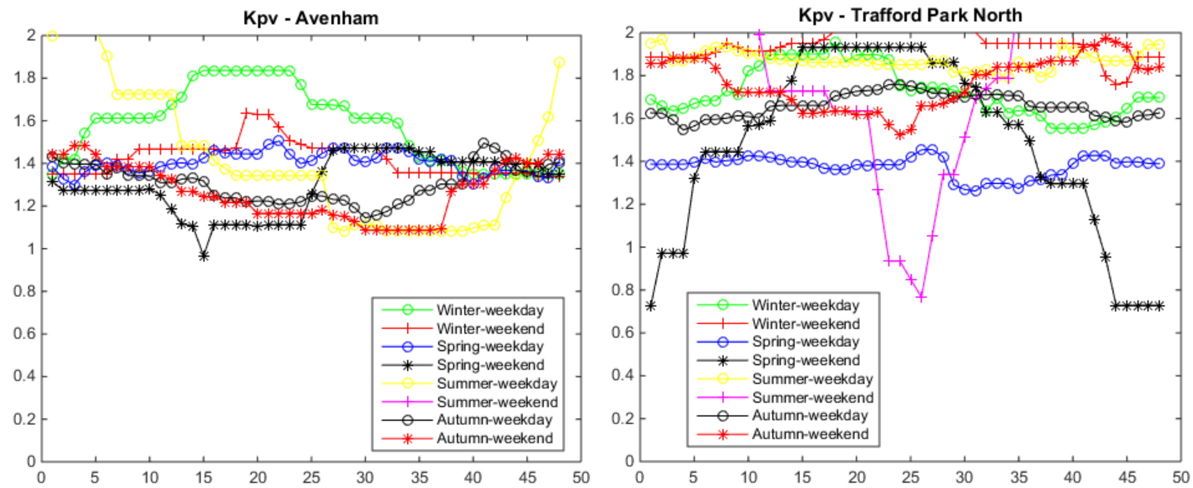



(a) Kp (b) Kq

**Figure 5.5. Mean values of $K_p$ and $K_q$ for Romiley substation obtained from 24hr (48x½ hr) voltage-demand matrix**

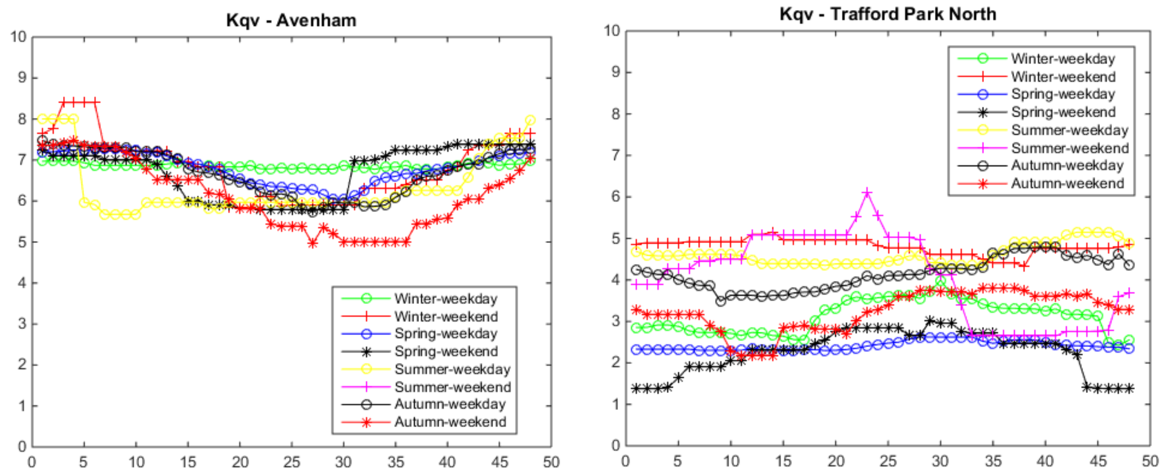
## 5.3.1 Voltage-Demand Matrix (48x½ hr): Example of 2 Industrial, 2 Domestic and 2 Mixed Substations

The seasonal voltage-demand 24 hr (48x½ hr) matrix is developed for all 60 selected substations. 60 primary substations fall into the three types of customer classes – (a) large industrial and commercial, (b) largely domestic and (c) mixed. 2 trialled substations from each type are presented here with seasonal means of $K_p$ and $K_q$ values. Fig. 5.6 to 5.8 presents average $K_p$ and $K_q$ values (48x½ hr) for 2 industrial (Avenham and Trafford Park North), 2 domestic (Fallowfield and Romiley) and 2 mixed (Victoria Park and Hyndburn Road) substations.



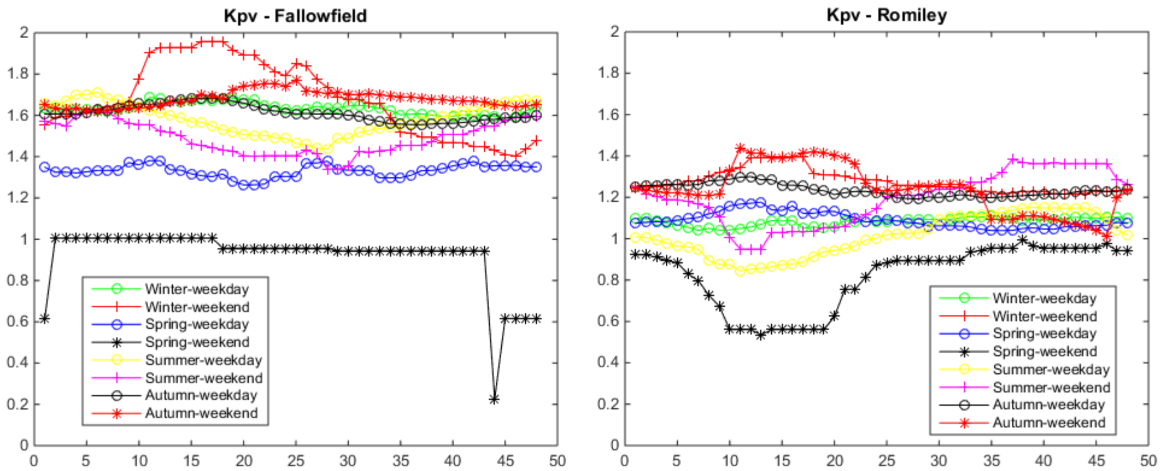

(a) Kp – Avenham (b) Kp – Trafford Park North

**Figure 5.6a. Mean values of $K_p$ for industrial substations: Avenham and Trafford Park North**

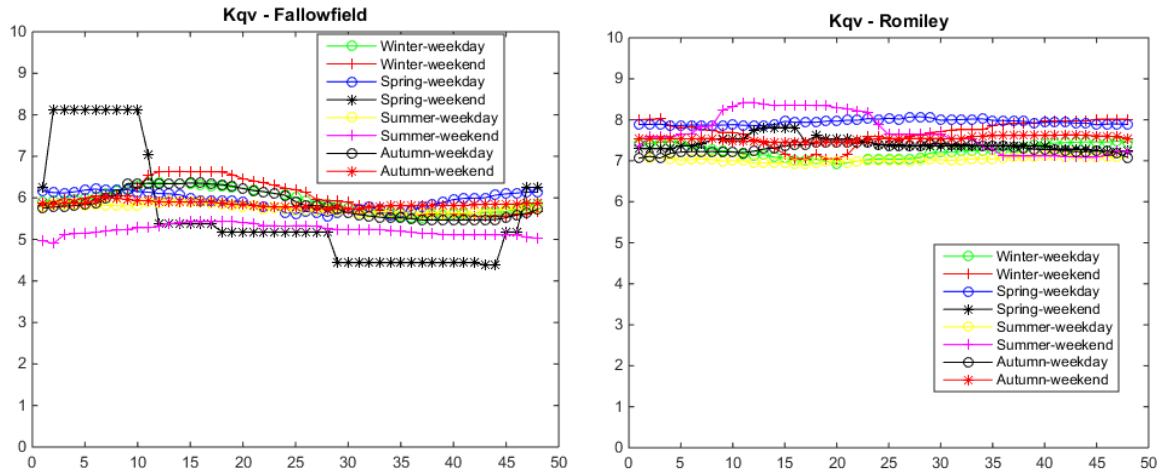



(c) Kq – Avenham (d) Kq – Trafford Park North

**Figure 5.6b. Mean values of $K_q$ for industrial substations: Avenham and Trafford Park North**

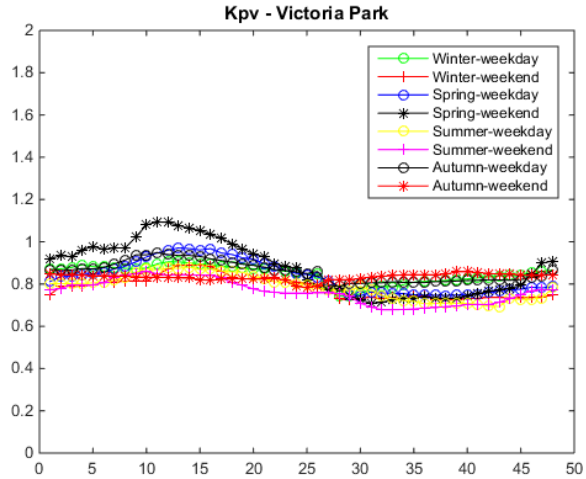



(a) Kp – Fallowfield (b) Kp – Romiley

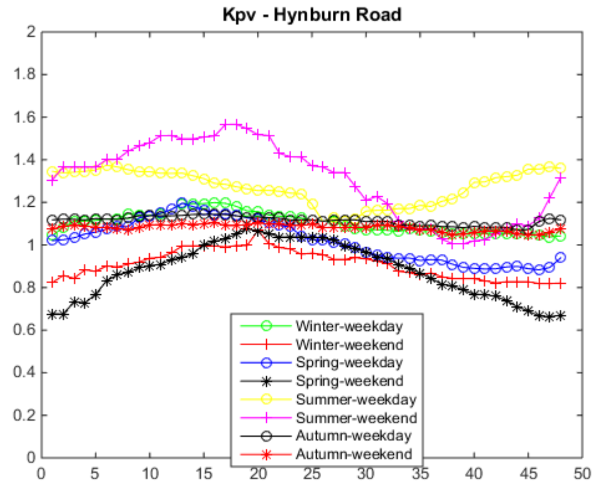



(c) Kq – Fallowfield (d) Kq – Romiley

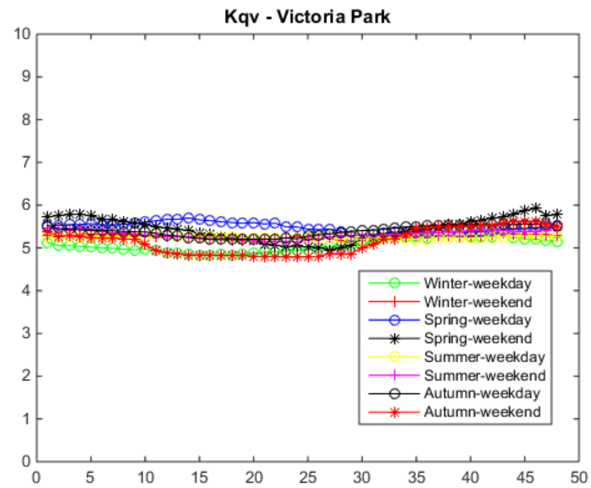
**Figure 5.7. Mean values of $K_p$ and $K_q$ for domestic substations: Fallowfield and Romiley**



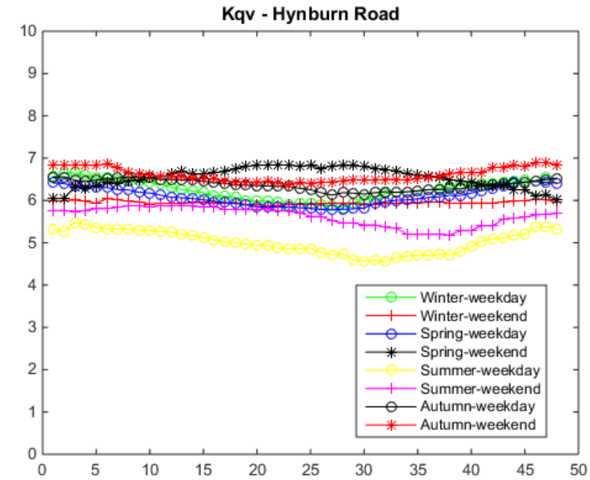

(a) Kp – Victoria Park




(b) Kp – Hyndburn Road




(c) Kq – Victoria Park




(d) Kq – Hyndburn Road

**Figure 5.8. Mean values of $K_p$ and $K_q$ for mix-type substations: Victoria and Hyndburn Road**

From Fig 5.6 – 5.8, it can be seen that the load model parameters describing weekday load behaviour are more consistent, i.e., less variable. Differences in weekdays and weekend parameters are influenced by both the changing load-mix of the substations and changes in consumption pattern during weekend (even though the overall load-mix may remain the same). The results for the rest 54 selected substations are given in the appendix as seasonal load model parameters.

Estimated load model parameter values can be summarized as shown in Table 5.2 and 5.3 below.

- *For domestic substations, average value of real power exponent for weekday is about 1.30 and reactive power exponent is about 6.06;*
- *For industrial and commercial substations, average value of real power exponent for a weekday is close to 1.48 and reactive power exponent is close to 5.58;*
- *For mixed-type substations, average value of real power exponent for a weekday is about 1.22 and reactive power exponent is about 5.90.*

**Table 5.2 Statistics of Kp values on weekdays of all 60 substations**

| | Mainly domestic | | | Industrial/commercial | | | Mixed | | |
|---|---|---|---|---|---|---|---|---|---|
| | Min | Avg | Max | Min | Avg | Max | Min | Avg | Max |
| **Winter** | 0.87 | 1.33 | 1.93 | 0.86 | 1.47 | 1.85 | 0.70 | 1.23 | 1.91 |
| **Spring** | 0.83 | 1.32 | 1.86 | 1.02 | 1.39 | 1.80 | 0.80 | 1.20 | 1.68 |
| **Summer** | 0.72 | 1.25 | 2.11 | 1.02 | 1.52 | 1.97 | 0.70 | 1.20 | 1.58 |
| **Autumn** | 0.67 | 1.31 | 1.91 | 0.95 | 1.53 | 1.98 | 0.71 | 1.23 | 1.80 |

**Table 5.3 Statistics of Kq values on weekdays of all 60 substations**

| | Mainly domestic | | | Industrial/commercial | | | Mixed | | |
|---|---|---|---|---|---|---|---|---|---|
| | Min | Avg | Max | Min | Avg | Max | Min | Avg | Max |
| **Winter** | 3.98 | 5.96 | 7.98 | 3.79 | 5.62 | 6.86 | 4.36 | 5.92 | 6.93 |
| **Spring** | 4.58 | 6.14 | 8.05 | 4.30 | 5.56 | 6.75 | 3.82 | 5.82 | 7.52 |
| **Summer** | 3.25 | 5.98 | 7.62 | 3.96 | 5.65 | 7.26 | 4.52 | 5.75 | 6.95 |
| **Autumn** | 4.41 | 6.16 | 8.06 | 2.41 | 5.49 | 6.79 | 4.26 | 6.10 | 7.58 |

The results presented include a detailed seasonal 24 hr (48 x ½ hr) voltage-demand relationship matrix for all 60 ENWL monitored substations (15 trial-1 and 45 non-trial-1 substations).

## 5.4 Validation of Voltage-Demand Matrix with Trial Data

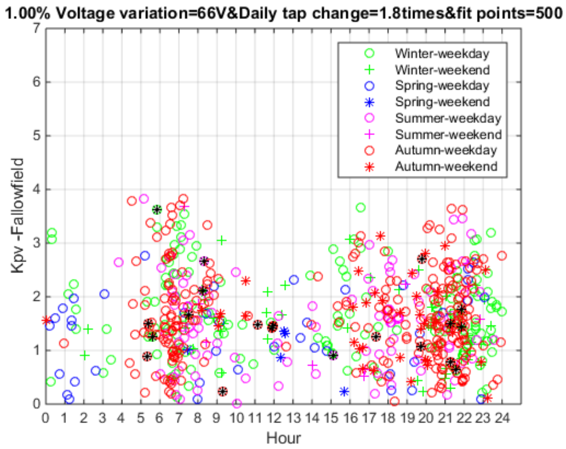
Appropriate tools and techniques have been developed for load model validation at non-trial hours of all 60 selected substations based on field measurement data. As mentioned before, among 60 substations, 15 substations have been undergone through trial-1 for the purpose of load modelling and the detailed time schedule for all trials can be found in the Appendix - CLASS test schedule. The seasonal load models will be validated by the trial data in this section.

For all 15 trialled substation, load models have been developed at trial hours and will be compared with the seasonal voltage-demand matrix. The validation is done for all 15 substations, however, for the length limit of this report, the comparison results of 2 substations are presented in Fig. 5.9, and the validation for the rest 13 trialled substations can be found in the Appendix - Validation with trial data.

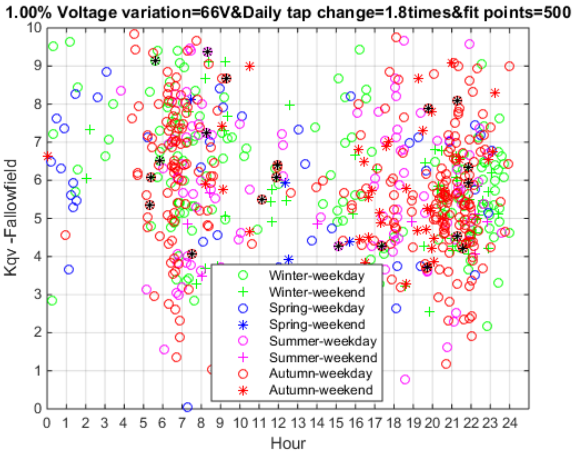
In Fig. 5.9, trials are highlighted by black asterisk ('*'), and the rest points are load parameters calculated by yearly field measurements (pairs of voltage/active power/reactive power), where circles ('o') represent weekdays of different seasons.

It can be seen that the trial data varies over a wide range for $K_p$ and $K_q$ values. This validates the development of the seasonal voltage-demand matrix which supplies a statistical mean (for seasonal load curves as well as maximum, minimum, $75^{th}$ and $25^{th}$ percentile values) to cover the variations due to various reasons, e.g. the changing load-mix of the substations and changes in consumption pattern during weekend.

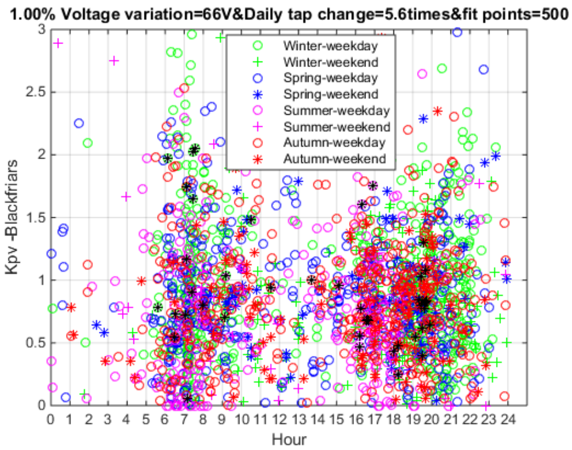
It can be noted that some substations may have more 'selected events' than the other, as shown in Fig. 5.9, due to the voltage change within a certain time window, e.g. 0 – 8 am. There are more than one voltage variation happens during this time, and all identified voltage variation have been taken as 'selected events' and their load models have been calculated.



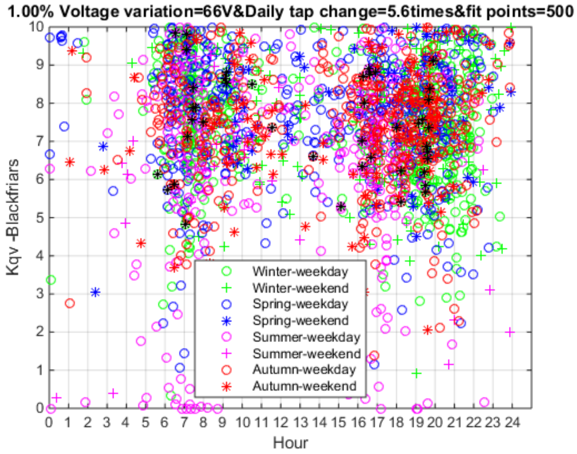

(a) Kp – Fallowfield




(b) Kq – Fallowfield




(c) Kp – Blackfriars




(d) Kq – Blackfriars

**Figure 5.9. Validation of $K_p$ and $K_q$ values against CLASS trial-1: Fallowfield and Blackfriars**

## 5.5 Voltage-Demand Matrix Summary: All 60 Substations

Electricity North West's distribution system covers a wide range of area; from scarcely populated regions to urban areas like Manchester. To ensure that the selection of 60 primary substations reflect the whole Electricity North West's region, the peak load share method has been developed before by the University of Manchester and a detailed description of the methodology can be found in [10]. Table 5.4 presents (statistical) load model parameters for all 60 substations. The types of primaries are categorised into three types: (1) industrial; (2) domestic; and (3) mix-type.

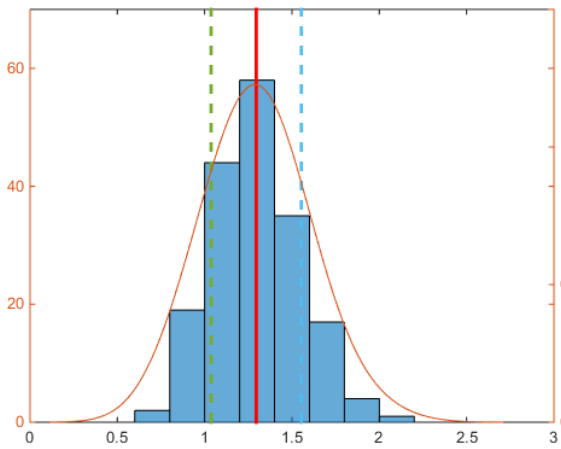
**Table 5.4 Minimum, maximum and average values of voltage-demand matrix for all 60 substations**

| # | Substation Name | Substation ID | Category (D=Domestic, M=Mixed, I=Industrial | Kp | | | Kq | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | min | max | mean | min | max | mean |
| 1 | Avenham | 400402 | I | 1.35 | 1.55 | 1.45 | 6.35 | 6.86 | 6.68 |
| 2 | Blackpool | 400113 | I | 1.40 | 1.98 | 1.75 | 5.94 | 7.14 | 6.35 |
| 3 | Kingsway | 305100 | I | 0.86 | 1.53 | 1.09 | 4.04 | 5.74 | 4.90 |
| 4 | Trafford PN | 100633 | I | 1.38 | 1.75 | 1.63 | 2.41 | 4.35 | 3.67 |
| 5 | Kirkby stephen | 609660 | M | 1.36 | 1.69 | 1.47 | 6.06 | 6.63 | 6.30 |
| 6 | Annie Pit | 609303 | M | 1.11 | 1.48 | 1.29 | 4.84 | 5.87 | 5.38 |

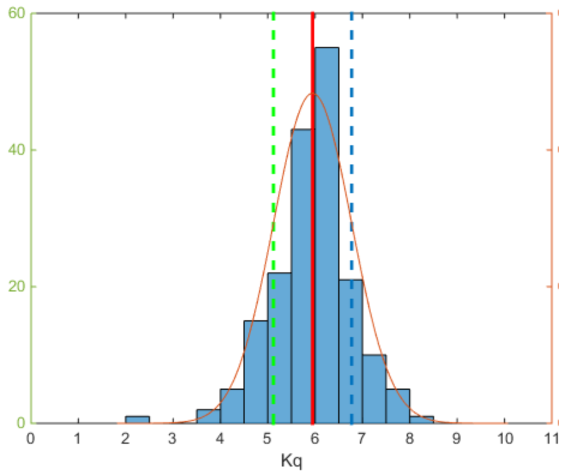
| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **7** | Chatsworth street | 609003 | M | 1.01 | 1.33 | 1.24 | 6.54 | 7.58 | 7.13 |
| **8** | Douglas street | 400406 | M | 0.91 | 1.03 | 0.98 | 6.03 | 7.17 | 6.51 |
| **9** | Moss side | 400221 | M | 1.09 | 1.34 | 1.20 | 4.96 | 5.59 | 5.30 |
| **10** | Tarleton | 400213 | M | 1.29 | 1.38 | 1.33 | 5.96 | 6.42 | 6.24 |
| **11** | Buckshaw | 400212 | M | 0.80 | 1.03 | 0.92 | 4.31 | 5.32 | 4.65 |
| **12** | Bamber Bridge | 400201 | M | 1.17 | 1.48 | 1.29 | 4.62 | 5.42 | 4.92 |
| **13** | Cleveleys | 400104 | M | 1.51 | 1.91 | 1.72 | 6.41 | 6.57 | 6.49 |
| **14** | Hynburn Road | 400013 | M | 1.02 | 1.30 | 1.15 | 4.84 | 6.33 | 5.86 |
| **15** | Wilmslow | 302529 | M | 1.31 | 1.46 | 1.38 | 6.12 | 6.47 | 6.35 |
| **16** | Hyde | 300061 | M | 1.18 | 1.29 | 1.25 | 5.63 | 5.89 | 5.76 |
| **17** | Chmamber Hall | 200205 | M | 1.28 | 1.37 | 1.34 | 6.27 | 7.09 | 6.77 |
| **18** | Central Manchester | 100508 | M | 1.15 | 1.29 | 1.24 | 5.04 | 6.41 | 5.81 |
| **19** | Dickinson Street | 100502 | M | 0.81 | 1.05 | 0.92 | 4.70 | 6.57 | 5.94 |
| **20** | Victoria Park | 100140 | M | 0.77 | 0.85 | 0.83 | 5.04 | 5.48 | 5.32 |
| **21** | Burrow Beck | 609910 | D | 1.51 | 1.78 | 1.63 | 4.97 | 6.46 | 5.47 |
| **22** | Westgate | 609907 | D | 1.20 | 1.57 | 1.42 | 5.82 | 6.90 | 6.15 |
| **23** | Egremont | 609351 | D | 1.07 | 1.54 | 1.35 | 6.02 | 6.87 | 6.42 |
| **24** | Cecil Street | 400103 | D | 1.39 | 1.54 | 1.45 | 5.75 | 6.23 | 5.97 |
| **25** | Griffin | 400006 | D | 1.49 | 1.61 | 1.53 | 6.19 | 6.43 | 6.30 |
| **26** | Littleborough | 304884 | D | 1.03 | 1.31 | 1.11 | 5.43 | 6.10 | 5.71 |
| **27** | Romiley | 302963 | D | 1.01 | 1.21 | 1.10 | 7.11 | 7.94 | 7.42 |
| **28** | South west macclesfield | 302660 | D | 1.48 | 2.11 | 1.79 | 4.77 | 6.21 | 5.58 |
| **29** | Willowbank | 302292 | D | 0.96 | 1.32 | 1.15 | 6.08 | 6.49 | 6.25 |
| **30** | Gowhole | 301671 | D | 1.02 | 1.46 | 1.23 | 5.77 | 6.32 | 6.01 |
| **31** | Bollington | 301435 | D | 1.04 | 1.30 | 1.14 | 5.83 | 6.56 | 6.10 |
| **32** | Winifred Road | 301304 | D | 1.14 | 1.26 | 1.20 | 5.24 | 6.55 | 5.85 |
| **33** | Belgrave | 300832 | D | 1.09 | 1.31 | 1.19 | 5.78 | 6.50 | 6.20 |
| **34** | Middleton junction | 300015 | D | 1.01 | 1.16 | 1.08 | 5.89 | 6.31 | 6.05 |
| **35** | Golborne | 205308 | D | 0.90 | 1.07 | 1.02 | 5.67 | 5.98 | 5.86 |
| **36** | Carr Street | 205306 | D | 1.24 | 1.61 | 1.49 | 4.84 | 6.76 | 6.08 |
| **37** | Skelmersdale | 200417 | D | 1.38 | 1.47 | 1.42 | 5.56 | 6.16 | 5.86 |
| **38** | Ashton | 200414 | D | 1.10 | 1.36 | 1.22 | 5.45 | 6.15 | 5.86 |
| **39** | Kitt Green | 200406 | D | 0.98 | 1.04 | 1.01 | 4.89 | 5.72 | 5.35 |
| **40** | Upholland | 200404 | D | 1.41 | 1.63 | 1.49 | 4.22 | 6.93 | 5.54 |
| **41** | Heady Hill | 200211 | D | 1.14 | 1.21 | 1.18 | 4.16 | 5.02 | 4.50 |
| **42** | Lostock | 200113 | D | 0.90 | 1.14 | 1.04 | 6.04 | 6.35 | 6.17 |
| **43** | Harwood | 200107 | D | 1.21 | 1.36 | 1.28 | 6.47 | 7.15 | 6.82 |
| **44** | Campbell Street | 200103 | D | 1.11 | 1.26 | 1.18 | 6.72 | 7.53 | 7.21 |
| **45** | Trinity | 100645 | D | 0.80 | 0.90 | 0.86 | 6.62 | 8.05 | 7.68 |
| **46** | Bridgewater | 100642 | D | 1.18 | 1.75 | 1.36 | 5.68 | 6.28 | 6.08 |
| **47** | Blackfriars | 100639 | D | 0.72 | 0.97 | 0.86 | 6.21 | 7.62 | 7.16 |
| **48** | Irlam | 100615 | D | 1.08 | 1.38 | 1.24 | 6.29 | 6.68 | 6.46 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **49** | Chassen Road | 100608 | D | 1.49 | 1.66 | 1.57 | 4.99 | 6.27 | 5.81 |
| **50** | Longsight | 100135 | D | 1.14 | 1.32 | 1.26 | 5.44 | 5.95 | 5.73 |
| **51** | Withington | 100131 | D | 1.26 | 1.74 | 1.49 | 5.28 | 5.71 | 5.55 |
| **52** | Stuart street | 100128 | D | 1.18 | 1.42 | 1.31 | 4.62 | 5.15 | 4.95 |
| **53** | Openshaw | 100125 | D | 1.34 | 1.47 | 1.39 | 5.41 | 5.83 | 5.66 |
| **54** | Didsbury | 100122 | D | 1.37 | 1.66 | 1.55 | 6.41 | 7.09 | 6.70 |
| **55** | Levenshulme | 100119 | D | 1.28 | 1.49 | 1.42 | 5.34 | 5.56 | 5.46 |
| **56** | Green Lane | 100117 | D | 1.15 | 1.36 | 1.27 | 3.71 | 6.69 | 5.78 |
| **57** | Fallowfield | 100114 | D | 1.33 | 1.70 | 1.55 | 5.72 | 6.02 | 5.88 |
| **58** | Denton east | 100110 | D | 1.50 | 1.90 | 1.62 | 5.15 | 6.74 | 6.19 |
| **59** | Droylsden east | 100107 | D | 1.38 | 1.62 | 1.49 | 5.74 | 6.29 | 6.04 |
| **60** | Baguley | 100103 | D | 1.26 | 1.60 | 1.38 | 6.07 | 6.33 | 6.21 |

To obtain a statistical view of all 60 monitored substations, normal distribution fit was applied to all max/min/mean values of all 60 substations, (i.e. totally 180 values) for $K_p$ and $K_q$, respectively. The normal distribution fitting for $K_p$ and $K_q$ are presented in Fig. 5.10. It can be seen from Fig 5.10 that the $\mu \mp \sigma$ is [1.03, 1.55], and [5.12, 6.77] for $K_p$ and $K_q$, respectively.




(a) Kp




(b) Kq

**Figure 5.10. Normal distribtion of $K_q$ and $K_q$ values for 60 monitored substations.**

The minimum, maximum, and average values for $K_p$ and $K_q$ for each of the 60 substations are plotted in Fig 5.11 and Fig. 5.12. The mean values of Industrial substations are marked by red asterisk ( '*'), mix-type by black circles and domestic substations by blue asterisk. The vertical lines cross each mean values connect the minimum and maximum values for each substation. The $\mu \pm \sigma$ for load parameters are also plotted in Fig 5.11 and Fig. 5.12.

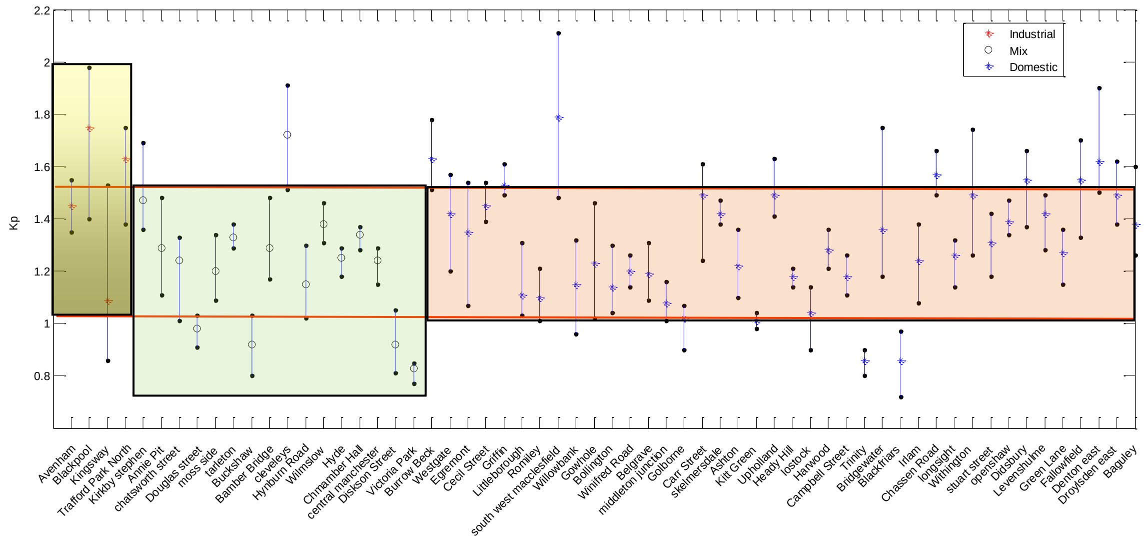



**Figure 5.11. Mean, maximum and minimum values of $K_p$ for 60 monitored substations**

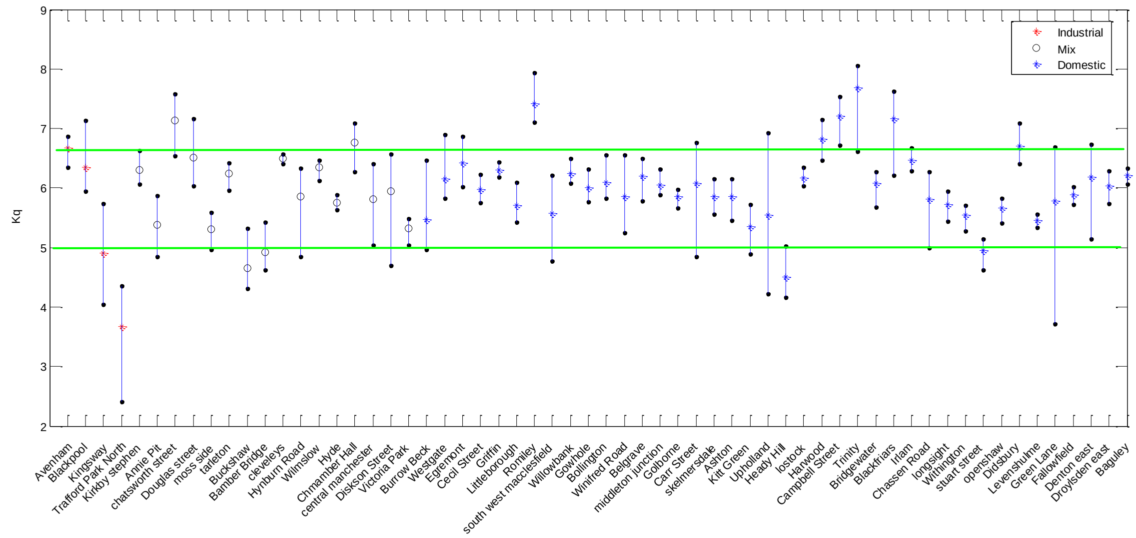



**Figure 5.12. Mean, maximum and minimum values of Kq for 60 monitored substations**

It can be seen from Fig. 5.11, according to the Peak Load Share method, the $K_p$ values for industrial substations are above 1.02 (i.e. $\mu - \sigma$ ), mixed-type substations are under 1.55 (i.e. $\mu + \sigma$ ), and domestic substations are between $\mu - \sigma$ and $\mu + \sigma$.

# 6 Conclusions

This report summarises the load model development and validation from field measurement data, and presented a voltage-demand relationship matrix. This section highlights the outcome of the research and accomplished tasks.

## 6.1 Outcomes and Task Accomplishments

There are three key milestones and deliverables of WP1, which have been promised and agreed upon, are as follows:

- **Load Model Development:** Load models for *all* 60 primary substations selected for the CLASS trials based on actual measurement data. This is more than what was originally planned as the original task was to develop appropriate load models for a representative set of non-trial buses only, i.e., load models were planned to be developed for 15 trail buses and for a sub-set of remaining 45 buses.
- **Load Model Validation:** Refinement and validation of load models based on field measurement data collected across entire annual cycle.
- **Voltage-Demand Relationship Matrix:** A voltage-demand relationship matrix which describe mathematically the voltage-demand relationship for every half-an-hour (of a day) of each season during the year for each characteristic demand profile and for *all* 60 primary substations.

The load modelling part (WP1) of the CLASS project interactively imports and processes measured load data; captures the required load characteristics, develops appropriate load models and provides a voltage-demand relationship matrix.

WP1 not only performed all agreed tasks and disseminated results as planned but also exceeded originally set objectives. All CLASS Successful Delivery Reward Criteria (SDRCs) have been achieved timely throughout the project. Key outputs of the WP1 are as follows:

- **Load Model Development:** Appropriate tools and techniques (software codes and programs) have been developed for data processing, filtering and load modelling (at trial hours at trial-1 substations, at non-trial hours at trial substations, and at other monitored substations where trials have not been carried out).
- **Load Model Validation:** Developed voltage-demand matrices for every half-an-hour intervals for all 15 trial-1 substations have been validated with trial-1 data.
- **Voltage-Demand Relationship Matrix:** Seasonal voltage-demand relationship matrices for every half-an-hour intervals for 15 trial-1 substations as well as for all remaining 45 non-trial-1 buses have been developed. (This is an extension of the originally planned work as voltage-demand relationship matrices have been developed for all trial and non-trial substations (all 60) instead for only a subset of non-trial substations).
  - ❖ Developed methodologies have been tested and applied to CLASS measurement data from 15 trial-1 and 45 non-trial-1 substations, which provides a full 24hr (48 x ½ hr) load matrix covering 4 seasons for 3 defined customer profile classes (mainly domestic, mainly industrial and commercial, and mixed), divided between weekdays and weekends.
  - ❖ Sensitivity/robustness analyses of the developed load model have been performed by outlier removal, application of different filtering techniques, and assessment of the lengths of fitting data window.
    - o *The load model developed by the trail data from June 2014 to March 2015 is compared with the WP1 seasonal load model developed by non-trial data.*
    - o *The two models fitting well with each other validate WP1 seasonal load model development methodology.*

- Statistical analysis of ENWL load measurement data has been presented in detail in the report, while some key results are as summarised below:
  - *Static load model is found to be the most appropriate load model for CLASS (load) measurement data as it captures the prolonged sustained response of the load following a voltage disturbance which is of interest in the CLASS project.*
  - *Static exponential load model is chosen for load modelling at all substations due to its simplicity and clear coherence in defining voltage-demand matrix.*
  - *It has been found that the load model parameters describing weekday load behaviour are more consistent, i.e., less variable. Differences in the weekdays and weekend parameters are influenced by both the changing load-mix of the substations and by changes in consumption pattern during weekend.*
- Estimated load model parameter values have been presented in Table 6.1 and 6.2 can be summarized as follows:
  - *For domestic substations, average value of real power exponent for weekday is about 1.30 and reactive power exponent is about 6.06;*
  - *For industrial and commercial substations, average value of real power exponent for a weekday is close to 1.48 and reactive power exponent is close to 5.58;*
  - *For mixed-type substations, average value of real power exponent for a weekday is about 1.22 and reactive power exponent is about 5.90.*

**Table 6.1 Statistics of Kp values on weekdays of all 60 substations**

| | Mainly domestic | | | Industrial/commercial | | | Mixed | | | | Seasonal avg. for all SS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Min | Avg | Max | Min | Avg | Max | Min | Avg | Max | | |
| **Winter** | 0.87 | 1.33 | 1.93 | 0.86 | 1.47 | 1.85 | 0.70 | 1.23 | 1.91 | | **1.34** |
| **Spring** | 0.83 | 1.32 | 1.86 | 1.02 | 1.39 | 1.80 | 0.80 | 1.20 | 1.68 | | **1.30** |
| **Summer** | 0.72 | 1.25 | 2.11 | 1.02 | 1.52 | 1.97 | 0.70 | 1.20 | 1.58 | | **1.32** |
| **Autumn** | 0.67 | 1.31 | 1.91 | 0.95 | 1.53 | 1.98 | 0.71 | 1.23 | 1.80 | | **1.36** |
| | | | | | | | | | | | |
| **Load types' average** | **1.30** | | | **1.48** | | | **1.22** | | | | |

**Table 6.2 Statistics of Kq values on weekdays of all 60 substations**

| | Mainly domestic | | | Industrial/commercial | | | Mixed | | | | Seasonal avg. for all SS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Min | Avg | Max | Min | Avg | Max | Min | Avg | Max | | |
| **Winter** | 3.98 | 5.96 | 7.98 | 3.79 | 5.62 | 6.86 | 4.36 | 5.92 | 6.93 | | **5.83** |
| **Spring** | 4.58 | 6.14 | 8.05 | 4.30 | 5.56 | 6.75 | 3.82 | 5.82 | 7.52 | | **5.84** |
| **Summer** | 3.25 | 5.98 | 7.62 | 3.96 | 5.65 | 7.26 | 4.52 | 5.75 | 6.95 | | **5.79** |
| **Autumn** | 4.41 | 6.16 | 8.06 | 2.41 | 5.49 | 6.79 | 4.26 | 6.10 | 7.58 | | **5.92** |
| | | | | | | | | | | | |
| **Load types' average** | **6.06** | | | **5.58** | | | **5.90** | | | | |

In summary, the results and analyses presented include a detailed yearly, seasonal, weekly and daily 24 hour (48 x ½ hr) voltage-demand relationship matrix for all 60 monitored substations (15 trial-1 and 45 non-trial-1 substations) of the ENWL distribution network associated with the CLASS project.

**Seasonal variations of the load model parameters**

Load model parameters (voltage exponent for real power, $K_p$ and reactive power, $K_q$) remain almost the same across all seasons. Seasonal range is [1.30 ~ 1.36] and [5.79 ~ 5.92], for $K_p$ and $K_q$, respectively. The seasonal variation is negligible. Though the amount of consumption and composition of load may change among different seasons, the response of aggregate load at the substation level remains almost the same. So, one yearly characteristic profile is sufficient for estimating load behaviour irrespective of the season of the year.

**Customer type effect on load model parameters**

Real power voltage exponent ($K_p$) values for domestic, industrial and mixed substations are 1.30, 1.48 and 1.22, respectively. The higher $K_p$ values of industrial substations are caused by two reasons. One reason is the presence of (possibly large) dynamic load in industrial substation which gives a higher power drop for a certain voltage drop. This makes the $K_p$ value higher. Another reason is the presence of higher noise and ripple in the industrial substation data. When averaging the power and voltage over a 9 minute window (selected window for load model development in this study), $K_p$ values become higher.

**Comparison with the literature (reason for higher values of $K_p$ and $K_q$)**

Load model parameter values obtained in this study are higher than the literature [12]. The ranges of $K_p$ in this study and literature are [0.67 ~ 2.11] and [0.62 ~ 2.00], respectively. The ranges of $K_q$ in this study and literature are [2.41 ~ 4.58] and [0.96 ~ 4.00], respectively. This is due to the change of load type and composition over time. Examples of loads which have higher $K_p$ and $K_q$ values are Fluorescent lights ($K_p$=1.96, $K_q$=7.4), unloaded transformer ($K_p$=3.4, $K_q$=11.5), microwave oven (24.17), TV/PC ($K_p$ =2, $K_q$=5.2), and battery charger ($K_p$=2.59, $K_q$=4.06) [7, 13]. New types of loads (including those mentioned in this subsection) are being connected and proportions of loads which have higher voltage exponent are increasing in the power network. This causes the higher $K_p$ and $K_q$ values.

## 6.2 Project Learnings

### 6.2.1 Data Collection and Sharing

Field measurement of 60 ENWL primary substations are monitored by high resolution devices and the monitored data are stored in iHost system. From the practices of the UOM-ENWL CLASS project, it has been identified that care needs to be taken when transferring the data from monitoring devices to iHost system.

Measured data has been processed and/or normalized and/or scaled at least at three stages before it has been passed for load modelling. In this series cascaded scheme, data resolution has been limited by the slowest device connected to the data acquisition system. Here, for example, data transfer capability and resolution of the data is limited due to the ‘data transfer interface’ deployed by the DNO which cannot handle data with resolution higher than 1second [3, 8].

### 6.2.2 How to Conduct a Tap for Dynamic Load Modelling

During UOM-ENWL CLASS project, 60 monitoring devices with 1 Hz sampling rate have been used to monitor the selected primary substations. To develop appropriate dynamic load models for future analysis, it is suggested to trip-off one of the two parallel transformers. The subsequent short-term load/voltage data (less than 30 seconds) is used to develop dynamic load models.

## 6.3 Acknowledgements

We would like to highly appreciate the financial support of Electricity North West in this project through the CLASS initiative. Our sincere gratefulness to the CLASS team of the Electricity North West (especially to Mr. Andy Howard, Mr. Steve Stott, Mr. Paul Turner, and Mr. Kieran Bailey) for taking part in technical discussions and providing insightful comments time-to-time. We are also indebted to former CLASS team member Ms. Victoria Turnham and Dr. Herb Castillo for their cooperation and feedback during initial phase of the project. We thank our academic colleagues from the University of

Manchester (WP2 and WP3) and Liverpool (WP3) who have given comment and opinion throughout the project. We also thankfully acknowledge the support of Nortech Management Ltd. for assistance and discussion regarding iHost data acquisition.

# 7 References

[1] Electricity_North_West, "CLASS trial design and associated test schedule. [available online]," 2014.

[2] K. N. Hasan and J. V. Milanovic, "Interim Profile Modelling Study " The University of Manchester & Electricity North West Limited, UK, 2015, [available online]: http://www.enwl.co.uk/docs/default-source/class-documents/university-of-manchester-interim-report-wp1.pdf?sfvrsn=4.

[3] K. N. Hasan, J. V. Milanović, P. Turner, and V. Turnham, "A step-by-step data processing guideline for load model development based on field measurements," in *IEEE PowerTech Conference,*, Eindhoven, The Netherlands, 2015.

[4] K. N. Hasan and J. V. Milanović, "Practical aspects of developing load models at distribution network buses based on field measurements," in *CIRED International Conference and Exhibition on Eelctricity Distribution,*, Lyon, France, 2015.

[5] Alstom. (2015). *iSTAT i500 High Performance Multifunction Transducer. [online]*.

[6] CIGRE_WG_C4.605, "Modelling and aggregation of loads in flexible power networks, Jovica V. Milanović, (Convenor), Julija Matevosiyan, Anish Gaikwad, Alberto Borghetti, Saša Ž. Djokić, Zhao Yang Dong, Andrew Halley, Lidija M. Korunović, Sergio Martinez Villanueva, Jin Ma, Pouyan Pourbeik, Fernanda Resende, Stefan Sterpu, Fortunato Villella, Koji Yamashita, Odin Auer, Karim Karoui, Dimitry Kosterev, Shu Kwan Leung, Dumisani Mtolo, Samila Mat Zali, Adam Collin, Yizheng Xu, ISBN: 978-2-85873-261-6," 2014.

[7] L. M. Korunovic, D. P. Stojanovic, and J. V. Milanovic, "Identification of static load characteristics based on measurements in medium-voltage distribution network," *IET Gen, Trans & Distr,* vol. 2, pp. 227-234, 2008.

[8] EPRI, "Measurement-based load modeling. [available online]: http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001014402, " 2006.

[9] D. P. Stojanović, L. M. Korunović, and J. V. Milanović, "Dynamic load modelling based on measurements in medium voltage distribution network," *Electric Power Systems Research,* vol. 78, pp. 228-238, 2008.

[10] I. R. Navarro, "Dynamic Load Models for Power Systems," PhD Thesis, Lund University, Sweden, 2002.

[11] D. J. Hill, "Nonlinear dynamic load models with recovery for voltage stability studies," *IEEE Trans on Power Systems,* vol. 8, pp. 166-176, 1993.

[12] J. V. Milanovic, K. Yamashita, S. Martinez Villanueva, S. Z. Djokic, and L. M. Korunovic, "International industry practice on power system load modeling," *IEEE Transactions on Power Systems,* vol. 28, pp. 3038-3046, 2013.

[13] P. Kundur, *Power System Stability and Control*: McGraw-Hill, New York, 1994.

# Appendix A – CLASS Test Schedule

| Trial No. | 1 | | 2 | | 3 | | 4 | | 5 | | 6 | | 7 | | 8 | | 9 | | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Substations** | **Date** | **Time** | **Date** | **Time** | **Date** | **Time** | **Date** | **Time** | **Date** | **Time** | **Date** | **Time** | **Date** | **Time** | **Date** | **Time** | **Date** | **Time** | **Date** | **Time** |
| Trafford Park North | May18 | 9-9:30 | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 | Oct06 | | Oct13 | | | | | | Nov17 | 10-16 |
| Dickinson Street | June10 | 7-9 | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 | Oct06 | | Oct13 | | Oct20 | | Oct27 | | Nov17 | 10-16 |
| Kitt Green | June17 | 7-9 | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 | Oct06 | | Oct13 | | Oct20 | | Oct27 | | Nov17 | 10-16 |
| Avenham | June03 | 7-9 | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 | | | Oct13 | | Oct20 | | Oct27 | | Nov17 | 10-16 |
| Central Manchester | June10 | 7-9 | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 | Oct06 | | Oct13 | | Oct20 | | Oct27 | | Nov17 | 10-16 |
| Fallowfield | May09 | 9-9:30 | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 | Oct06 | | Oct13 | | Oct20 | | Oct27 | | Nov17 | 10-16 |
| Romiley | | | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 | Oct06 | | Oct13 | | | | Oct27 | | Nov17 | 10-16 |
| Wilmslow | | | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 | Oct06 | | Oct13 | | Oct20 | | Oct27 | | Nov17 | 10-16 |
| Egremont | May18 | 13-15 | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 | Oct06 | | Oct13 | | | | Oct27 | | Nov17 | 10-16 |
| Ashton (Golborne) | May09 | 7-9 | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 | Oct06 | | Oct13 | | | | | | Nov17 | 10-16 |
| Buckshaw | June03 | 7-9 | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 | Oct06 | | Oct13 | | Oct20 | | Oct27 | | Nov17 | 10-16 |
| Victoria Park | | | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 | Oct06 | | Oct13 | | Oct20 | | | | Nov17 | 10-16 |
| Hyndburn Road | June10 | 7-9 | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 | Oct06 | | | | | | | | Nov17 | 10-16 |
| Blackfriars | May09 | 7-9 | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 | Oct06 | | Oct13 | | | | | | Nov17 | 10-16 |
| Bridgewater | | | June24 | 7-9 | June25 | 15-17 | July01 | 7-9 | July02 | 15-17 | | | | | | | | | | |

| Trial No. | 11 | | 12 | | 13 | | 14 | | 15 | | 16 | | 17 | | 18 | | 19 | | 20 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Substations** | **Date** | **Time** | **Date** | **Time** | **Date** | **Time** | **Date** | **Time** | **Date** | **Time** | **Date** | **Time** | **Date** | **Time** | **Date** | **Time** | **Date** | **Time** | **Date** | **Time** |
| Trafford Park North | Nov24 | 10-16 | Dec1 | 16-20 | Dec08 | 00-08 | Dec15 | 20-00 | Jan5 | 01-00 | Jan19 | 16-20 | Feb02 | 16-20 | Feb16 | 00-08 | Feb23 | 08-16 | Mar02 | 16-00 |
| Dickinson Street | Nov24 | 10-16 | Dec1 | 16-20 | Dec08 | 00-08 | Dec15 | 20-00 | Jan5 | 01-00 | Jan19 | 16-20 | Feb02 | 16-20 | Feb16 | 00-08 | Feb23 | 08-16 | Mar02 | 16-00 |
| Kitt Green | Nov24 | 10-16 | Dec1 | 16-20 | Dec08 | 00-08 | Dec15 | 20-00 | Jan5 | 01-00 | Jan19 | 16-20 | Feb02 | 16-20 | Feb16 | 00-08 | Feb23 | 08-16 | Mar02 | 16-00 |
| Avenham | Nov24 | 10-16 | Dec1 | 16-20 | Dec08 | 00-08 | Dec15 | 20-00 | Jan5 | 01-00 | Jan19 | 16-20 | Feb02 | 16-20 | Feb16 | 00-08 | Feb23 | 08-16 | Mar02 | 16-00 |
| Central Manchester | Nov24 | 10-16 | Dec1 | 16-20 | Dec08 | 00-08 | Dec15 | 20-00 | Jan5 | 01-00 | Jan19 | 16-20 | Feb02 | 16-20 | Feb16 | 00-08 | Feb23 | 08-16 | Mar02 | 16-00 |
| Fallowfield | Nov24 | 10-16 | Dec1 | 16-20 | Dec08 | 00-08 | Dec15 | 20-00 | Jan5 | 01-00 | Jan19 | 16-20 | Feb02 | 16-20 | Feb16 | 00-08 | Feb23 | 08-16 | Mar02 | 16-00 |

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Romiley | Nov24 | 10-16 | Dec1 | 16-20 | Dec08 | 00-08 | Dec15 | 20-00 | Jan 5 | 01-00 | Jan 19 | 16-20 | Feb02 | 16-20 | Feb16 | 00-08 | Feb23 | 08-16 | Mar02 | 16-00 |
| Wilmslow | Nov24 | 10-16 | Dec1 | 16-20 | Dec08 | 00-08 | Dec15 | 20-00 | Jan 5 | 01-00 | Jan 19 | 16-20 | Feb02 | 16-20 | Feb16 | 00-08 | Feb23 | 08-16 | Mar02 | 16-00 |
| Egremont | Nov24 | 10-16 | Dec1 | 16-20 | Dec08 | 00-08 | Dec15 | 20-00 | Jan 5 | 01-00 | Jan 19 | 16-20 | Feb02 | 16-20 | Feb16 | 00-08 | Feb23 | 08-16 | Mar02 | 16-00 |
| Ashton (Golborne) | Nov24 | 10-16 | Dec1 | 16-20 | Dec08 | 00-08 | Dec15 | 20-00 | Jan 5 | 01-00 | Jan 19 | 16-20 | Feb02 | 16-20 | Feb16 | 00-08 | Feb23 | 08-16 | Mar02 | 16-00 |
| Buckshaw | Nov24 | 10-16 | Dec1 | 16-20 | Dec08 | 00-08 | Dec15 | 20-00 | Jan 5 | 01-00 | Jan 19 | 16-20 | Feb02 | 16-20 | Feb16 | 00-08 | Feb23 | 08-16 | Mar02 | 16-00 |
| Victoria Park | Nov24 | 10-16 | Dec1 | 16-20 | Dec08 | 00-08 | Dec15 | 20-00 | Jan 5 | 01-00 | Jan 19 | 16-20 | Feb02 | 16-20 | Feb16 | 00-08 | Feb23 | 08-16 | Mar02 | 16-00 |
| Hyndburn Road | Nov24 | 10-16 | Dec1 | 16-20 | Dec08 | 00-08 | Dec15 | 20-00 | Jan 5 | 01-00 | Jan 19 | 16-20 | Feb02 | 16-20 | Feb16 | 00-08 | Feb23 | 08-16 | Mar02 | 16-00 |
| Blackfriars | Nov24 | 10-16 | Dec1 | 16-20 | Dec08 | 00-08 | Dec15 | 20-00 | Jan 5 | 01-00 | Jan 19 | 16-20 | Feb02 | 16-20 | Feb16 | 00-08 | Feb23 | 08-16 | Mar02 | 16-00 |
| Bridgewater | | | | | | | | | | | | | | | | | | | | |

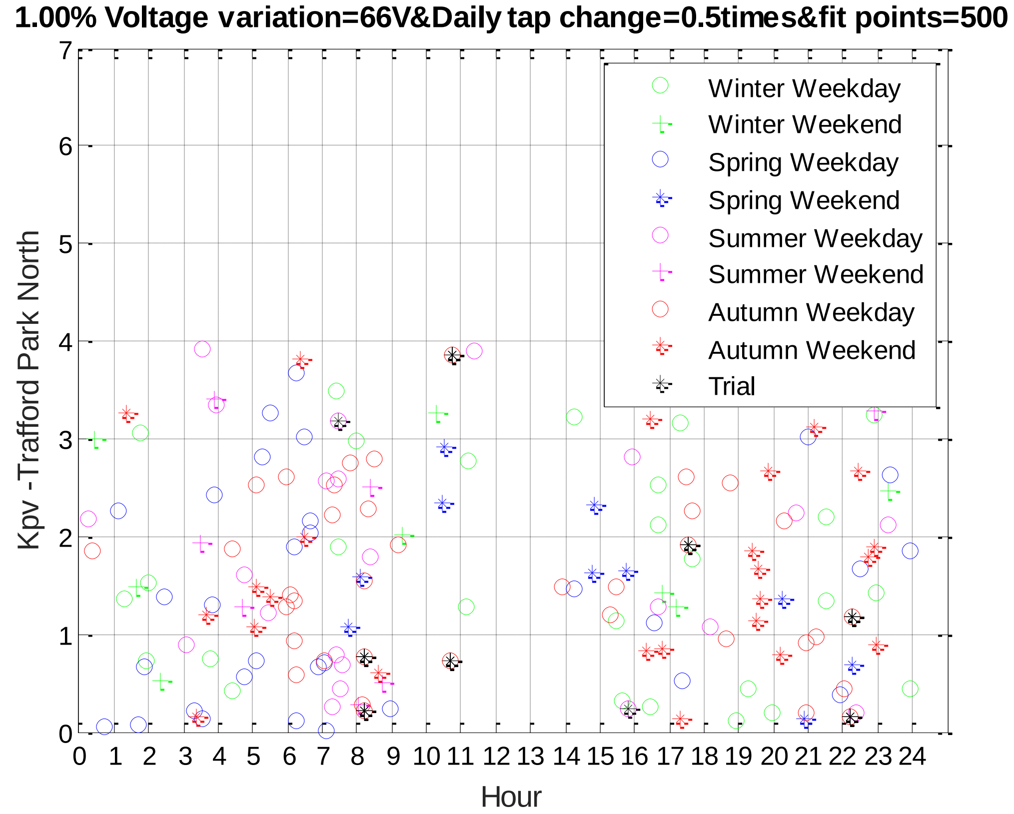
Yellow – weekend
Grey – need to look at data files for **actual** test time

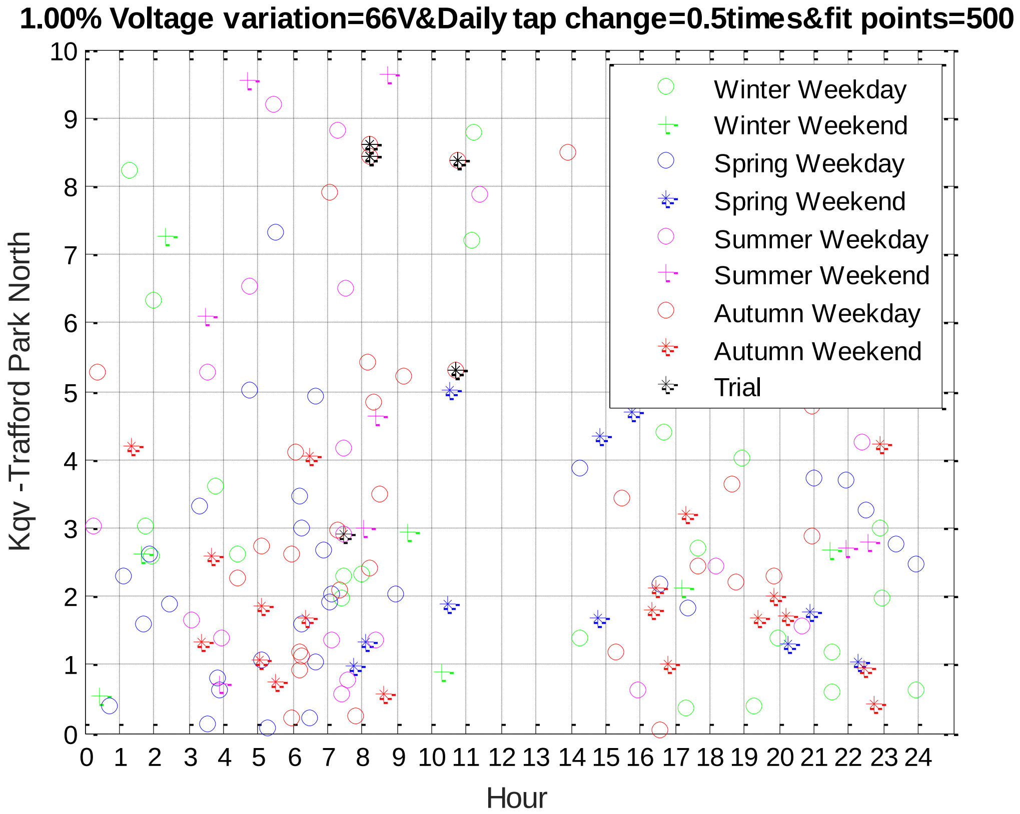
# Appendix B – Validation with Trials for Trial-1 Substations

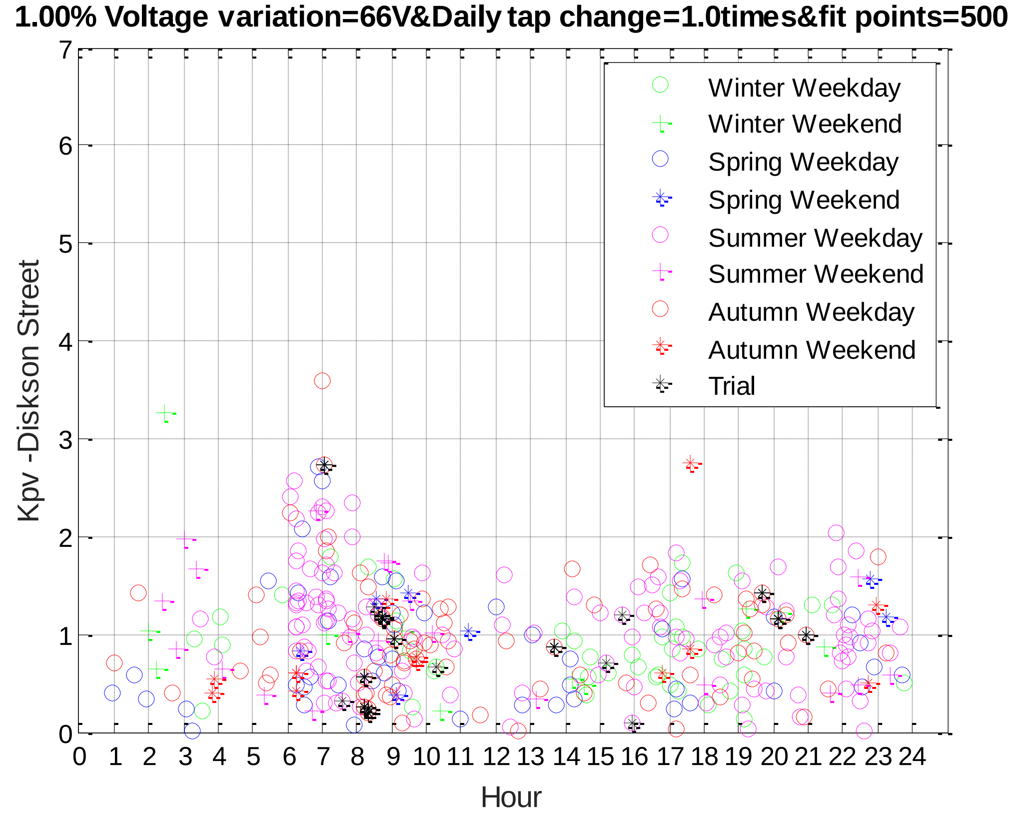
Notes

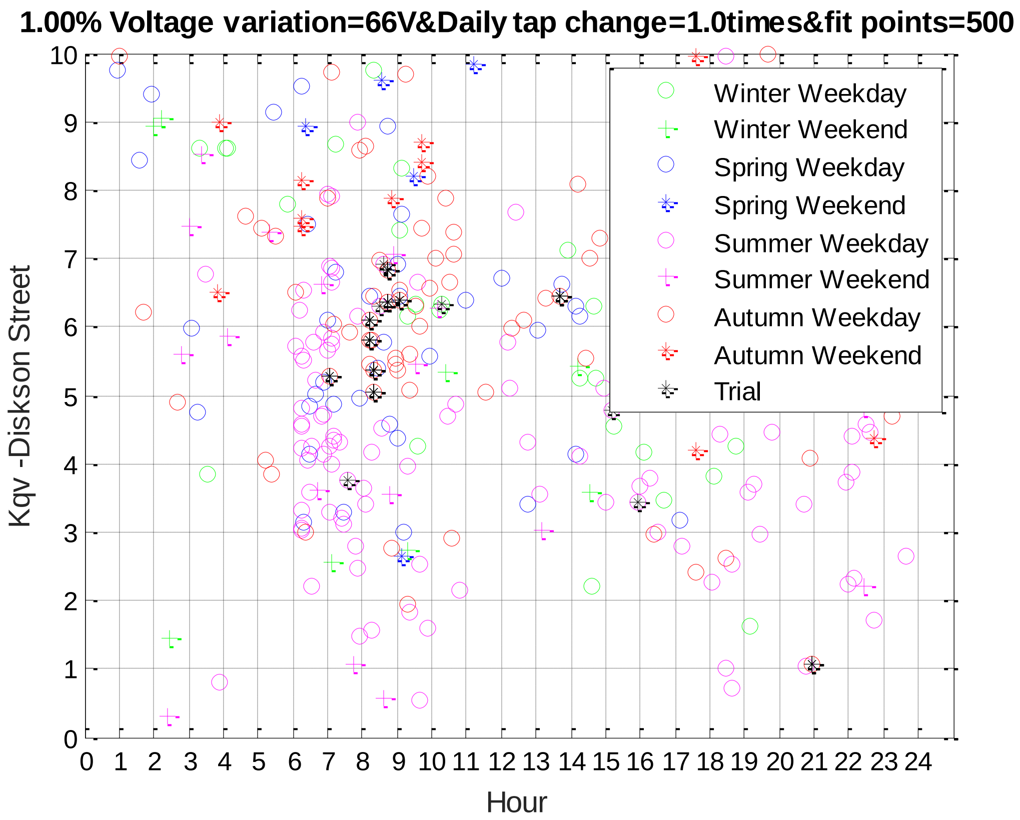
1. All the trial data are analysed in this report and plotted as '*'.

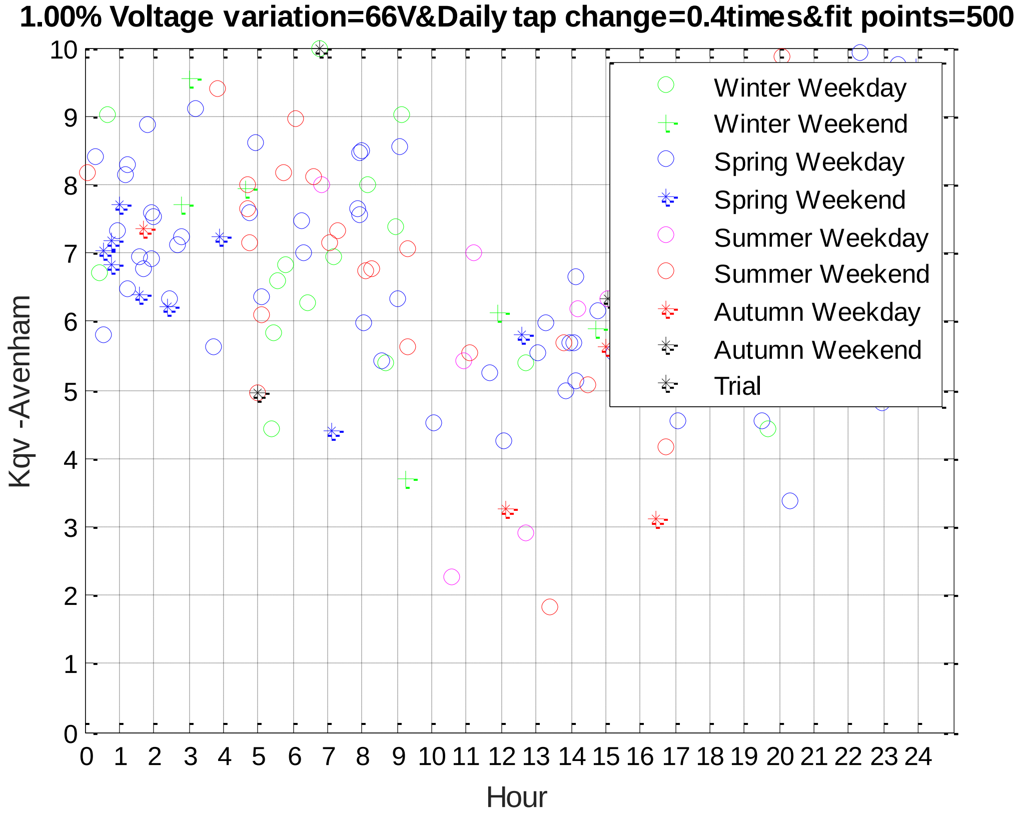
2. Some trial data of substations like Egemont, buckshaw and Bridgewater are insignificant compared to natural power, and are lower than the 1% voltage variation, which is used for load modelling in this report. It should be aware that no black '*' in these figures does not mean that no trial data is identified. It is just the voltage variation of trial data is lower than the threshold used for load modelling.

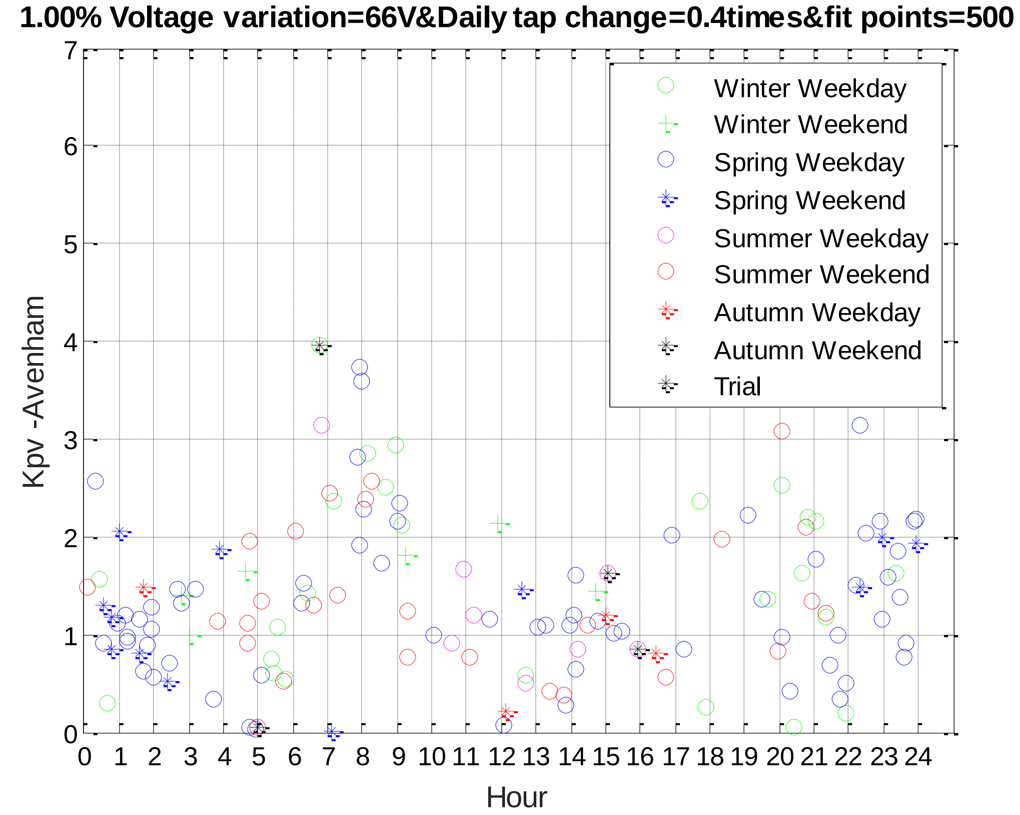

1.00% Voltage variation=66V&Daily tap change=0.5times&fit points=500
Kpv -Trafford Park North
Hour
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend
Trial

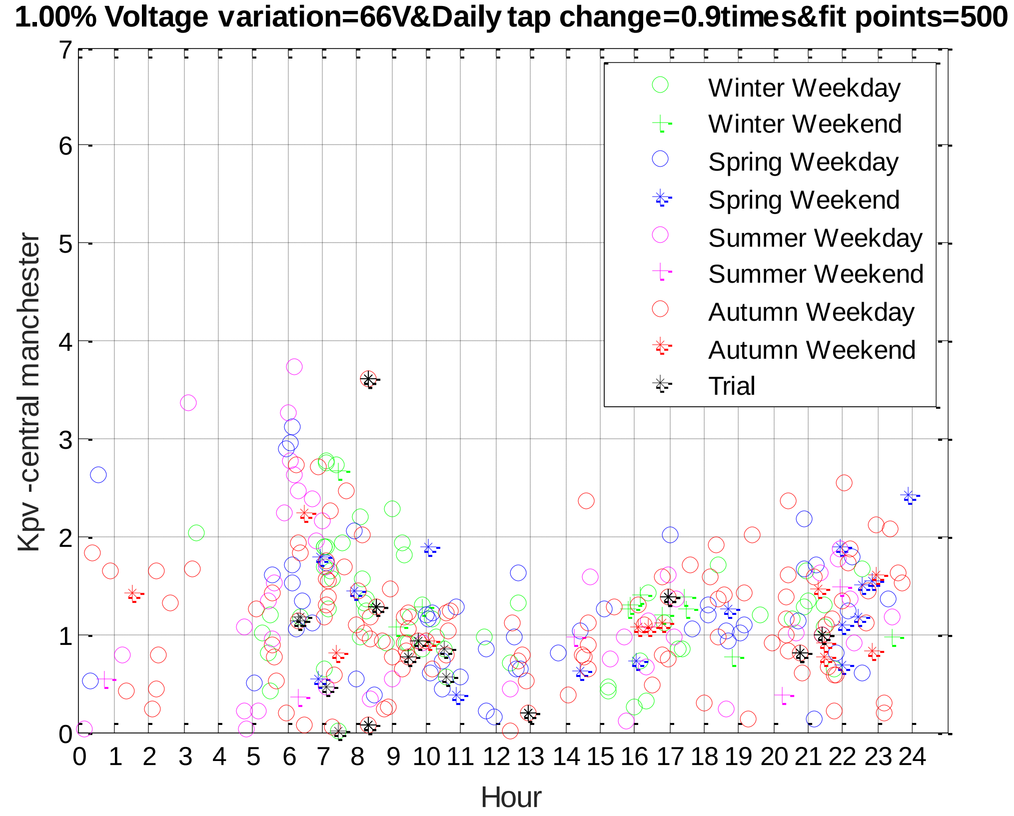

1.00% Voltage variation=66V&Daily tap change=0.5times&fit points=500
Kqv -Trafford Park North
Hour
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend
Trial

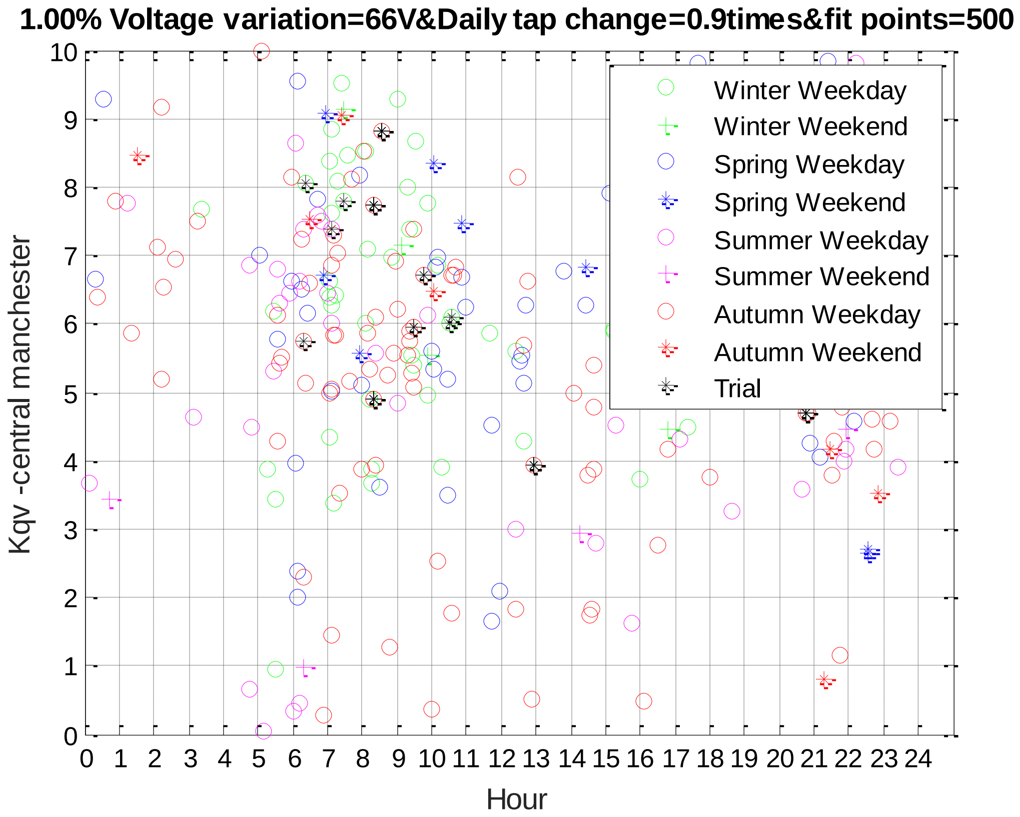

1.00% Voltage variation=66V&Daily tap change=1.0times&fit points=500
Kpv -Diskson Street
Hour
0 1 2 3 4 5 6 7
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend
Trial

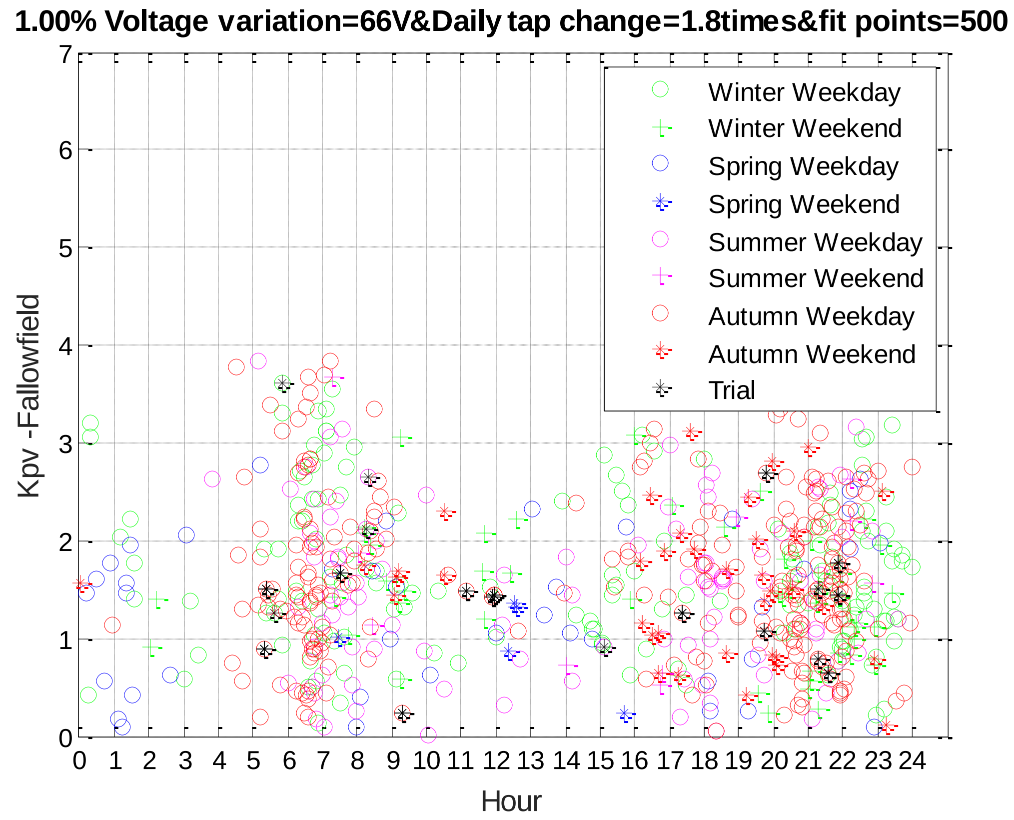

1.00% Voltage variation=66V&Daily tap change=1.0times&fit points=500
Kqv -Diskson Street
Hour
0 1 2 3 4 5 6 7 8 9 10
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend
Trial

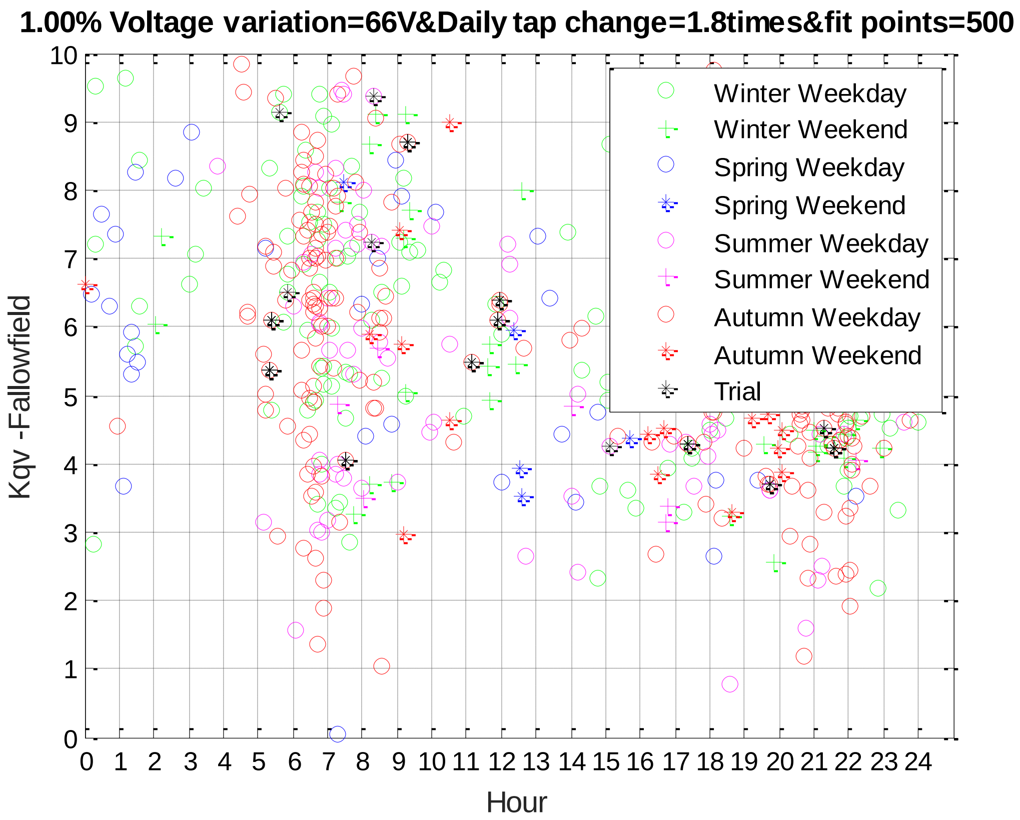

1.00% Voltage variation=66V&Daily tap change=0.4times&fit points=500
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend
Trial
Kqv -Avenham
Hour

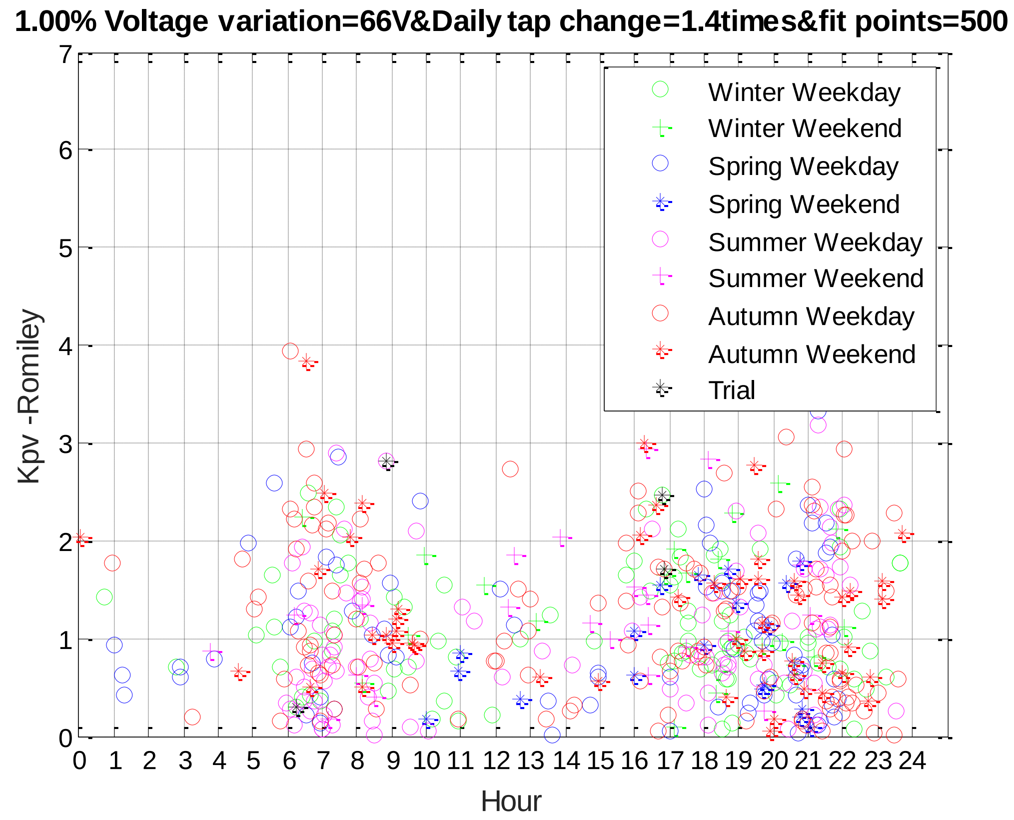

1.00% Voltage variation=66V&Daily tap change=0.4times&fit points=500
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend
Trial
Kpv -Avenham
Hour

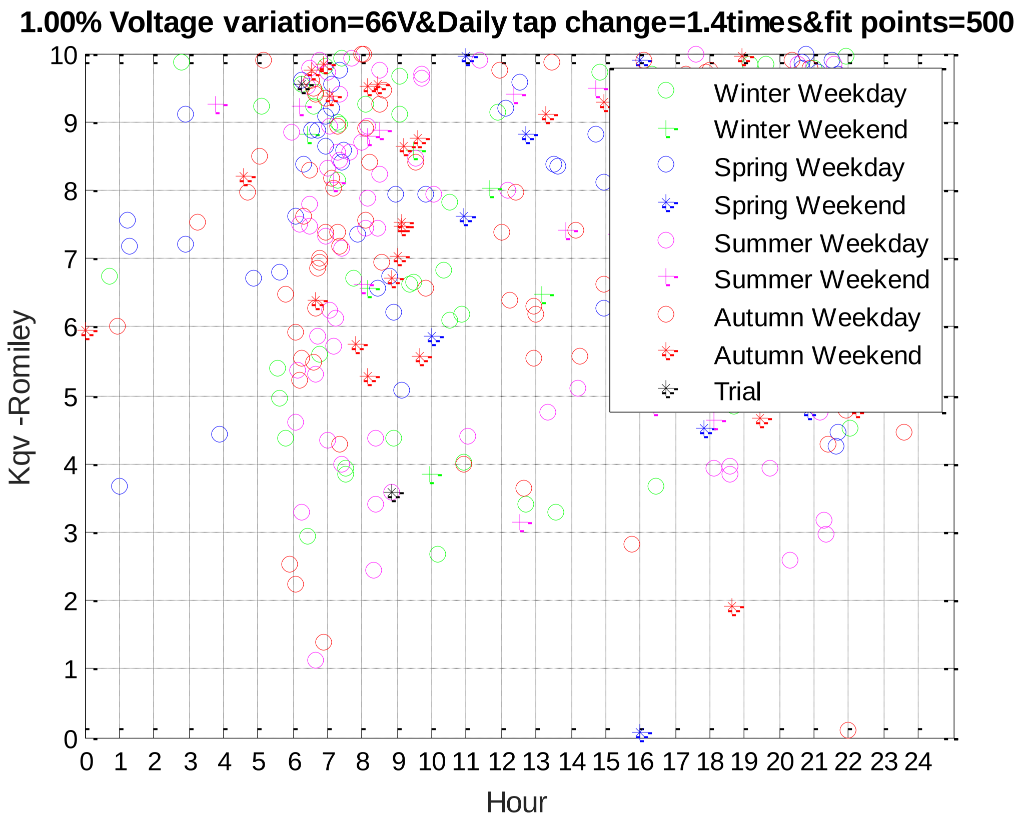

1.00% Voltage variation=66V&Daily tap change=0.9times&fit points=500
Kpv -central manchester
Hour
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend
Trial

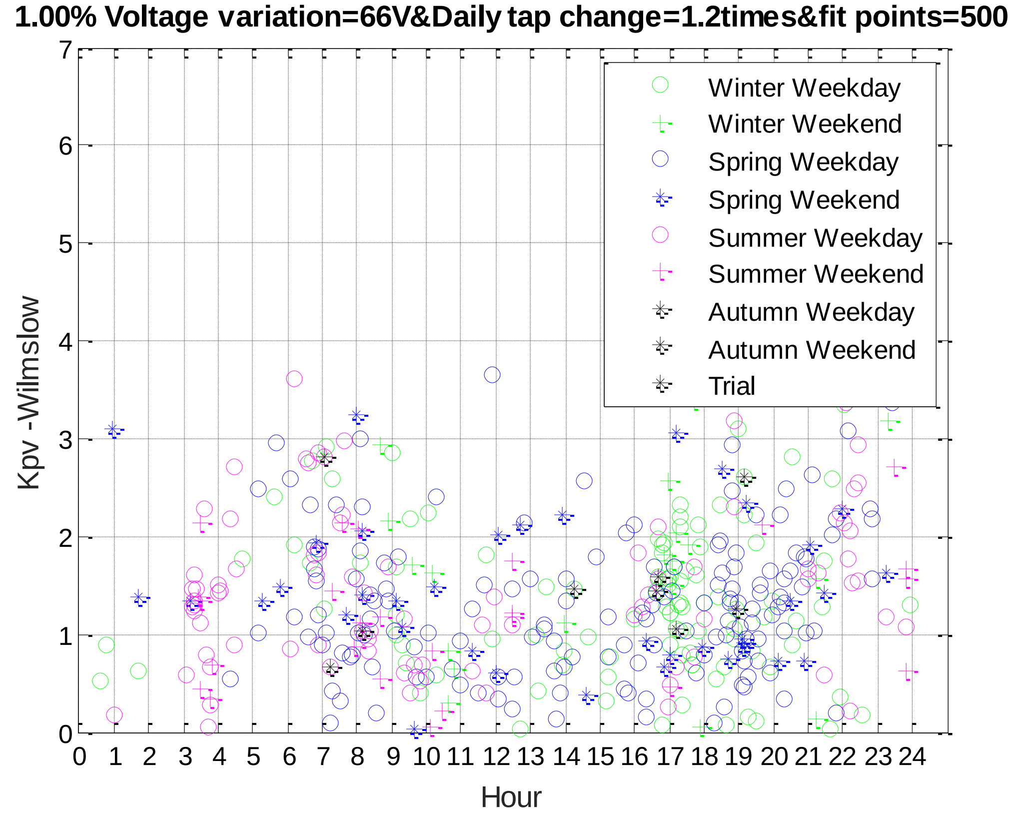

1.00% Voltage variation=66V&Daily tap change=0.9times&fit points=500
Kqv -central manchester
Hour
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend
Trial

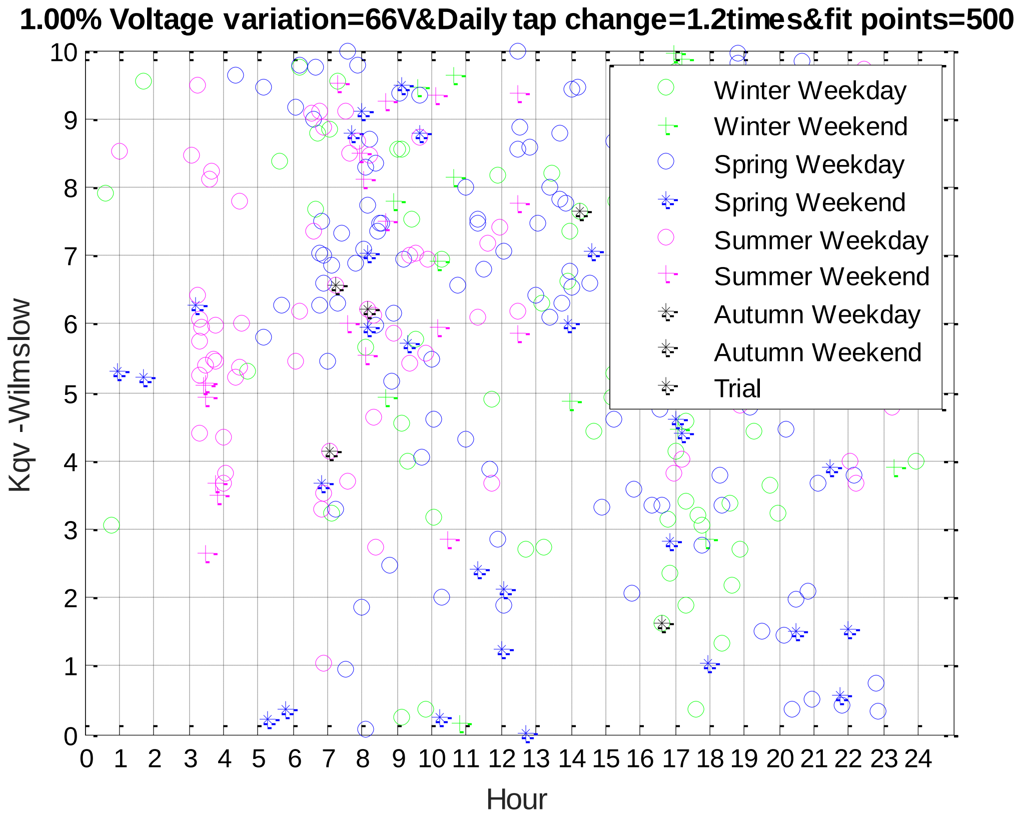

1.00% Voltage variation=66V&Daily tap change=1.8times&fit points=500
Kpv -Fallowfield
Hour
0
1
2
3
4
5
6
7
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend
Trial

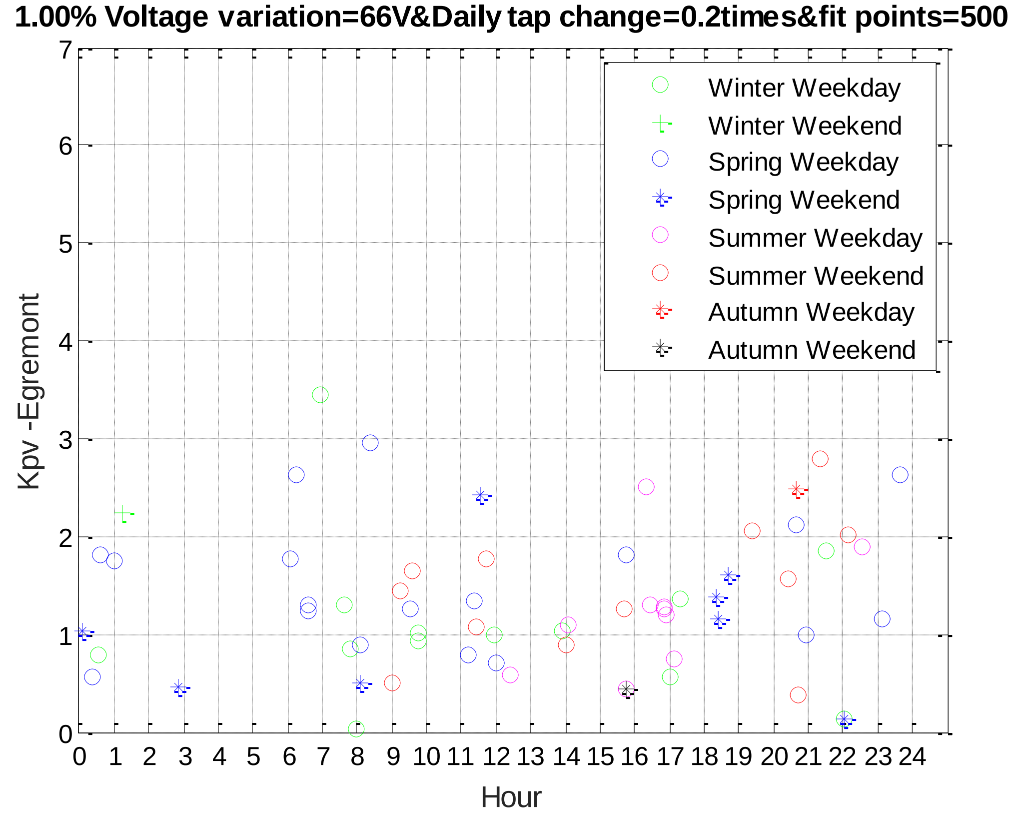

1.00% Voltage variation=66V&Daily tap change=1.8times&fit points=500
Kqv -Fallowfield
Hour
0
1
2
3
4
5
6
7
8
9
10
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend
Trial

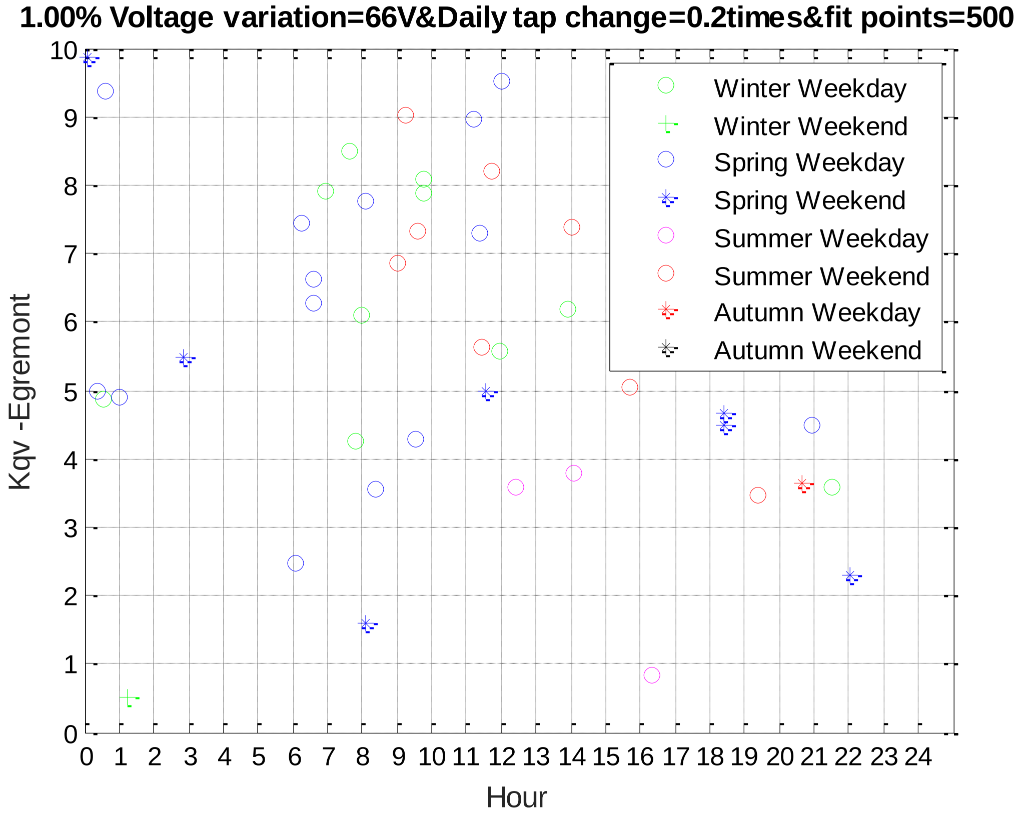

1.00% Voltage variation=66V&Daily tap change=1.4times&fit points=500
Kpv -Romiley
Hour
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend
Trial

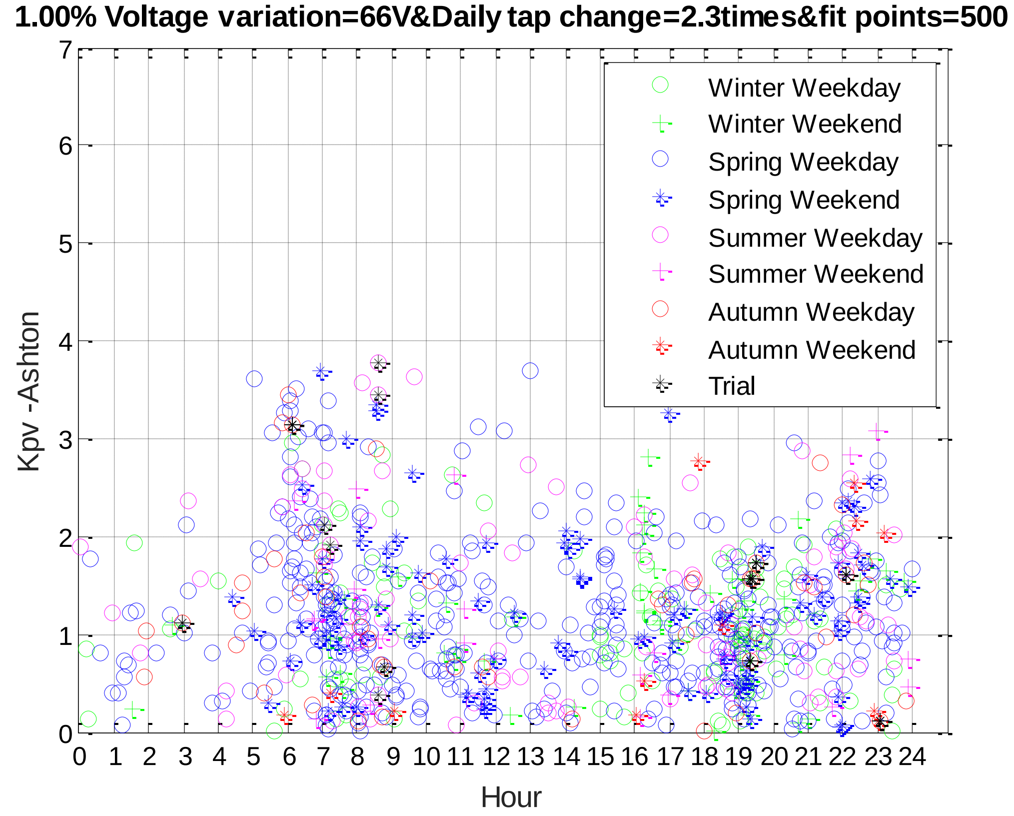

1.00% Voltage variation=66V&Daily tap change=1.4times&fit points=500
Kqv -Romiley
Hour
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend
Trial

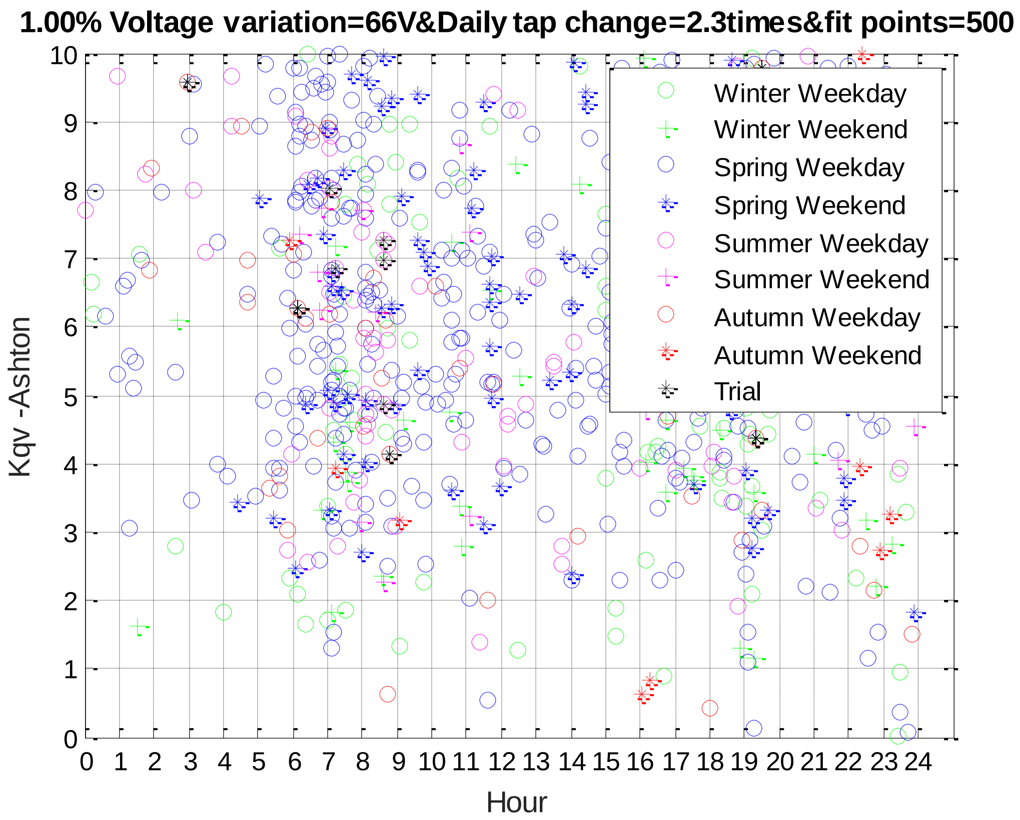

1.00% Voltage variation=66V&Daily tap change=1.2times&fit points=500
Kpv -Wilmslow
Hour
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
0
1
2
3
4
5
6
7
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend
Trial

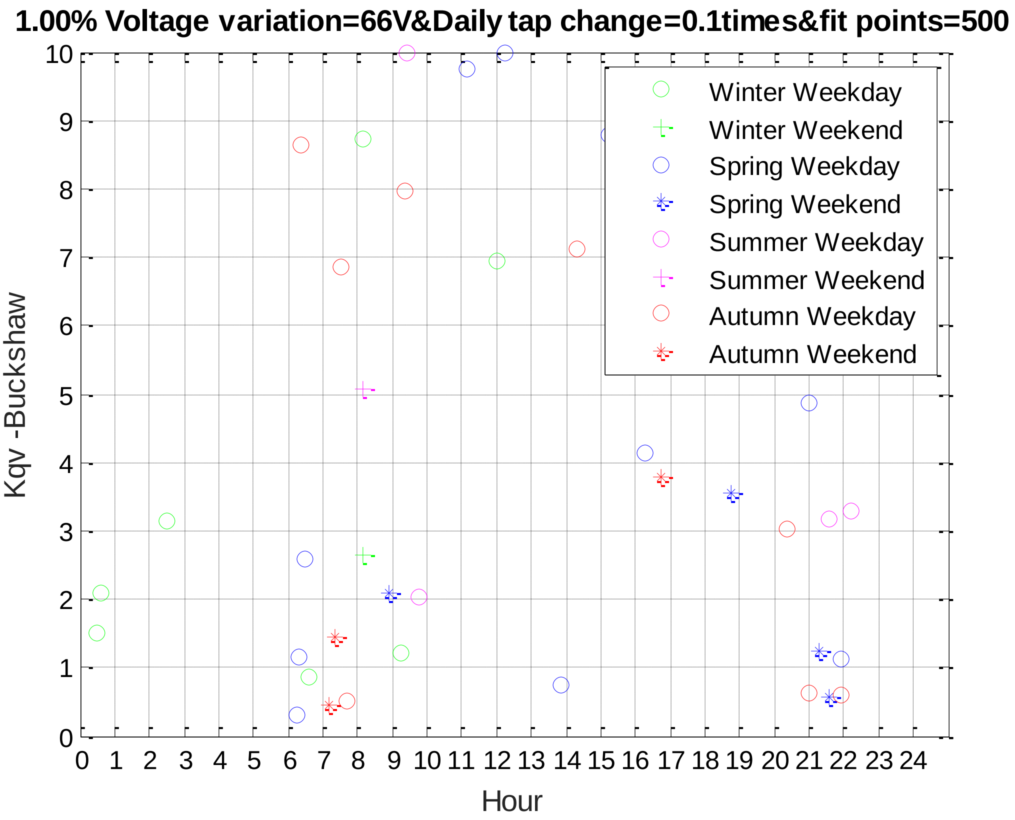

1.00% Voltage variation=66V&Daily tap change=1.2times&fit points=500
Kqv -Wilmslow
Hour
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
0
1
2
3
4
5
6
7
8
9
10
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend
Trial

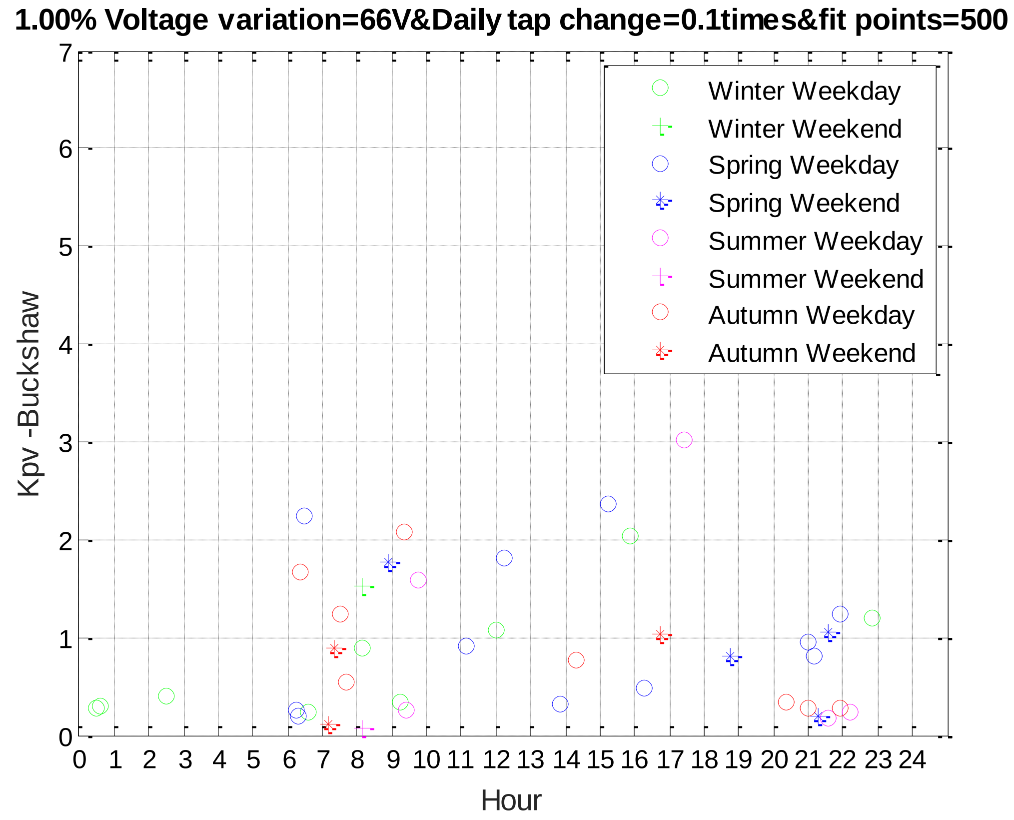

1.00% Voltage variation=66V&Daily tap change=0.2times&fit points=500
Kpv -Egremont
Hour
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend

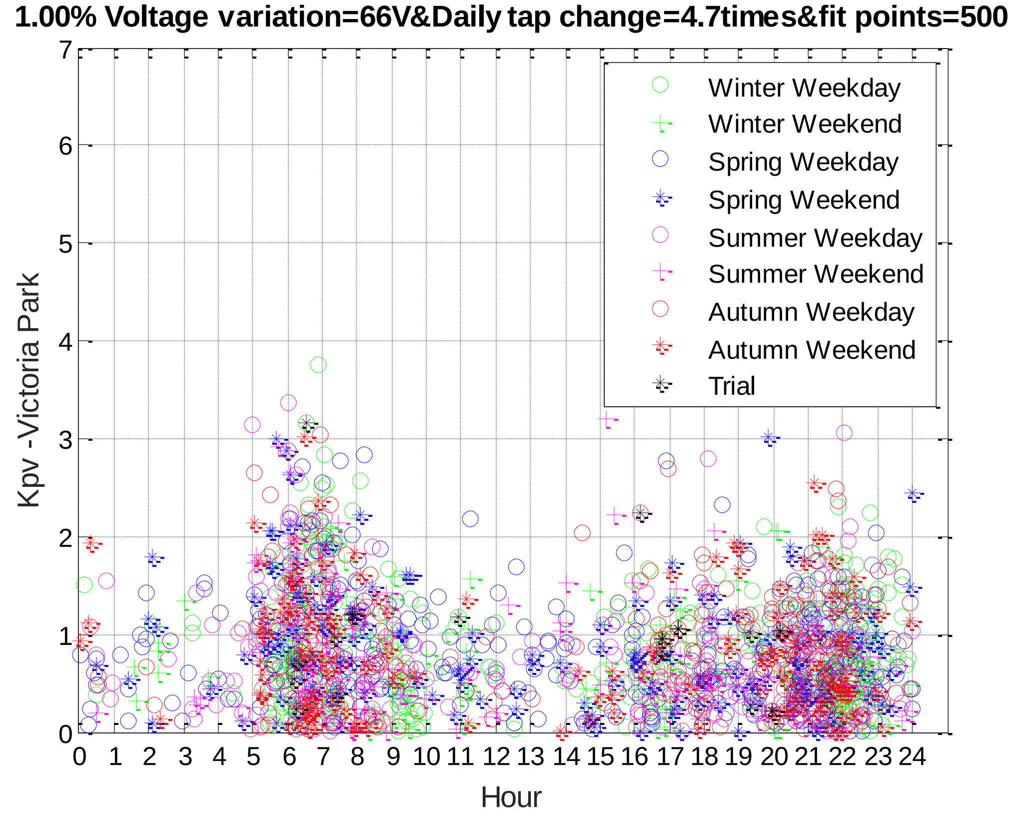

1.00% Voltage variation=66V&Daily tap change=0.2times&fit points=500
Kqv -Egremont
Hour
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend

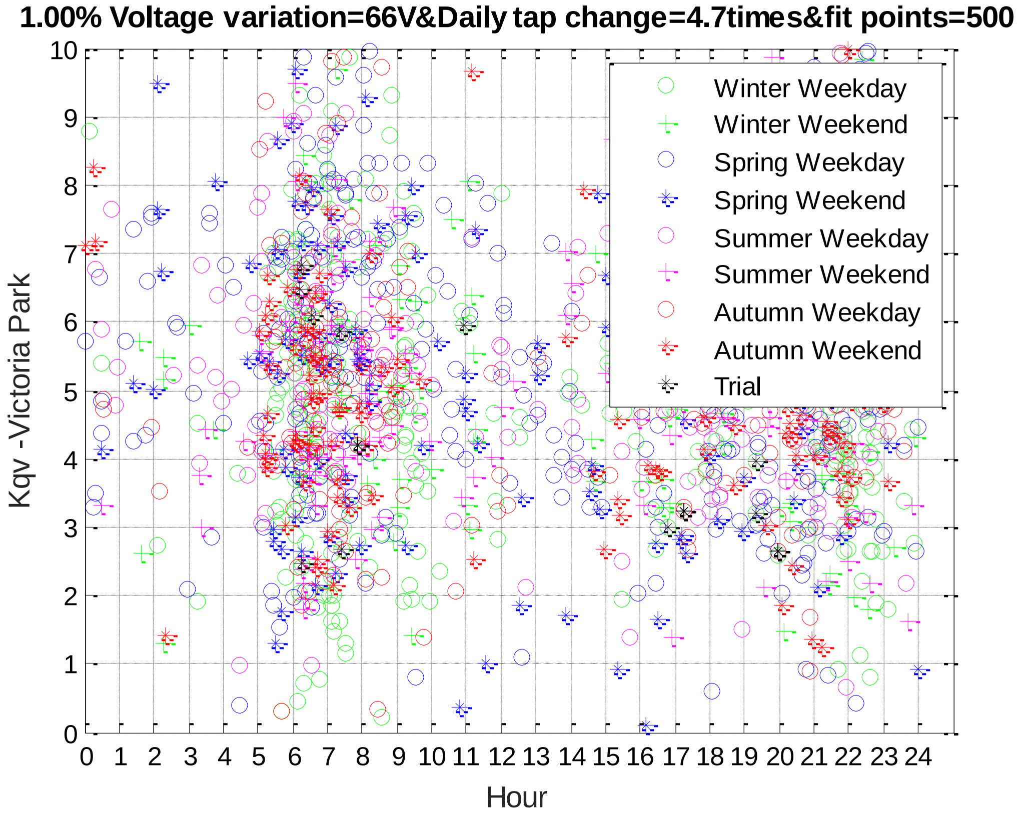

1.00% Voltage variation=66V&Daily tap change=2.3times&fit points=500
Kpv -Ashton
Hour
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
0 1 2 3 4 5 6 7
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend
Trial

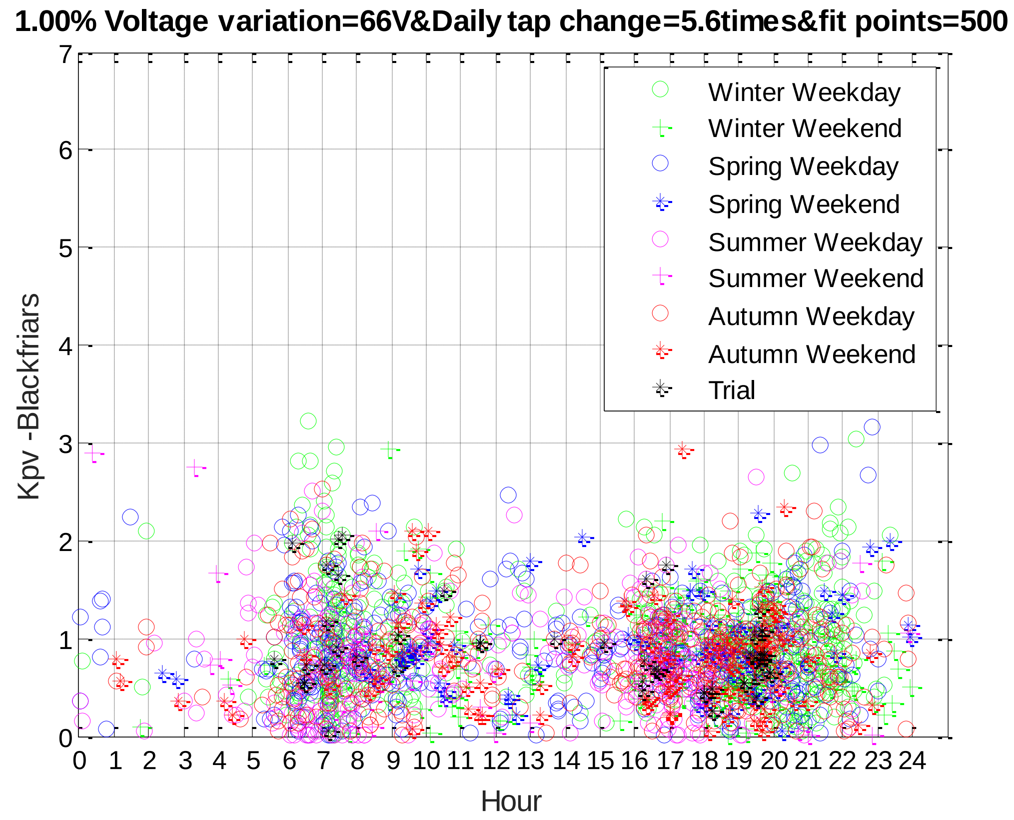

1.00% Voltage variation=66V&Daily tap change=2.3times&fit points=500
Kqv -Ashton
Hour
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
0 1 2 3 4 5 6 7 8 9 10
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend
Trial

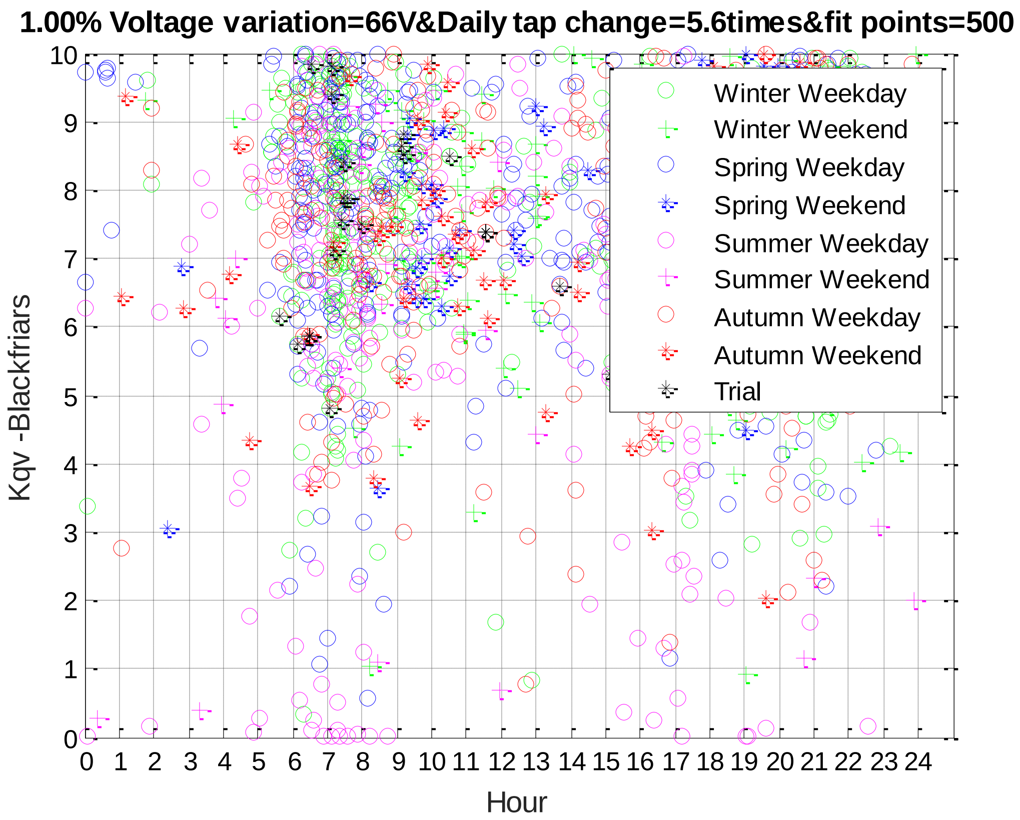

1.00% Voltage variation=66V&Daily tap change=0.1times&fit points=500
Kqv -Buckshaw
Hour
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend

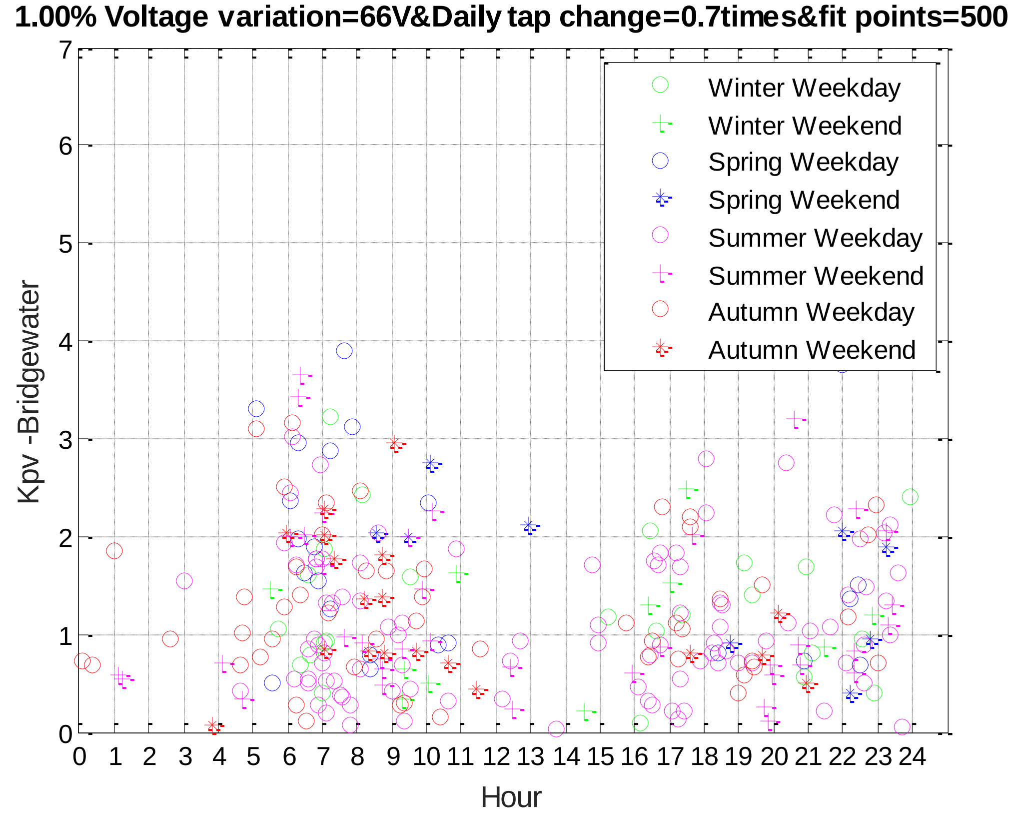

1.00% Voltage variation=66V&Daily tap change=0.1times&fit points=500
Kpv -Buckshaw
Hour
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend

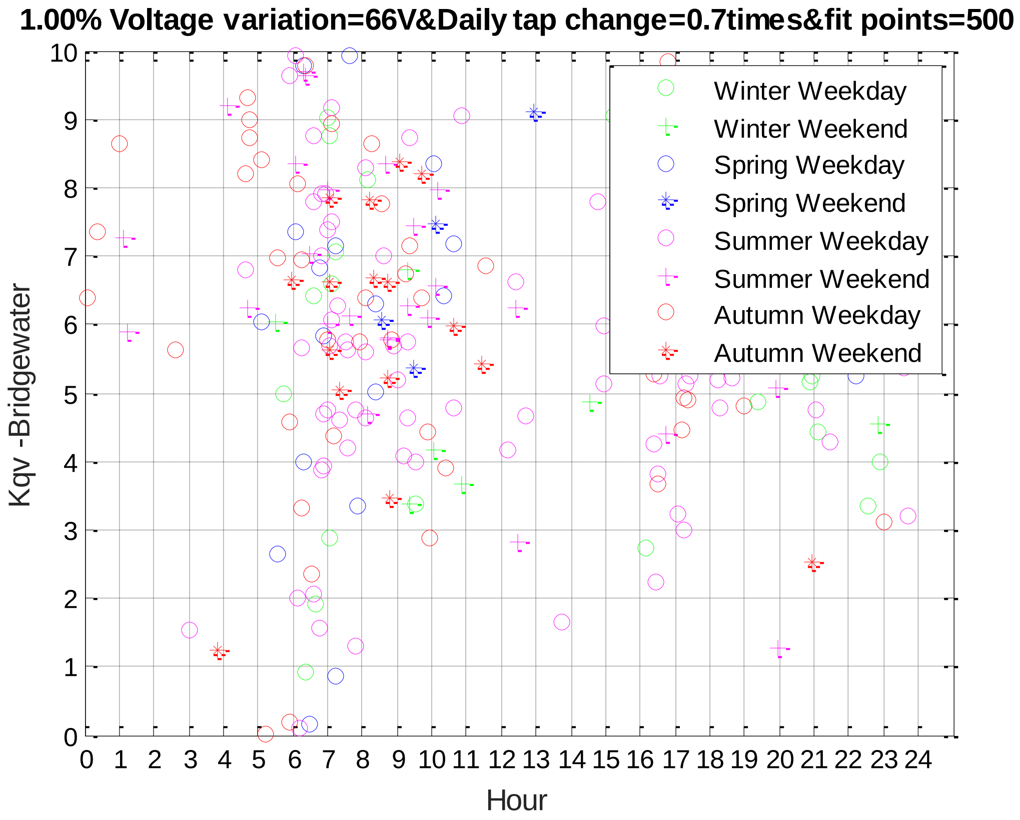

1.00% Voltage variation=66V&Daily tap change=4.7times&fit points=500
Kpv -Victoria Park
Hour
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
0 1 2 3 4 5 6 7
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend
Trial

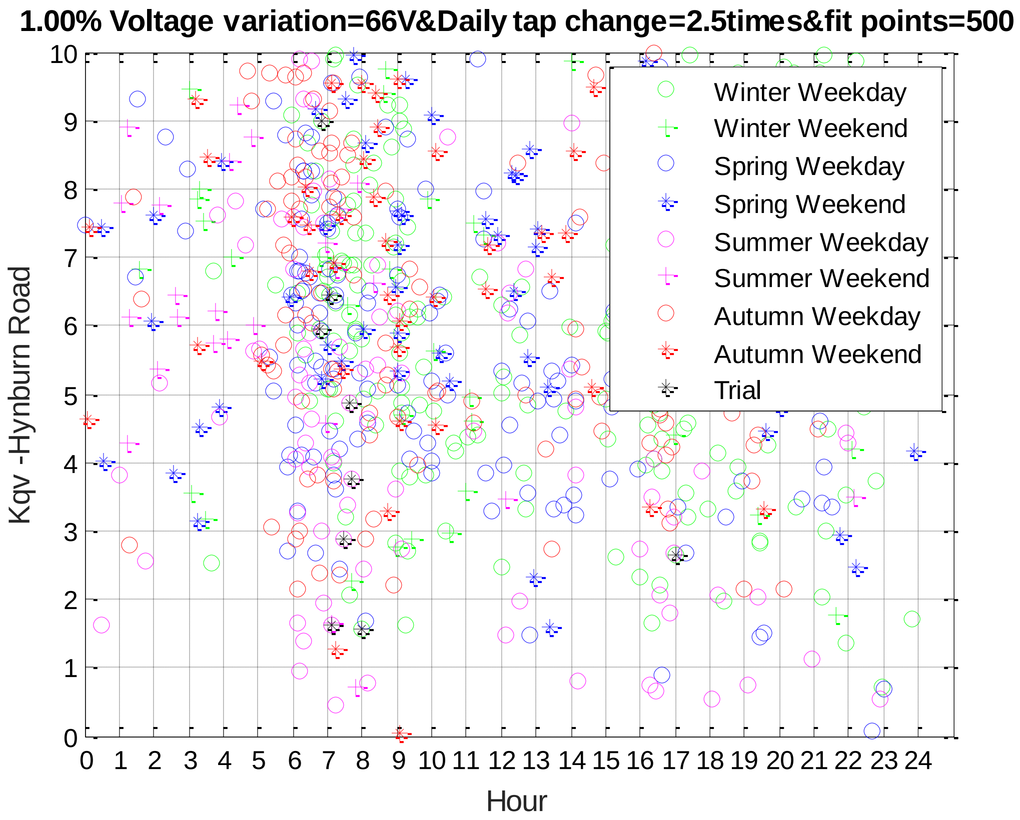

1.00% Voltage variation=66V&Daily tap change=4.7times&fit points=500
Kqv -Victoria Park
Hour
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
0 1 2 3 4 5 6 7 8 9 10
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend
Trial

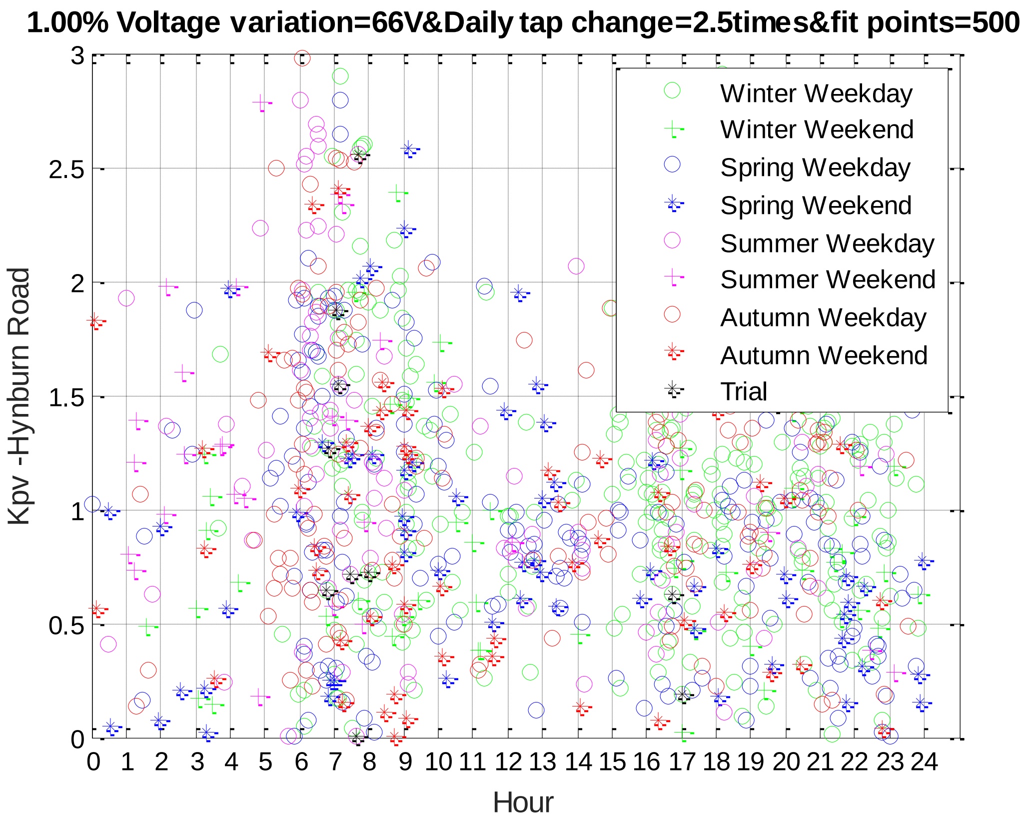

1.00% Voltage variation=66V&Daily tap change=5.6times&fit points=500
Kpv -Blackfriars
Hour
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
0 1 2 3 4 5 6 7
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend
Trial

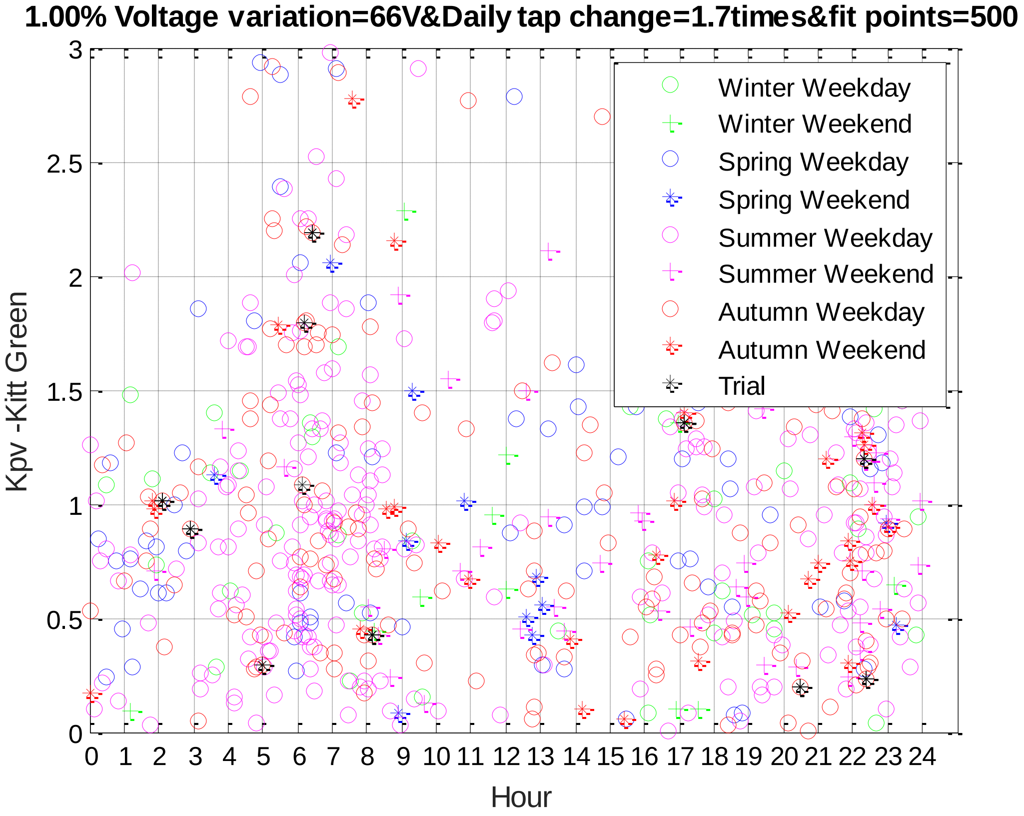

1.00% Voltage variation=66V&Daily tap change=5.6times&fit points=500
Kqv -Blackfriars
Hour
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
0 1 2 3 4 5 6 7 8 9 10
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend
Trial

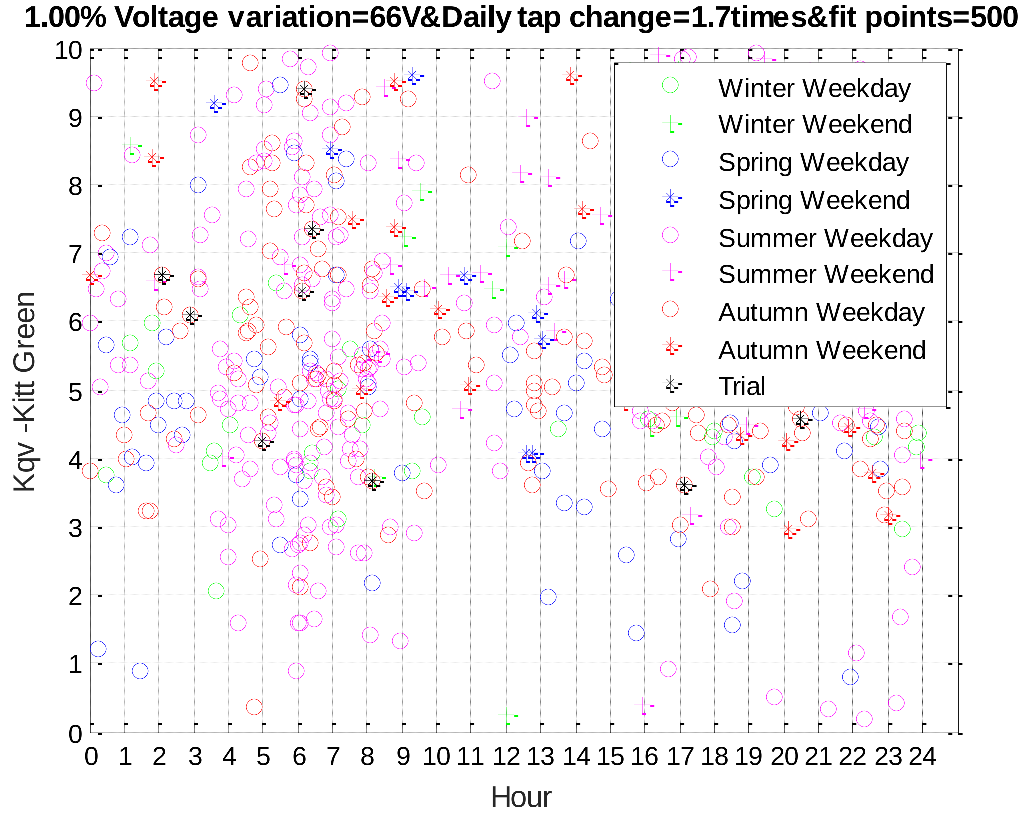

1.00% Voltage variation=66V&Daily tap change=0.7times&fit points=500
Kpv -Bridgewater
Hour
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend


1.00% Voltage variation=66V&Daily tap change=0.7times&fit points=500
Kqv -Bridgewater
Hour
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend


1.00% Voltage variation=66V&Daily tap change=2.5times&fit points=500
Kqv -Hynburn Road
Hour
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend
Trial


1.00% Voltage variation=66V&Daily tap change=2.5times&fit points=500
Kpv -Hynburn Road
Hour
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend
Trial


1.00% Voltage variation=66V&Daily tap change=1.7times&fit points=500
Kpv -Kitt Green
Hour
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend
Trial


1.00% Voltage variation=66V&Daily tap change=1.7times&fit points=500
Kqv -Kitt Green
Hour
Winter Weekday
Winter Weekend
Spring Weekday
Spring Weekend
Summer Weekday
Summer Weekend
Autumn Weekday
Autumn Weekend
Trial

# Appendix C – Load Models for All 60 Substations

60 excel files for 60 substations have been provided separately.