University of Southern Queensland

Faculty of Health, Engineering and Sciences

Investigation of Low Voltage Regulation Opportunities on the Distribution Network

A dissertation submitted by

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Abstract

The low voltage electricity network is a large distribution asset designed to deliver electricity to customers whilst maintaining voltage within statutory limits. Recent increases in solar photovoltaic connections have changed the way electricity flows through the network. Instead of flowing from generators, through transmission networks, through distribution networks and then to customers, electricity can now flow in either direction. This can cause voltage issues to customers.

This research project investigates the use of emerging low voltage regulation technologies to address performance issues on the LV network. The initial part of this project investigates four types of LV regulation opportunities, which are a Gridco Systems Inline Power Regulator (IPR), a distribution transformer with an on load tap changer, a transformer with electronic regulation and installing a Volt VAR regulator device.

The core component of this project assesses the Gridco Systems IPR as a viable means of addressing LV regulation problems as this device has been installed within the Energex network. Voltages were measured before and after the IPR was installed and the measured data compared to the modelled data.

There has also been a cost benefit analysis completed to ensure that this alternative is the most cost effective solution in these scenarios.

The results show that the IPR maintains the voltage within statutory limits and a tighter range than before the IPR was installed. The results also indicate that there is the ability to provide greater PV hosting capacity on the LV network. The field based trial will continue after this project is completed to ensure the device is suitable in all seasons for Australian conditions.

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Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Shaun Rosendale

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Signature

13 October 2016

Date

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Glossary of Terms

DAPR	Distribution Annual Planning Report
DG	Distributed Generator
IPR	Inline Power Regulator
kV	Kilo Volt
LV	Low Voltage
LVABC	Low Voltage Aerial Bundled Cable
LVR	Low Voltage regulator
NPV	Net Present Value
OLTC	On Load Tap Changer
PV	Photovoltaic
RDT	Regulated Distribution Transformers
SCADA	Supervisory Control and Data Acquisition
SVC	Static Var Compensator
SWER	Single Wire Earth Return
TAPR	Transmission Annual Planning Report
Var	Volt-Ampere Reactive
Volt	Voltage

Chapter 1. Introduction

As electricity distribution networks need to change due to the ever increasing distributed generation (DG) being installed, there is a need for the low voltage (LV) network to be able to handle the bi-directional energy flow. This project investigates voltage regulation opportunities on the LV network. This also includes a field base trial of a padmounted In-line Power Regulator (IPR) on the LV network to assist in maintaining the quality of supply to all of the customer's on the network.

1.1 Background Information

The following information provides the background to the electricity supply network and will assist in understanding this research project.

1.1.1. Overview of the Electricity Supply Network

Electrical energy is mainly produced by large generation plants that can be owned and operated by either government or private enterprise. As electrical energy cannot be stored in large quantities, there needs to be adequate capacity to supply power to customers at all times.

The electricity network was originally designed for power to flow from generators, through transmission networks, through distribution networks and then to customers.

A pictorial representation of the electricity supply chain is shown in Figure 1.1.

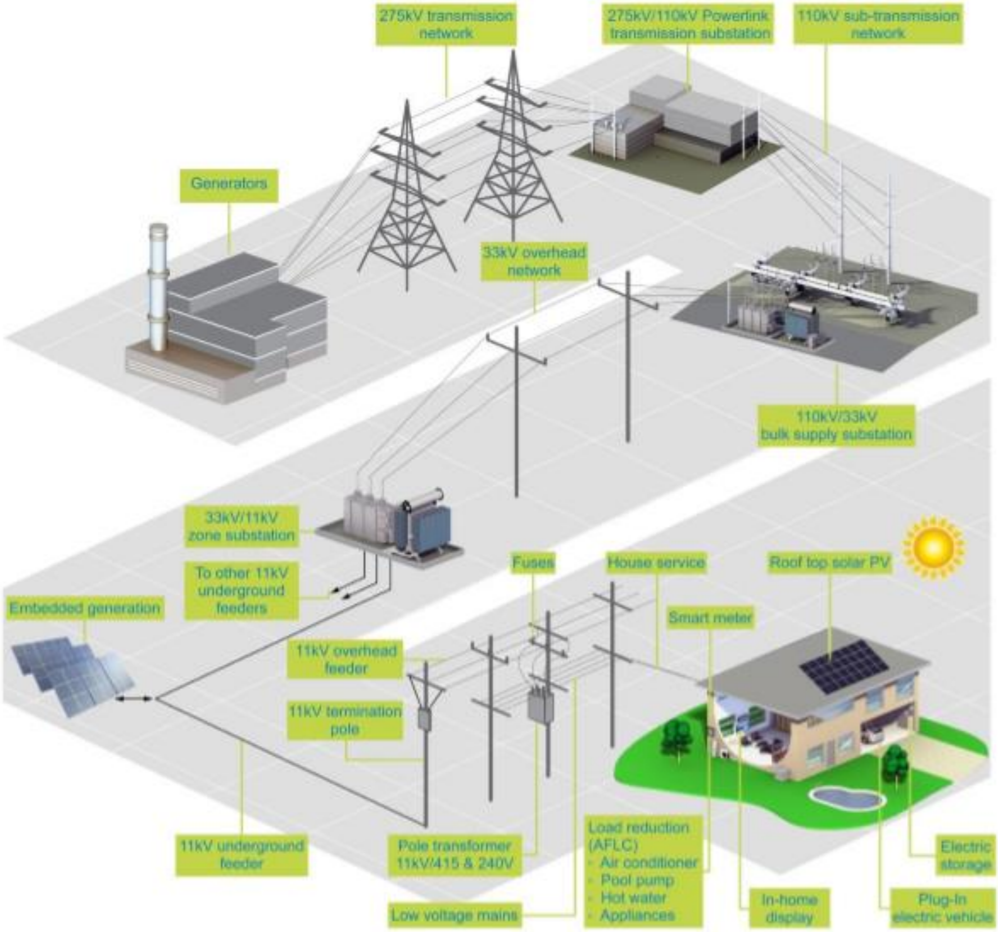

Figure 1.1 – Typical Electricity Supply Chain by Energex (DAPR)

1.1.2. Electricity Supply Networks in Queensland

The movement of electrical energy through generation, transmission and distribution network in Queensland is governed by legislation in the "Electricity Act 1994" and the "Electricity Regulation 2006".

The electrical supply networks in Queensland consist of three main parts. They are the power generation plants which are either government owned corporations or privately owned, a transmission network which is operated by Powerlink Queensland and is a government owned corporation and distribution networks which are operated by Energex in south east Queensland and Ergon Energy for the area outside of south east Queensland.

The Energex DAPR 2015 reports that the electricity supply network consists of approximately 23,100 km of 11 kV overhead and underground cables and approximately 25,100 km of LV overhead and underground cables.

The Ergon Energy DAPR 2015 reports that the electricity supply network consists of approximately 118,300 km of 11 kV, 12.7 kV and 19.1 kV overhead and underground cables and approximately 20 - 25,000 km of LV overhead and underground cables.

1.1.3. LV Networks

The LV electricity network is a large distribution asset that was originally designed to deliver electrical energy from the transformer to the customer. This was also whilst maintaining voltage within statutory limits. However, due to there being limited monitoring devices in the network its quantitative performance remains largely unknown.

The LV electricity network has changed in recent times due the large amount of solar photovoltaic (PV) installed. The LV network has become an extremely important part of the electricity network.

PV installations use inverters to connect to the electricity network and feed back to the grid in the event of producing excess energy, The inverters of the PV installations are set to operate in a voltage bandwidth, and if the electricity network's voltage exceeds this then the inverter will trip off. This leaves customers unhappy and the electricity distributor needing to rectify the situation. This may require the electricity distributor to augment the network which can cost hundreds of thousands of dollars depending on the work required to rectify the quality of supply.

1.1.4. Quality of Supply

Customers on the electricity network have an expectation that the supply authority that they purchase their electricity through will provide a supply that is maintained within a set of limits and will not have an adverse effect on any of their equipment.

The Electrical Regulations 2006 outline that the local supply authority is required to maintain the voltage level at the customer's terminals within ± 6% of 240 V, which equates to 225.6 V to 254.4 V.

Grid connected PV inverters will only operate while connected to the electricity supply grid. The output of the inverter is covered in the Australian Standard AS4777 and is required to comply with this standard. This should prevent inverters creating a voltage rise on the electricity network.

1.2 Project Aims and Objectives

The aim of this project is to assess the Gridco Systems IPR as a viable means of addressing LV regulation on the south east Queensland electricity distribution network.

The objectives of this project are as follows:

- Review the background on LV networks including, traditional design methodology, voltage statutory limits and traditional augmentation methods for voltage issues.
- Review four different low voltage regulation technologies, which are a Gridco Systems In-line Power Regulator (IPR), a distribution transformer with an on load tap changer, a transformer with electronic regulation and installing a Volt VAR regulator device.
- Investigate the benefits of each option and look at real world scenarios.
- Carry out analysis of LV networks before and after the IPR is installed.
- Calculate the net present value of a traditional LV augmentation project and the new IPR installation.
- Monitor the voltage after the installation of the IPR and compare to modelled results.
- Create an Augmentation Decision Process to assist the planners in deciding when to use the new product.

1.3 Project Site Selection

This project looks at two different LV network locations where there have been previous issues with quality of supply. These sites have had voltage investigations carried out and options investigated using traditional methods to rectify power quality issues. Both of the sites had prior planning carried out to determine a solution; however the options were not cost effective and therefore alternative methods have been investigated.

The first site is in a semi-rural area that is supplied via an overhead network. The 11 kV that supplies the transformer runs along a council controlled road reserve. The LV network then traverses private properties and an unformed road reserve to another council controlled road reserve. The 11 kV does not follow the LV network through private property. The existing LV network from the transformer consists of 120m of three phase 7/.104 copper conductor and then 385m of 95mm^2 aerial bundled cable (LVABC). The LV network is shown in Figure 1.2.

Figure 1.2 – Existing LV network of site 1 from Energex GIS system

The voltage and current recorded at the transformer of site 1 is shown in Figure 1.3 and the voltage and current at the end of the LV network is shown in Figure 1.4. This shows the voltage at the transformer ranges between 250V and 239V and the voltage at the end of the LV feeder ranges between approximately 253V and 222V. This is on the upper limit of the maximum allowable voltage 254.4V and the LV feeder goes below the minimum allowable voltage limit of 225.6V.

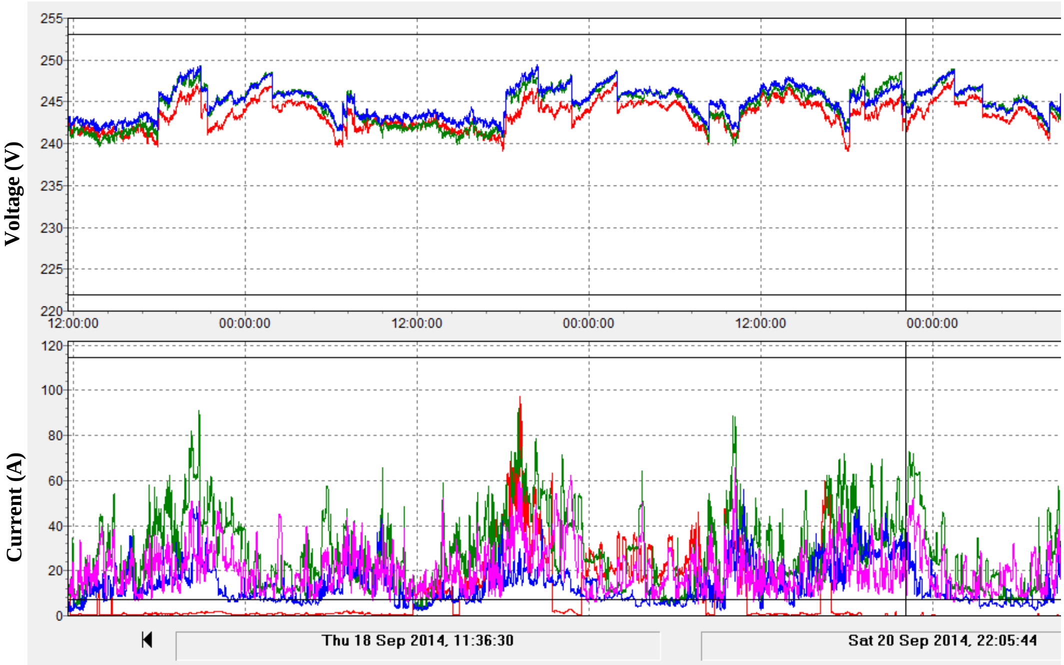

Figure 1.3 – Voltage and current measured at transformer at site 1 by Energex

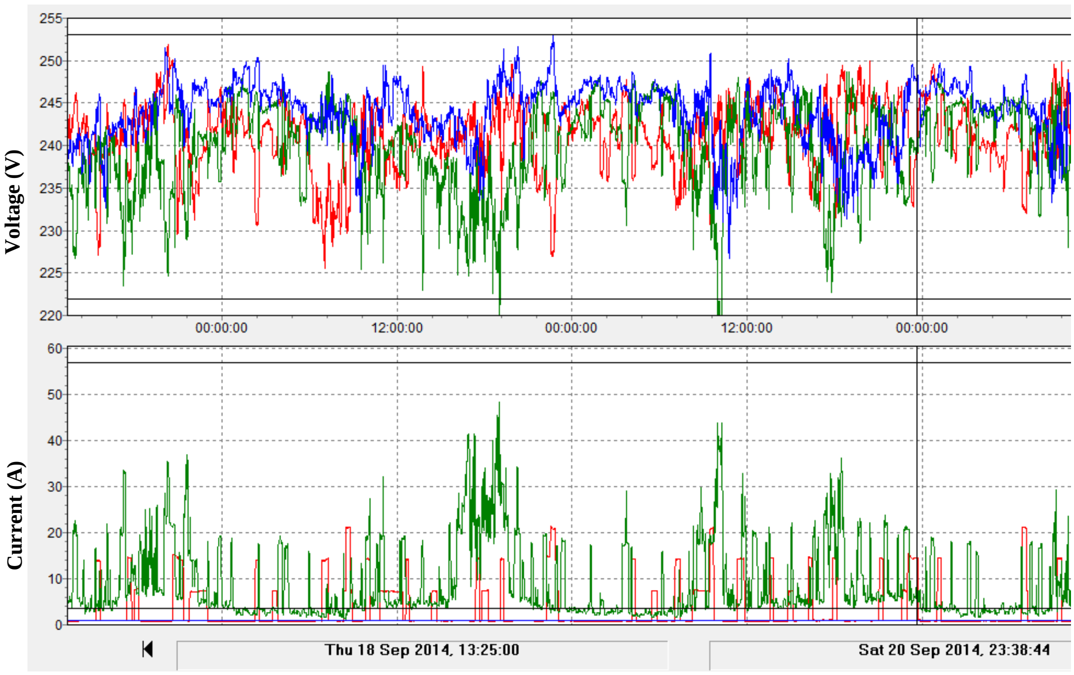

Figure 1.4 – Voltage and current measured at end of LV network at site 1 by Energex

Planning was completed for this site and it was determined using a program that models the LV network called LV DROP Version 8.0.3, that reconductoring the existing 7/.104 copper conductors with LVABC may just restore the voltage levels to the required statutory limits, however there was concern that it would not rectify the quality of supply issues for all scenarios. The existing voltage drop calculations are shown in Figure 1.5 and the voltage drop calculations for the reconductored section is shown in Figure 1.6. As can be seen there is still almost 10V drop at the ends of the network.

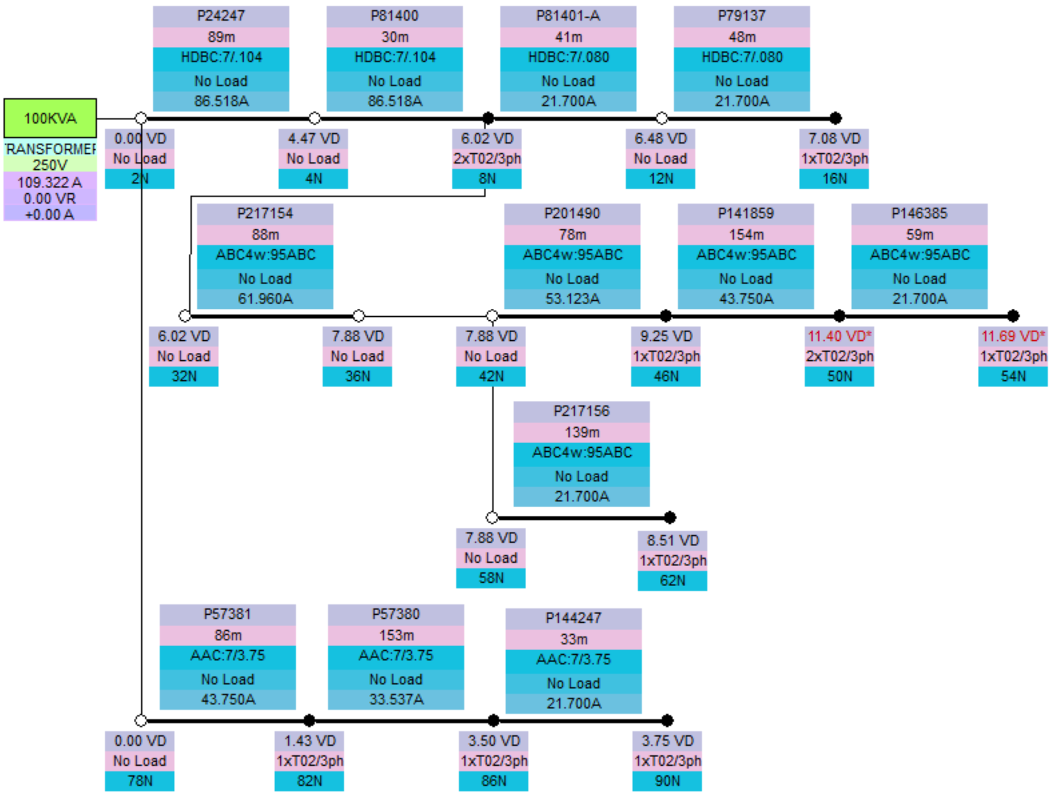

Figure 1.5 – Model of Voltage Drop of Site 1 with existing network by User

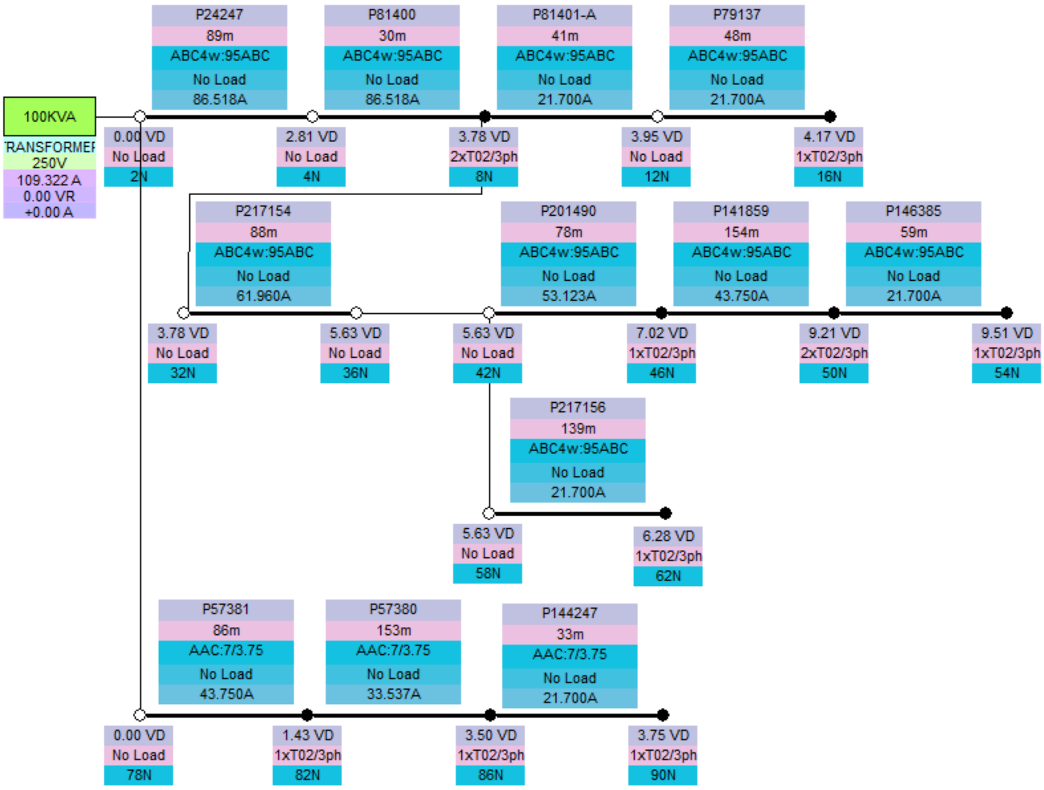

Figure 1.6 – Model of Voltage Drop of Site 1 with reconductoring by User

Another option considered was to extend the 11 kV through private property and the unformed road reserve, and to install a new pole mounted transformer on the adjoining council controlled road reserve. A new LV open point could be created to split up the LV network. This option required the 11kV to be installed underground due to the heavy vegetation in the area. Also to install underground would have required horizontal directional drilling in this area due to the steep terrain. This option went through the design and estimate phase, however the estimated construction cost was excessive.

The second site is also in a semi-rural area that is supplied via both an overhead and underground network. The 11 kV network stops at the existing pole transformer, where the LV network runs overhead for 35m with 95mm^2 LVABC and then runs underground with a mix of 240mm^2 and 120mm^2 aluminium cable for 405m. There are no spare conduits installed along the property boundaries. The LV network is shown in Figure 1.7.

Figure 1.7 – Existing LV network of Site 2 from Energex GIS system

The voltage and current recorded at the transformer at site 2 is shown in Figure 1.8 and the voltage and current at the end of the LV network is shown in Figure 1.9. This shows the voltage at the transformer ranges between 248V and 236V and the voltage at the end of the LV feeder ranges between approximately 255V and 232V.

The voltage at the end of the LV feeder exceeds the upper limit of the maximum allowable voltage 254.4V and goes close to the minimum allowable voltage limit of 225.6V.

Figure 1.8 – Voltage and current measured at transformer at site 2 by Energex

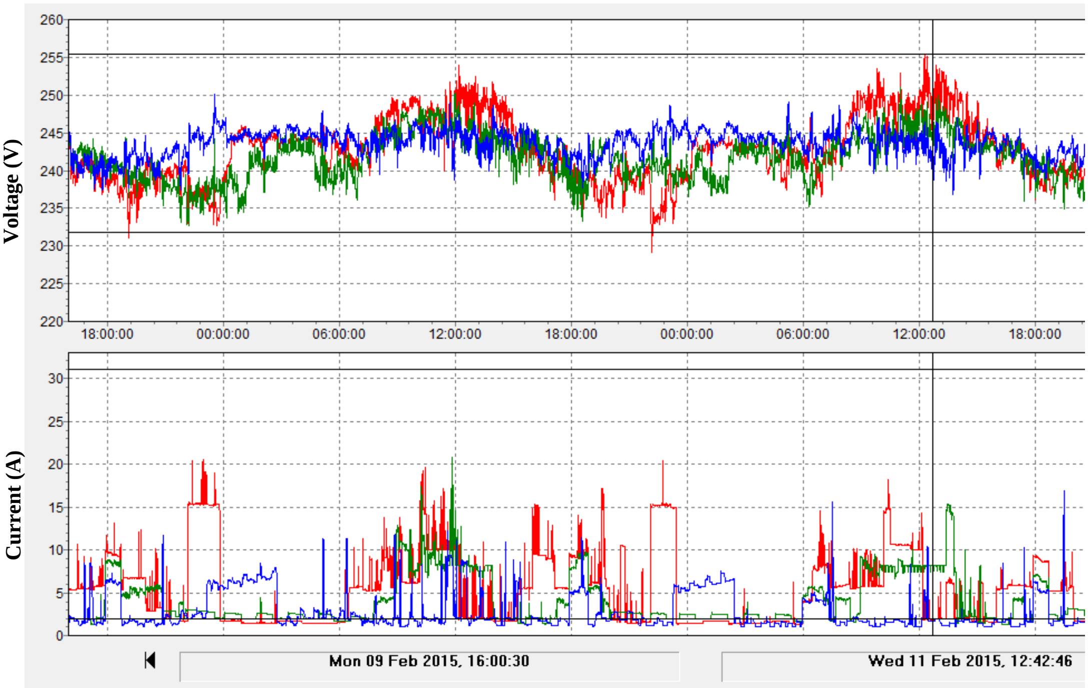

Figure 1.9 – Voltage and current measured at end of LV network at site 2 by Energex

There were also dips recorded when a swimming pool heat pump started. This is at the end of the LV network and shows that the voltage on one phase drops to approx. 222V when there is a starting current of 80A on one phase. This is shown in Figure 1.10.

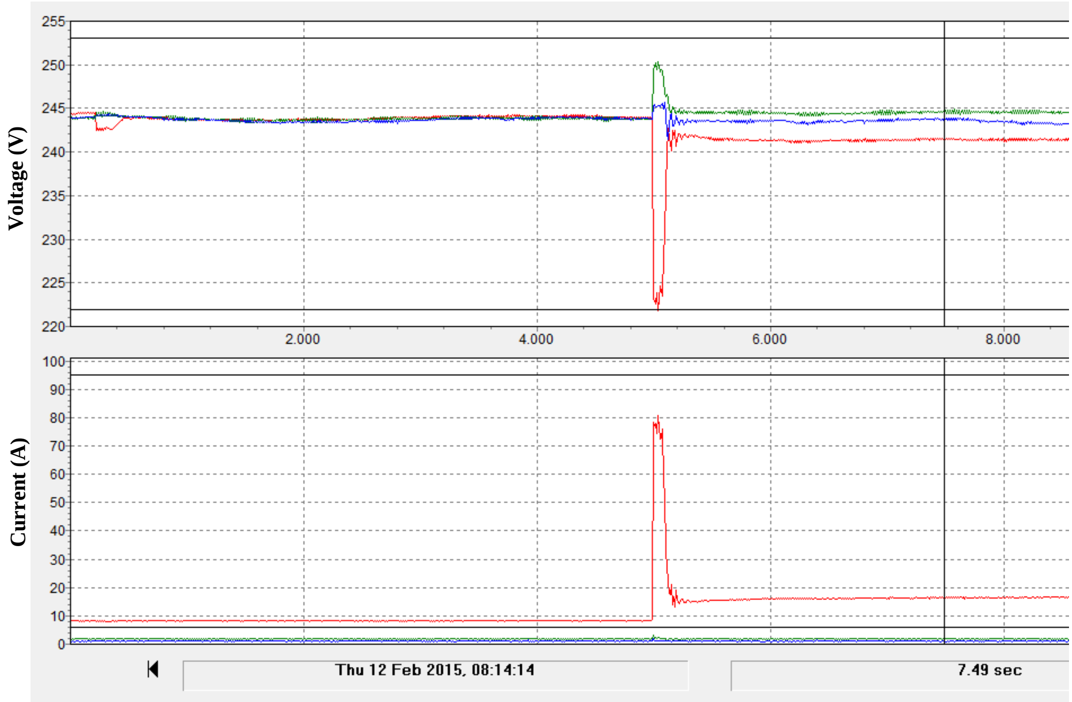

Figure 1.10 – Instantaneous voltage profile by Energex

There were limited options for this site; however a voltage drop study was carried out. The voltage drop of the existing network is shown in Figure 1.11 which shows the voltage drop at the end of the network has a voltage drop greater than 10V. The option of replacing the sections of 120mm^2 to 240mm^2 would provide a minimal improvement, however it would be very difficult to replace the cable as there are no spare conduits.

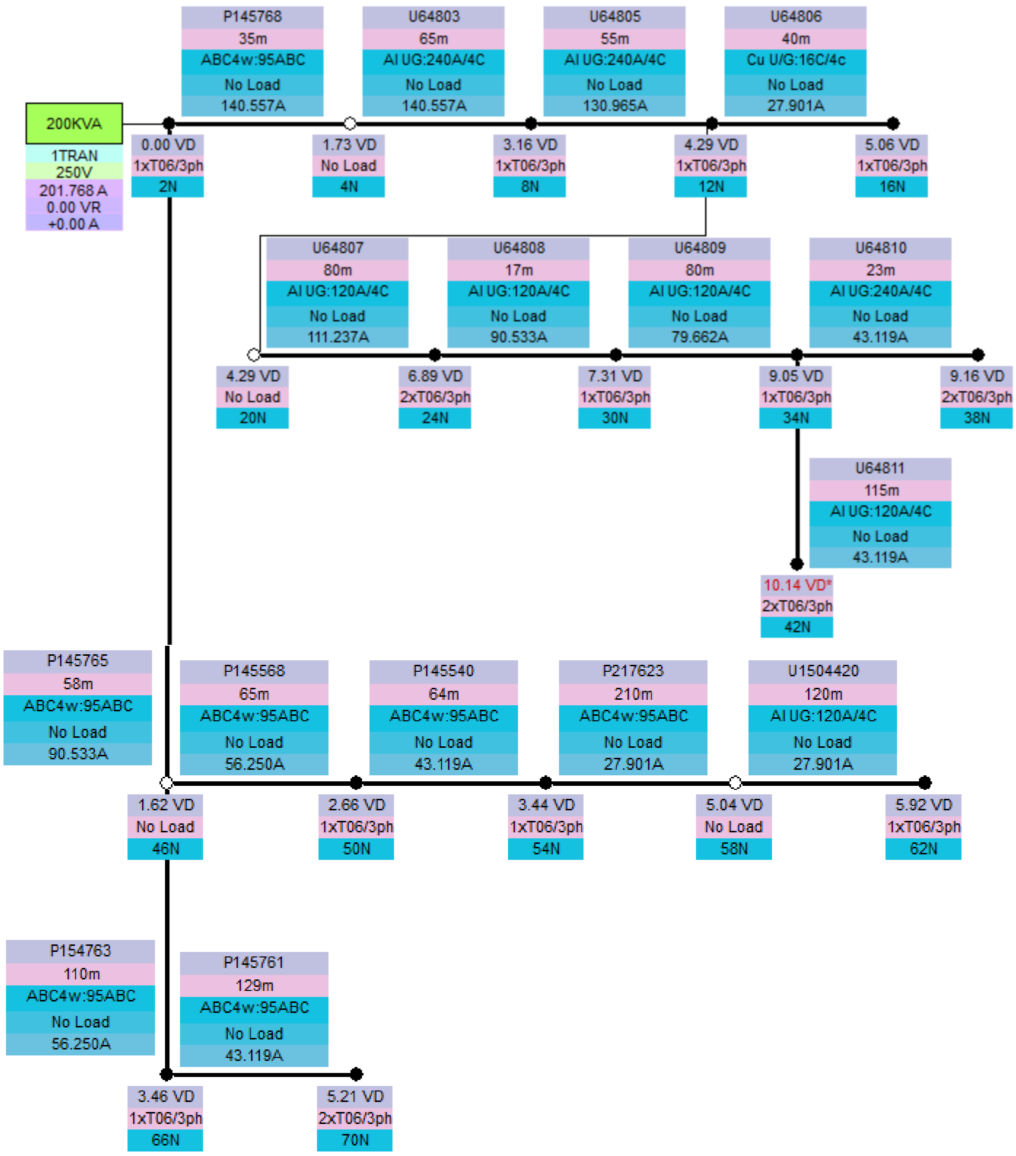

Figure 1.11 – Model of Voltage Drop of Site 2 with existing network by User

Another option considered was to open trench or horizontal directional drill and extend the 11 kV underground up the street and install a new padmounted transformer. This option would require the approval from the local council to install the device on the road reserve (which is not normally done) and also would require finding a suitable site that would not impact on any of the property owners. This option was estimated before going into design and found that the costs were also excessive.

Due to the complexities and the costs of rectifying the existing network at these two sites, it was decided to trial the new LV regulator to determine if this could be a viable alternative in situations similar to these.

Chapter 2. Literature Review

This review was conducted to increase knowledge regarding the research project. There were a few objectives considered relevant to this project which were:

- Defining a LV network
- The changing LV network,
- The traditional approach to rectifying voltage issues
- Investigate four different types of LV regulation.

2.1 A Low Voltage Network

As stated by Hadjsaid, N. & Sabonnadiere, J. (2011), the electricity network consist of three basic segments, which are generation, network and consumers. The network segment can also be split into two segments, which are the transmission system and the distribution system. These systems are different in the make-up, voltage levels, size and operations.

One section of a distribution system is made up by the LV network. The LV network is often a radial network that is used to connect customers to the network. In a rural area, the LV network is normally made up of poles and insulated bundled cables or bare open wire overhead cables. In built up areas, the LV network is normally made up of an insulated underground cable and connection pillars, often installed on the road reserve aligning with property boundaries. These cables are often tied to other LV networks through open points, so that if a fault occurs, there is a means of restoring supply to non-affected areas.

The Energex Supply and Planning Manual, Section 3.3 summarizes the requirements for low voltage systems. This outlines the Electricity Regulation 2006, that any local supply authority is required to maintain the voltage level at the consumer's terminals within ± 6% of 240 V. This translates to a voltage range of 225.6 V to 254.4 V at the consumer's terminals

To ensure the voltage level is maintained at every consumer's terminals of a supply authority, the total voltage drop along the network must be limited to a maximum value. This value is subject to a number of items which include the terminal voltage and the transformer, the effects of unbalance on the network and the maximum voltage drop on services.

The Energex Supply and Planning Manual states that the allowable balanced voltage drop on the LV network from the transformer terminals to the furthest connection point is 10 volts for an overhead network or 11 volts for an underground network. This is based on the transformer at full load with a minimum secondary voltage of 242 volts.

This outlines the voltage range that Energex is required to maintain in the LV network to the customers point of supply.

2.2 The Changing LV Network

In the past, as stated by Hyland, et al. (2003), the LV network has been planned and designed to provide capacity to supply customer loads. The electricity industry has used a common practice for designing and investigating low voltage networks that can be traced to the methods of J Boggis. The approach is to estimate the maximum demand on the network by a group of customers over a set time frame, which is normally one year. From this a voltage drop calculation is made by using the expected maximum demand at each node with the impedance model of the given LV network. Supply authorities gain from diversity, as the maximum demand of a group of customers is less than the sum of the maximum demands of the individuals.

As stated by Hadjsaid (2011), the major role of the LV network entails moving at any given moment, the power required by the customer. Also at present there is no way to store electrical energy on a large scale, it is therefore essential to be able to maintain a constant and real time balance between customer consumption and the generation. This also needs to include all electricity losses in the networks. A sudden imbalance between the generators and the customer's consumption can induce wide spread blackouts for part or all of an electrical system.

This is the way LV networks have been designed in the past, to transfer electricity in one direction. However due to a rather rapid reduction in the price of PV panels, combined with generous feed in tariffs, there has been a swift increase in the installation of private customer PV installations. This can create a high penetration of PV on distribution feeders, which can cause voltage regulation problems, especially in the case of a partly cloudy day, where there will be high variability in the output from the PV panels Barnes (2013).

This change can create power quality issues which can cause disturbances to residential, commercial and industrial customers.

Also the increase of PV installations on a LV network can cause a voltage rise, especially if the majority of PV installations are further along the LV network. The voltage rise at the end of the feeder can be high enough to cause the inverters to trip off due to overvoltage conditions.

2.3 The Traditional Approach to Rectifying Voltage Issues

The traditional approach to rectify voltage issues is outlined in the Energex Supply and Planning Manual 2012. Table 4.2.1 from this manual provides an Overview of Power Quality Parameters and is shown in Table 2. 1.

Table 2. 1 – Overview of Power Quality Parameters by Energex

Parameter	**Measurement Philosophy**	**Planning Level**	***Performance Standard***	**Target Level**
Voltage regulation	*Routine*	Zone Sub: +6% to -3% Dist. Sub: to be determined	*LV: 240V, ±6%* *MV: generally ±5% and ±10% at all times except for contingency events*	To be determined
Voltage unbalance	*Routine at 3ph sites*	To be determined	Table 5.	To be determined
Current unbalance – customer sites	*Routine* at certain sites	<performance standard	LV: max demand current (30 minute values) in any phase not to exceed the max demand current in other phases by more than 20 amperes or 20% <30kV: the current (30 minute values) in any phase is not >105% and or <95% of the average of the currents in the three phases. ≥30kV: the current (30 minute values) in any phase drawn is not >102% and/or <98% of the average of the currents in the three phases.	N/A
Neutral-Earth voltage difference	*Case specific*	<<performance standard	<10 volts at the *point of supply*	N/A
Voltage swells	*Routine*	< performance standard	National Electricity Rules curve – Figure 2	N/A
Voltage fluctuations & flicker	*Case specific*	Refer table	Refer Table	N/A
Voltage sags	*Routine*	< performance standard	Undefined at this stage	To be determined
Transients	*Case specific*	N/A	Appendix B provided indicative transient levels – customers to protect.	N/A
Power frequency	*Routine* at certain sites	*Bulk supply points* - *Performance standard:* Grid-Normal Isol. gens - *Performance standard:* Isol. generators: Norm.	Grid – Normal: 50Hz, ±0.15Hz, Excursion band: 50Hz, ±0.25Hz Isolated Generator – Normal: 50Hz, ±0.5Hz	N/A
Harmonics	THD – *Routine*	*LV THD: 7.3%* 11-22kV: 6.6% 33kV: 4.4% 66kV: 4.1% 132kV: 3.0%	*LV & MV THD: 8%* Individual harmonics: Table 6 Telecommunications coupling - HB88 limits: Table 11	To be determined
Notching	*Case specific*	Appendix B	Depth: 20% of nominal fundamental peak V Oscillation amplitude: 20% of nominal fundamental peak V and Table 6	N/A
DC Offset	*Case specific*	< performance standard	Voltage - <10 volts Current – yet to be determined.	N/A
Mains signalling interference	*Case specific*	< performance standard	Meister curve: Figure 8	N/A
Conducted *Non-Network-Frequency-Related Interference*	*Case specific*	< performance standard	CISPR limits for conducted emissions: Figure 9	N/A
Radiated *Non-Network-Frequency-Related Interference*	*Case specific*	< performance standard	*Powerline interference* – AS/NZS2344 limits: Table 7 Equipment - CISPR limits: Figure 10	N/A
Electric and magnetic fields	*Case specific*	< performance standard	National Health and Medical Research Council limits: Table 10	N/A
Power factor	*Routine* at certain sites	LV Customers: >0.8 but not leading 1-50kV: 0.90 lag to 0.90 lead 50-250kV: 0.95 lag	Table 14: >0.8 lagging but depends on nominal voltage level.	To be determined

Section 3.3.4 of Energex's Supply and Planning Manual covers Voltage Management and outlines typical solutions to voltage management solutions. These are

• Assess the number of connections per phase of the customer (PV systems and customer loads) and balance them as required.

• Change the tap setting on the distribution transformer.

• Shift LV links.

• Investigate ways to reduce voltage drop by possibly reconductoring.

• Increase the size of the distribution transformer to remove any overloading condition.

• Split the LV network by installing another distribution transformer.

• Alter the set point voltage on the PV inverter.

These are explained further below:

• Assess the number of connections per phase of the customer (PV systems and customer loads) and balance them as required.

> The initial requirement is to count the number of customers (including PV installations) on each phase and attempt to balance the load over all three phases. This can be a trial and error approach, however it is also the most cost effective option.

• Change the tap setting on the distribution transformer.

> If the voltage is too high or low, then there is the option to raise or lower the distribution transformer one tap. Changing the tap position will normally adjust the voltage level approximately 7V. Once the LV network is balanced this may be required. To do this requires a power outage to the customers for a short period of time.

• Shift LV links.

> If the distribution transformer is overloaded and an adjoining transformer is lightly loaded, then there is the option of transferring some load from one transformer to another. This is done by moving a set of LV links (to be used as the new LV open point).

• Investigate ways to reduce voltage drop by possibly reconductoring.

If the existing LV mains are an older or small conductor with a high impedance, then it may be beneficial to reconductor the LV overhead mains. Replacing the conductors can reduce significant losses and voltage drop. The size of the existing mains will dictate if this option is suitable.

• Increase the size of the distribution transformer to remove any overloading condition.

If the existing transformer is overloaded and the LV network does not have any voltage issues, then replacing the transformer for a larger one can be the best solution.

• Split the LV network by installing another distribution transformer.

If the existing transformer is overloaded and there are voltage issues on the LV network, then installing a new transformer to break up the LV area may be required.

• Alter the set point voltage on the PV inverter.

2.4 Four Different Types of LV Regulation

The four different types of LV regulation that this project looks at are:

1. Distribution transformer with an on load tap changer
2. Distribution transformer with electronic regulation
3. A STATCOM device
4. A Gridco Systems In-Line Power Regulator (IPR)

2.4.1. Distribution Transformer with an On Load Tap Changer

As stated by Esslinger & Witzmann (2012), with a regular distribution transformer the ratio between the primary and secondary voltage is unable to be changed while on load. Power transformers utilise an On Load Tap Changer (OLTC) which is now being proposed in LV distribution transformers. The cost has limited this in the past, nevertheless this is now being considered as an option due to the number of DG's now in LV networks.

As stated by Berger et al. (2013), the use of OLTC's on the high and very high voltages has been used for decades with great success. At the LV level, the Regulated Distribution Transformers (RDT's) have only become available in recent times. In situations on the LV network where there is a relatively regular distribution of load and generators, a RDT can provide great results.

Navarro-Espinosa & Ochoa (2015) state that the use of an OLTC on a distribution transformer allows the ratio between the primary and secondary voltages of the transformer to be varied. This is useful for regulation purposes, and depending on the configuration of the LV network, the location of the transformer and load point will dictate the suitability.

In these cases, the strategy for regulation is to set the transformer at a fixed voltage level throughout the day. This target is meant to alleviate all voltage rise and voltage drop issues.

These are now being manufactured by the company Wilson Transformers, and come in a capacity of 315kVA. The specifications for the transformers can be found in Appendix B.

The distribution transformer with an OLTC has the benefit of OLTC's being installed for many years on power transformers and therefore is not new technology. They can easily be installed on a pole which provides flexibility in choosing the optimum location to suit the needs of the network. The Wilson Transformers model at 315kVA has a large capacity and so will suit a number of sites. It would be beneficial if a smaller capacity transformer, of 100kVA or 200kVA could be available for the smaller LV areas. The output voltage bandwidth will be reduced compared to a standard distribution transformer, however the bandwidth will not be as tight as the other devices.

2.4.2. Distribution Transformer with Electronic Regulation

The Regformer from the company Tyree, is a voltage regulating distribution transformer that is being trialed within the Energex area. As outlined in "Regformer – The Smart Voltage Regulated Distribution Transformer for the SmartGrid", it is a distribution transformer that is electronically controlled. Voltage regulation is attained by using power electronics with the transformer.

The Regformer is a 100kVA pole mounted transformer that uses power electronics to regulate the LV terminals of the transformer. The voltage is controlled separately from the load power factor and current flow and the Regformer can regulate each phase voltage separately. The microprocessor controller of the Regformer is capable of discrete sampling and has the ability to act as a Supervisory Control and Data Acquisition (SCADA) point for monitoring purposes.

The microprocessor controller is from MicroPlanet who has used the controller previously on a single wire earth return (SWER) network with an LV regulator (LVR) on the Ergon Energy network, Cavanagh et al. (2014). The LVR had an 80A continuous rating and could boost or buck the incoming line voltage 16%. This provided an output voltage band of ±1%. These devices proved to be very suitable in the SWER environment and options for a future three phase model were investigated. A photo of the single phase unit on a SWER transformer site is shown Figure 2. 1.

Figure 2. 1 – MicroPlanet LVR on SWER transformer by T&D

The MicroPlanet controller has proven to operate in the Ergon Energy SWER network and has been installed in the Regformer transformer.

The Regformer is currently under a 12 month trial at Energex to determine how suitable it will be on the LV distribution network. The device has been installed on a LV network as shown in Figure 2. 2. This location was chosen as it has a reasonably long LV network of approximately 500m in each direction from the transformer. A photo of the device is shown in Figure 2. 3.

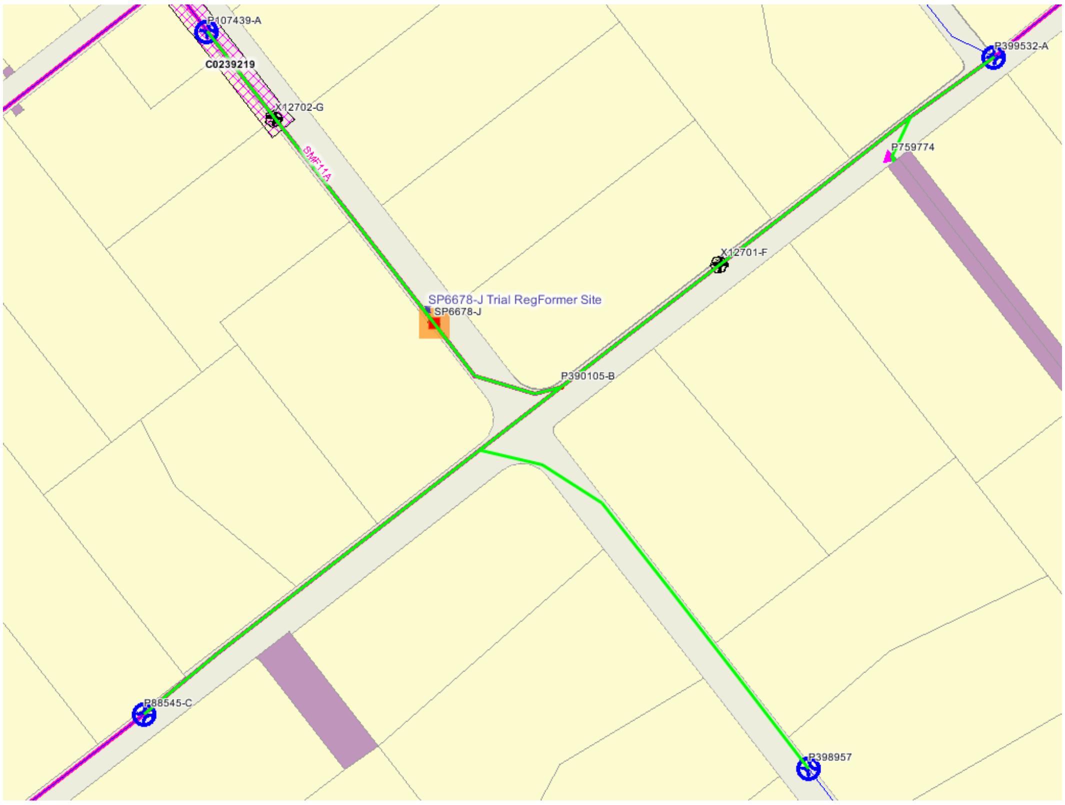

Figure 2. 2 – LV Feeder of RegFormer Trial by Energex

Figure 2. 3 – RegFormer Trial site by Energex

The Regformer distribution transformer has the Microplanet controller for the power electronics component of the inbuilt regulator. This should provide a tight output voltage bandwidth which should maintain a more consistent supply to the customers. The transformer is a pole mounted device which provides the flexibility in choosing the optimum location to suit the needs of the network. It is a 100kVA device which will suit a lot of sites in the more semi-rural and rural networks.

2.4.3. STATCOM Device

Moharana, et al. (2013) states that a Statcom is technically a solid state voltage source converter that is connected in parallel to the distribution network through an AC side reactor. The Statcom has no mechanical inertia.

The way a Statcom operates is as follows, if the supply voltage and the fundamental component of the output voltage of the Statcom are in-phase then the current that flows in the direction of the Statcom will be 90^{o} lagging or leading to the supply voltage. The Statcom also operates when the fundamental voltage of the Statcom is larger than the supply and lagging. The Statcom will then run in full capacitive mode and will supply reactive power to the network. If the Statcom current lags the network voltage, the Statcom will run in inductive mode by adding VAR's to the network. The phase angle between the Statcom output voltage and the supply voltage is what is used to control the reactive power that is either generated or absorbed by the Statcom.

Tavakoli Bina, (2005) showed a prototype installation of a 250kVAR D Statcom as a viable option that can be used in practical applications.

As stated by Efkarpidis (2014), the D-Statcom can be used to improve power quality on the distribution network. It can be used to alleviate issues such as voltage fluctuation and flicker, voltage unbalances and current distortion. D-Statcom's are more flexible than Static Var Compensator's (SVC's) and the reactive power is more independent of the actual voltage on the connection point. Also where SVC's can inadvertently introduce harmonic currents and voltage flicker the D-Statcom can be used to reduce current harmonics.

Mokhtari et al. (2014) states that the principal functions of a D Statcom are to:

- lessen voltage peaks and dips on sensitive loads
- regulate voltage
- assist in the control of reactive power
- minimise the effect of voltage flicker

Energex is currently trialing a D-Statcom unit on a LV network to view the impact that they can have. The LV network that it is connected to is a long urban LV feeder and it is shown in Figure 2. 4.

The Energex D Statcom unit has been constructed on a dual axle trailer to make it portable and therefore suitable for connecting to LV networks. It consists of a bank of Toshiba lithium ion 40Ah batteries and three Starsine 20kVA Model EE20 single phase four-quadrant grid interactive inverters. A photo of the trailer is shown in Figure 2. 5 and of the batteries and controller is shown in Figure 2. 6.

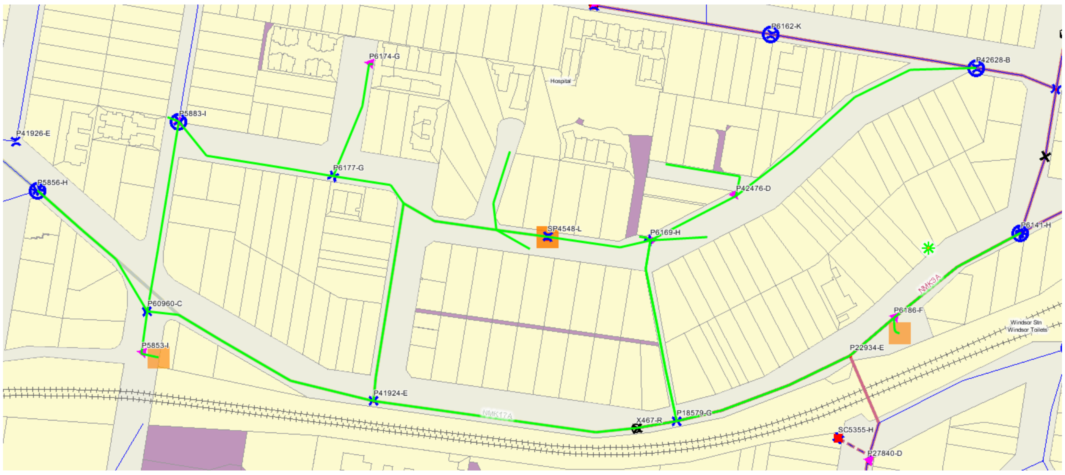

Figure 2. 4 – LV Feeder and D-Statcom Trial site by Energex

Figure 2. 5 – Energex Trailer mounted D Statcom unit

Figure 2. 6 – Batteries and Statcom unit in Energex trailer

As stated by Blažič, B. & Papič, I. (2004), the D-Statcom device is shunt connected to the network as shown in Figure 2. 7. This is how the D-Statcom device is connected to the Energex LV network, however there is also a LV Main Fuse Isolator and a set of 100A LV fuses on the trailer to provide isolation of the device.

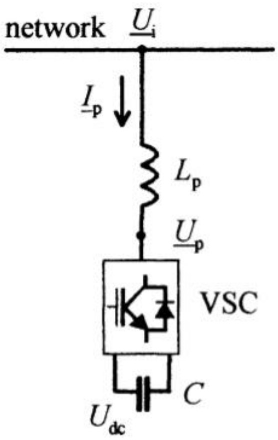

Figure 2. 7 – Basic D-Statcom Circuit by Blažič, B. & Papič, I. (2004)

2.4.4. Gridco Systems In-line Power Regulator (IPR)

An American company, Gridco Systems, has manufactured a freestanding 150kVA LV regulator that utilises power electronics to provide dynamic voltage regulation, reactive power compensation and harmonic cancellation. This regulator is the basis for this project.

Innovations in LV power electronics are becoming more widely recognized as an option to maintain power quality on a network. A new LV IPR has been produced to be able to provide dynamic voltage regulation, reactive power compensation, harmonic cancellation and to be able to be integrated in an existing network operators communications and operating systems, Leitermann, Olivia et al. (2015).

As a voltage profile will change in varying conditions, it is necessary to model different scenarios to accommodate the different conditions. These scenarios include high load with no PV and low load with max PV. This modelling provides assurance that the proposed IPR will be suitable, Barnes, et al. (2014).

To ensure the IPR will operate as expected, it is important to accurately model the exisitng network.

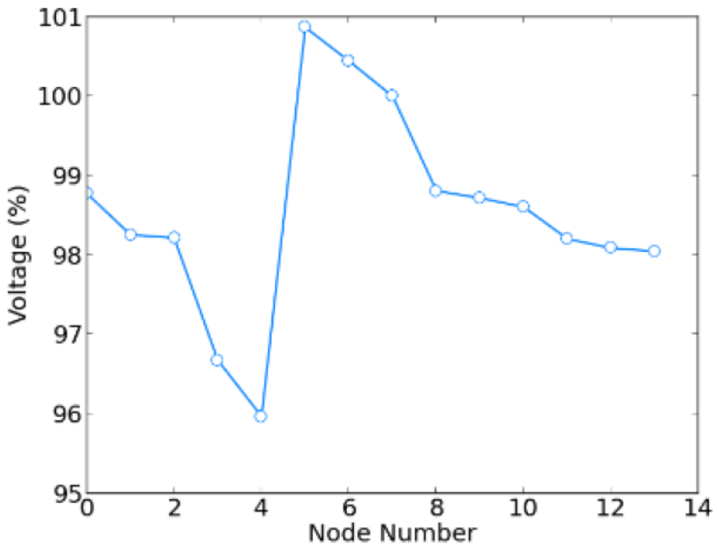

Figure 2. 8 – Voltage profile for high load with no PV scenario by Barnes et al. (2014)

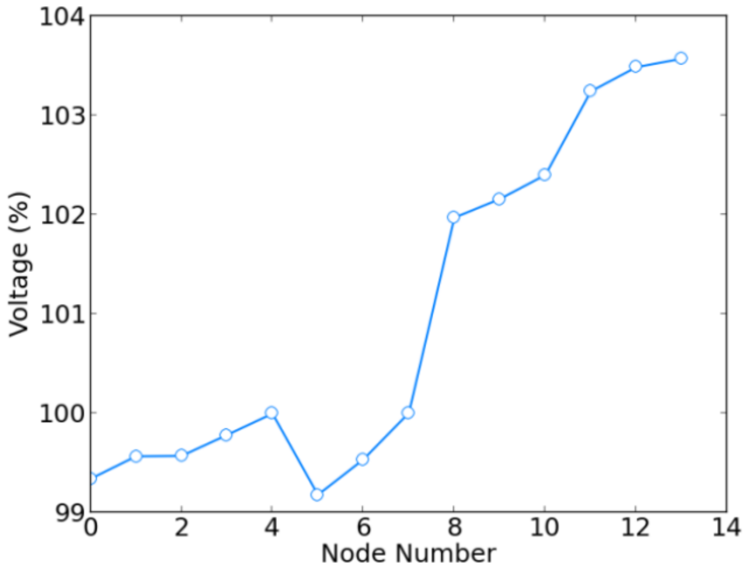

Figure 2. 9 – Voltage profile for low load with max PV scenario by Barnes et al. 2014

Barnes et al. (2014) have compared a number of characteristics for the different of LVR architectures, This is summarized in Table 2. 2.

Table 2. 2 – Comparison of Different LVR Architectures against LVR Relevant Characteristics by Gridco Systems

	STATCOM	AC/AC Buck-Boost	UPFC (shunt/series)	UPFC (series/shunt)
Concept	Current source	Voltgae source	Current & voltage source	Current & voltage source
Reactive power support	Y	N	Y	Y*
Partially rated converters	Y/N**	Y	Y	Y
Number of converters	1	1	2	2
Feeder X/R sensitivity for voltage regulation	High	None	None	None
Harmonic current mitigation	Y	N	Y	Y
Harmonic voltage mitigation	N	Y	Y	Y

*Not ideal for larger reactive current support due to need for series section to progress

**Very dependent on the percent voltage swing as a fraction of feeder/transformer base reactance

A company has used a similar IPR that was installed as part of this project. A field test was carried out where the IPR was installed in the network approximately 250m downstream of the distribution transformer. The remaining network extended approximately another 250m past the device. The IPR uses unified power flow controller architecture. The device can regulate load-side voltage and can inject reactive current and cancel source-side current harmonics. The device capabilities are available regardless of the direction of power flow, enabling use in systems with high DG penetration. Leitermann, Olivia et al. (2015)

The results they found are shown in Figure 2. 10.

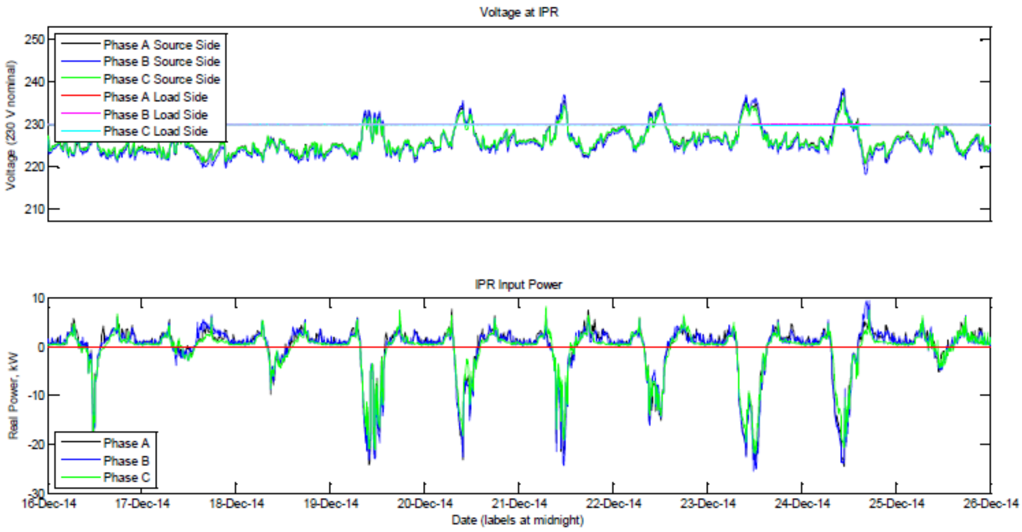

Figure 2. 10 – Measured Voltage at Source side and Load side of IPR and IPR Input Power by Leitermann, Olivia et al. 2015

The IPR is a padmounted device. A photo of the device is shown in Figure 2. 11 and the specification is shown in Table 2. 3.

Figure 2. 11 – Gridco Systems In-line Power Regulator (IPR) 150kVA padmounted device by Gridco Systems

Table 2. 3 – Gridco Systems IPR Specification

3-Ph 150 kVA Pad/Pedestal-Mounted IPR Specifications	
Phase	Three
Rating	150 kVA
Form	Standalone Pad or Pedestal Mount
Frequency	60 or 50 Hz
Source Voltage	480/277 or 400/230 VAC Nominal
Source Voltage Range	-25% to +30% of Nominal
Load Voltage Regulation	Boost/Buck up to ±8% of Nominal; ±0.5% accuracy; Programmable set point or dead-band
VAr Compensation Range	10% of rating (expandable), leading/lagging; Programmable VAr or PF set point
Harmonic Correction	3^{rd} to 15^{th}, odd order; Programmable source current & load voltage enable/disable
Harmonic Distortion	Voltage THD < 3% Current TDD < 5%
Efficiency	$\geq$ 99%
Cooling	Passive (air)
Enclosure	NEMA-4 (IP65)
Noise	< 35 dB
Operating Temperature	-40° to +50° C
Dimensions (H x W x D)	57” x 82” x 24” (1439 x 2083 x 600 mm)
Weight	~2650 lbs. (1200 kg)
Operation / Management	Autonomous, local, remote, peer-to-peer
Communication (via DGC)	Secure DNP 3.0, Secure Web Services, IEC 60870-101/104 (future), IEC 61850 (future)

Also as outlined in Gridco Systems (2015), there is the capability of the existing LV network being able to maintain power quality with additional PV connections, as shown in Figure 2. 12 and Figure 2. 13.

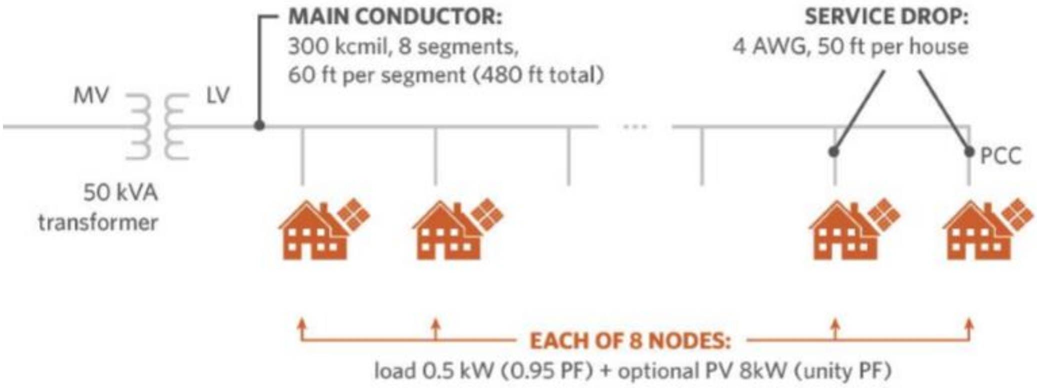

Figure 2. 12 – Single chain secondary network by Gridco Systems

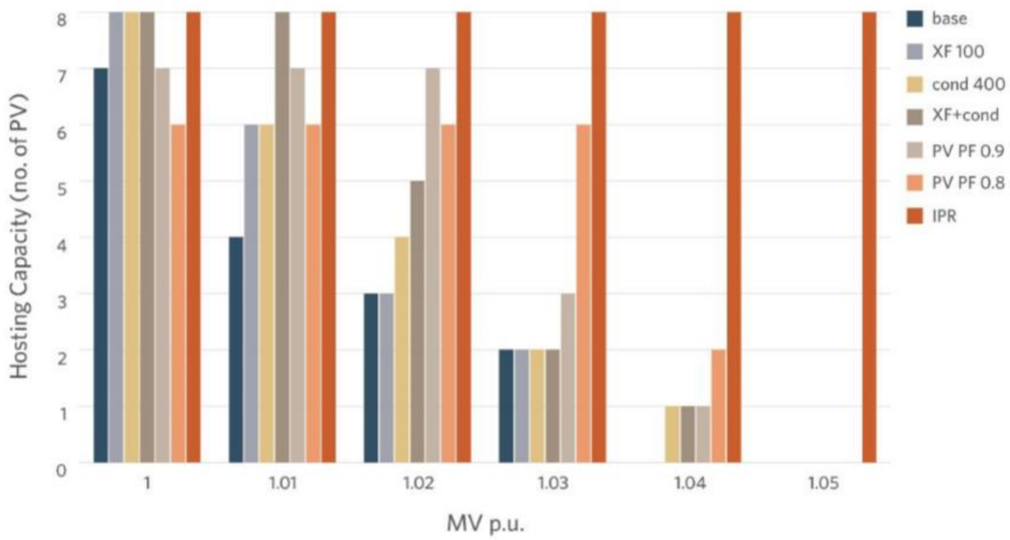

Figure 2. 13 – Hosting capacity of single chain network by Gridco Systems

The PV hosting capability has also been modelled as part of this project to ascertain if this will be a viable opportunity for the future. This will be discussed in greater detail in the next Chapter.

The Gridco Systems IPR is a ground mounted device which makes connecting it to an underground network possible, compared to the pole mounted devices. The IPR can be connected to an overhead network however extra LV underground cables are required to connect it to the network.

As the IPR utilises power electronics, it should provide a tight output voltage range which will maintain a more consistent supply to the customers. The IPR can be installed along an LV feeder and therefore the 150kVA rating should be suitable in most urban and semi-rural areas. Also the location of the device can be flexible to suit the local conditions.

When considering if the IPR is a suitable option, the LV feeder needs to be checked to see if there is an existing tie to another LV feeder or a possible tie in the future. If there is a tie then the LV regulator may not be suitable due to network switching or a possible overload under abnormal network conditions.

2.5 Summary of Four Different Types of LV Regulation

A summary of the four different types of LV regulators is shown in Table 2. 4. This shows the benefits of the regulators and how they compare.

Table 2. 4 – Summary of LV Regulators

	Transformer with OLTC	RegFormer Transformer	Statcom	IPR
Pole mounted device	Yes	Yes	No	No
Capacity	315kVA	100kVA	20kVA	150kVA
Flexibility in relocating device	No	No	Yes	No
Maintain steady voltage output	No	Yes	Yes	Yes
Provide Harmonic cancellation	No	No	Yes	Yes
Provide Var Support	No	No	Yes	Yes
Remote Connectivity Available	Yes	Yes	Yes	Yes

Chapter 3. Methodology

The following sections provide the methodology that was used to complete this project.

The LV network has become an extremely important part of the electricity network partly because of the large scale introduction of residential solar PV installations. The distributor’s LV network requires a quality of supply that allows the PV inverters to operate in a voltage bandwidth, and if the electricity network’s voltage exceeds this then the inverter will trip off. This leaves customers unhappy and the electricity distributor needing to augment the network.

With assistance from my place of employment this project has been chosen to seek opportunities to improve the quality of supply of LV networks.

The two sites that have been chosen for this project are where an existing quality of supply issue exists and they are complicated and expensive to rectify using traditional methods as outlined in Chapter 1.

The modelling of the existing LV network at the each site was completed to determine a suitable location of the new IPR. This was completed by the company Gridco Systems, utilising the distribution system modelling tool called “CYME” and also the LV network has been modelled by the user using the program LV Drop 8.0.3

The design and construction was completed with some minor inconveniences. The main issue at site 1 was the new IPR was installed in a different location that had been given preliminary approval too. The new location was accepted by all parties and the project progressed. Another minor issue was that the earth link on the IPR would not fit the standard cable connections that were used. This was overcome by agreement with the manufacturer to install a new earth bar to make the connections to.

Data collection and review of the data after installation identified the effectiveness of the IPR devices and shows how they are performing.

Cost Benefit Analysis of the project was completed and an augmentation decision process was created to assist planners in determining when to use the IPR.

3.1 Network Modelling

The two sites have been modelled by the company that is supplying the IPR, Gridco Systems, utilising the distribution system modelling tool called "CYME" and as part of the project, the LV networks have been modelled using the program LV Drop 8.0.3.

The LV Drop program has the capability of modelling a LV network. The first step is selecting the transformer size and then building the LV network by adding each conductor segment which includes the conductor size and route length. The user can then add customer loads at the relevant node points to the model as well as any PV installations.

In the modelling of the two sites, a standard customer load of 3kVA per premise was used and the size of the PV installations used, were as per their inverter size that has been approved through Energex.

3.1.1 Site 1 Modelling

Modeling of the first site of the existing network was completed by Gridco Systems and is shown in Figure 3. 1. The existing network was also modelled using LV Drop version 8.0.3 by the user and this is shown in Figure 3. 2.

Figure 3. 1 shows a voltage drop greater than 5% at the end of the LV network. Figure 3. 2 shows a voltage drop of 12V which is 5%.

From this it has been determined that the optimal location to install the new IPR is shown in Figure 3. 3.

The network has been modelled by Gridco Systems with the new IPR installed in both Peak Load scenario, Figure 3. 4, and no load scenario, Figure 3. 5 and by the user with LV Drop in both Peak Load scenario, Figure 3. 6 , and no load scenario, Figure 3. 7.

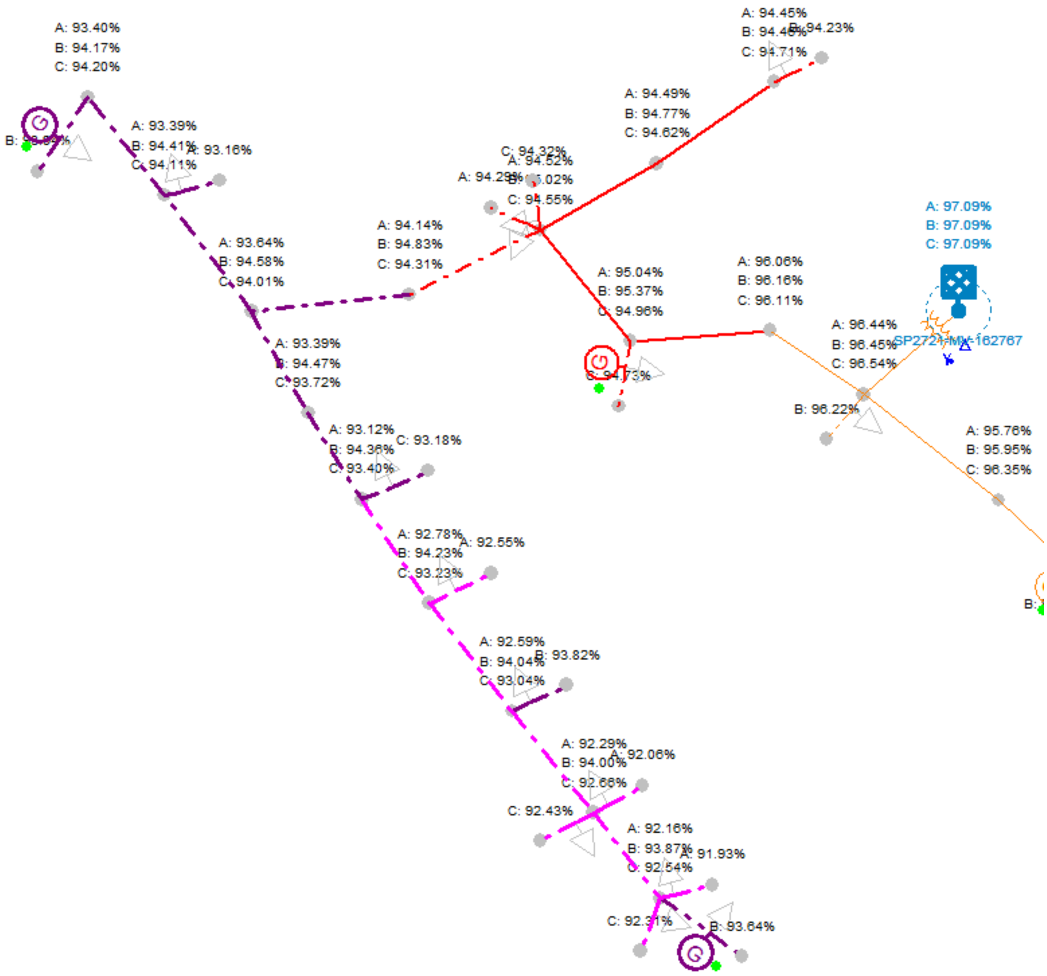

Figure 3. 1 – Model of Existing Network at Site 1 by Gridco Systems

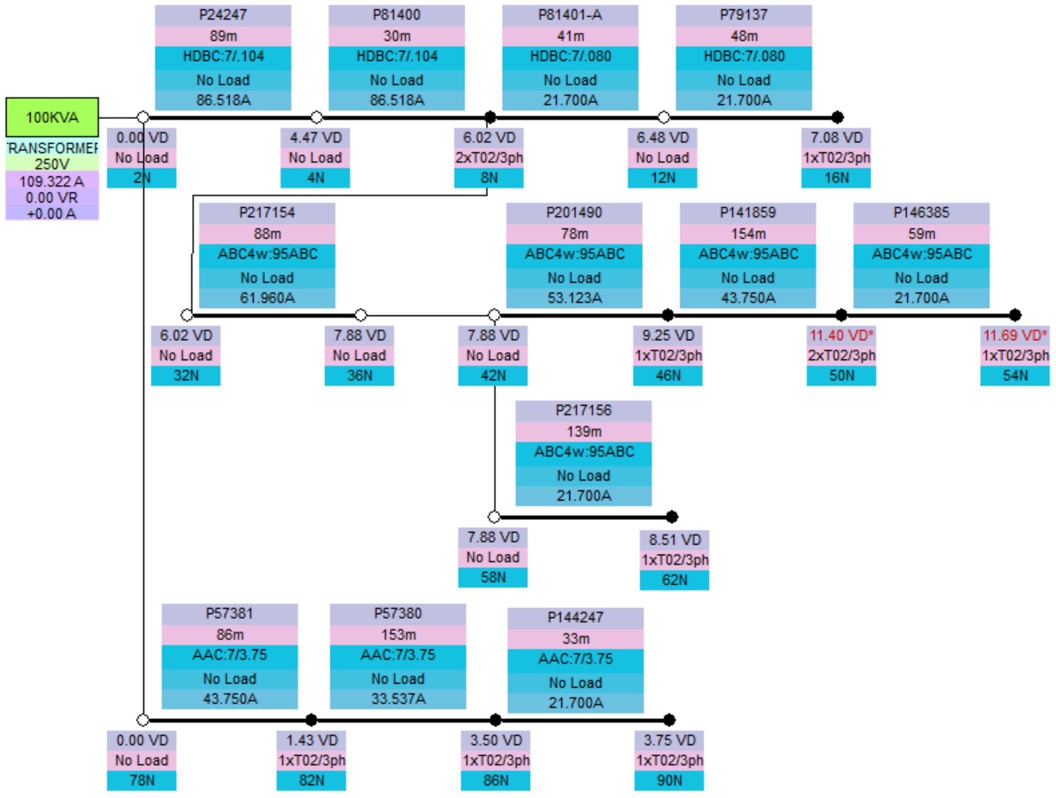

Figure 3. 2 – Model of Voltage Drop of Site 1 with existing network by User

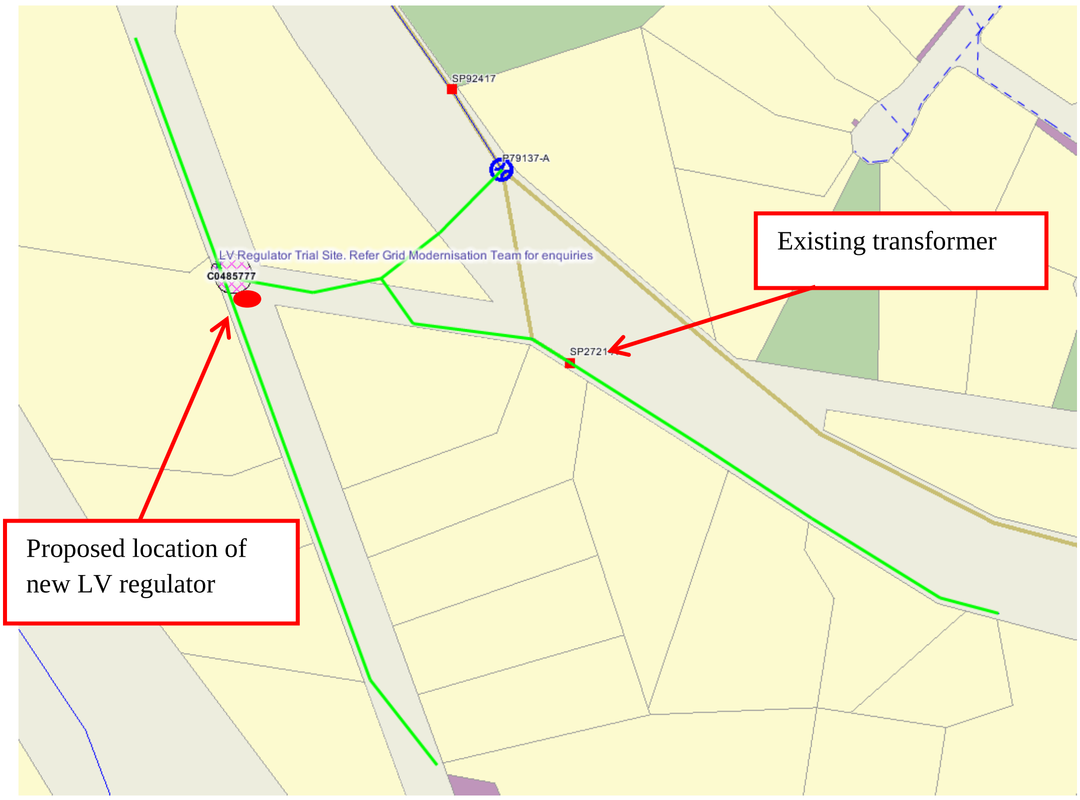

Figure 3. 3 – LV network of Site 1 showing proposed IPR location by Energex GIS system

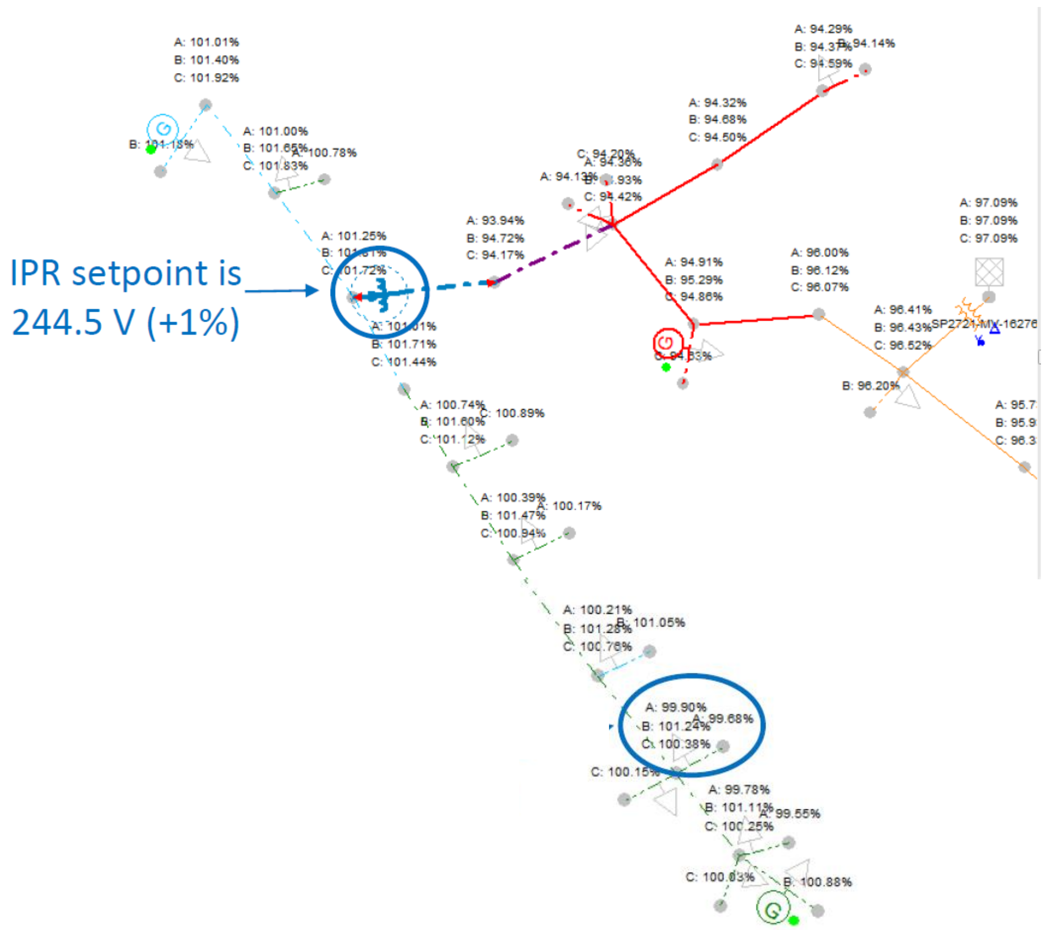

Figure 3. 4 – Model of Network at Peak Load No PV at Site 1 with IPR installed by Gridco Systems

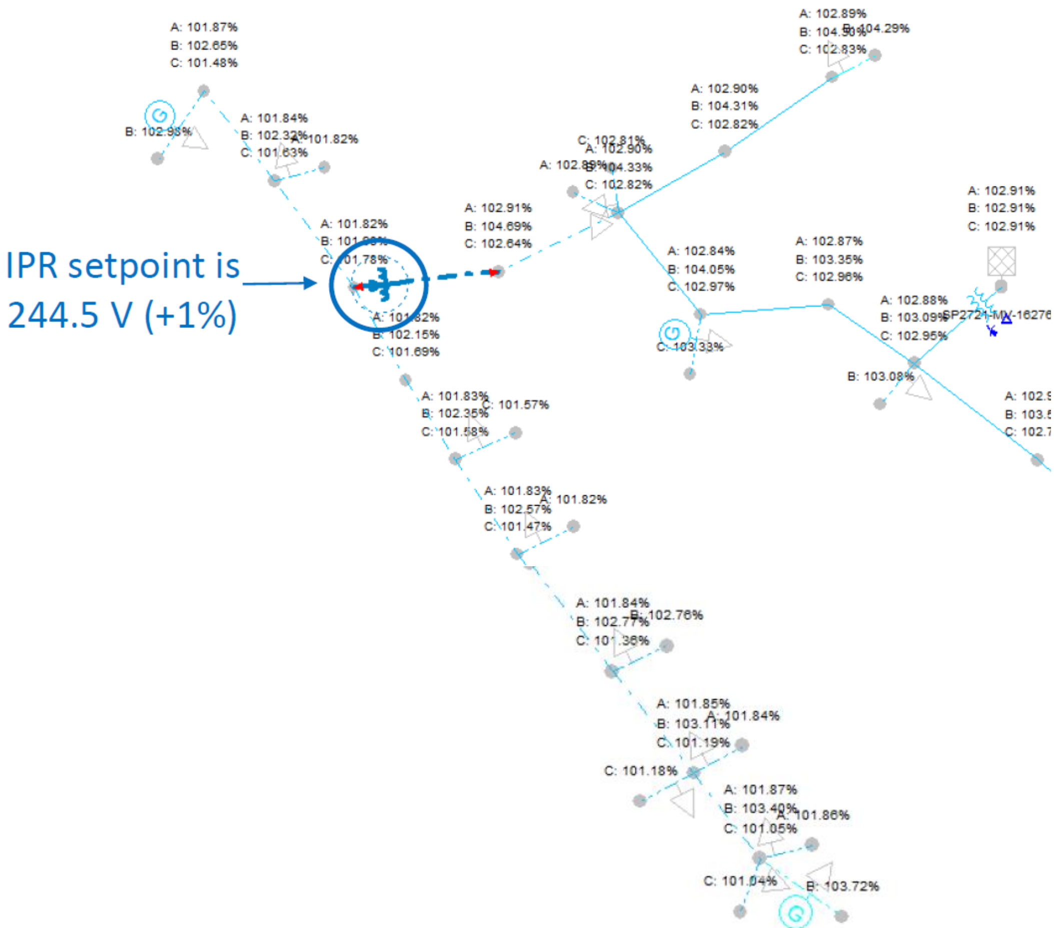

Figure 3. 5 – Model of Network at Minimum Load with Full PV at Site 1 with IPR installed by Gridco Systems

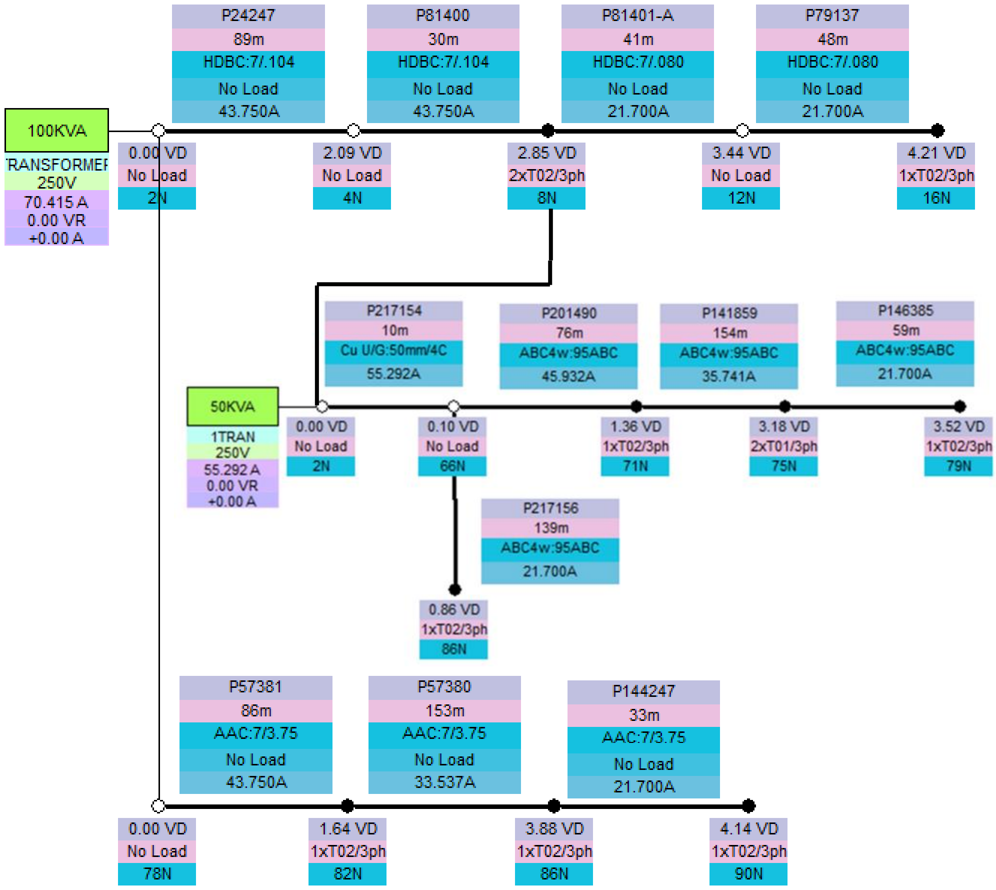

Figure 3. 6 – Model of Network at Peak Load Low PV at Site 1 with IPR installed by User

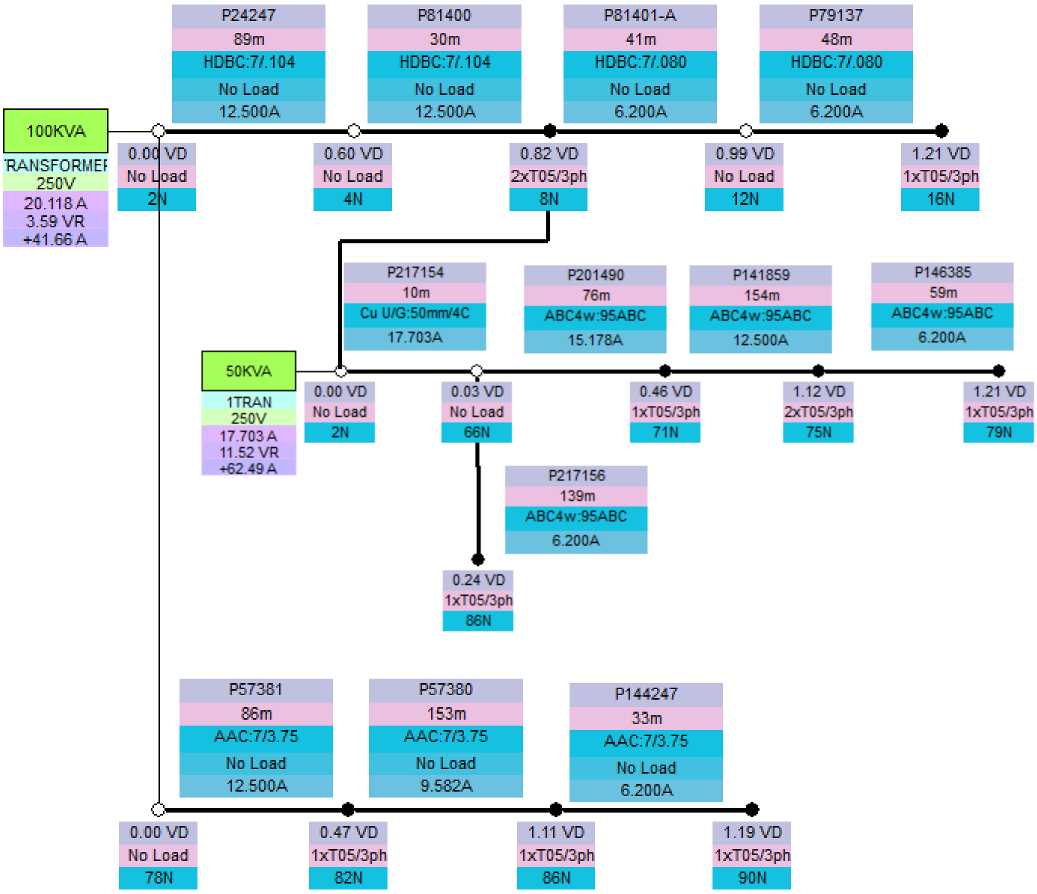

Figure 3. 7 – Model of Network at Minimum Load with Full PV at Site 1 with IPR installed by User

Figure 3. 4 shows a proposed voltage drop past the new regulator of 2% at the end of the LV feeder. Figure 3. 5 shows a proposed voltage drop past the new regulator of 2% at the end of the LV feeder.

Figure 3. 6 shows a proposed voltage drop past the new regulator and at the end of the LV feeder of 4V during times of peak load and low PV (eg 6 – 8 pm). This model shows a peak load of 125A. Figure 3. 7 shows a proposed voltage drop past the new regulator and at the end of the LV feeder of 2V during times of low load and peak PV (eg 10 am – 2 pm). This model shows a peak load of 37A while there is 25kW of PV connected.

3.1.2 Site 1 Possible Additional PV Hosting Capacity Model

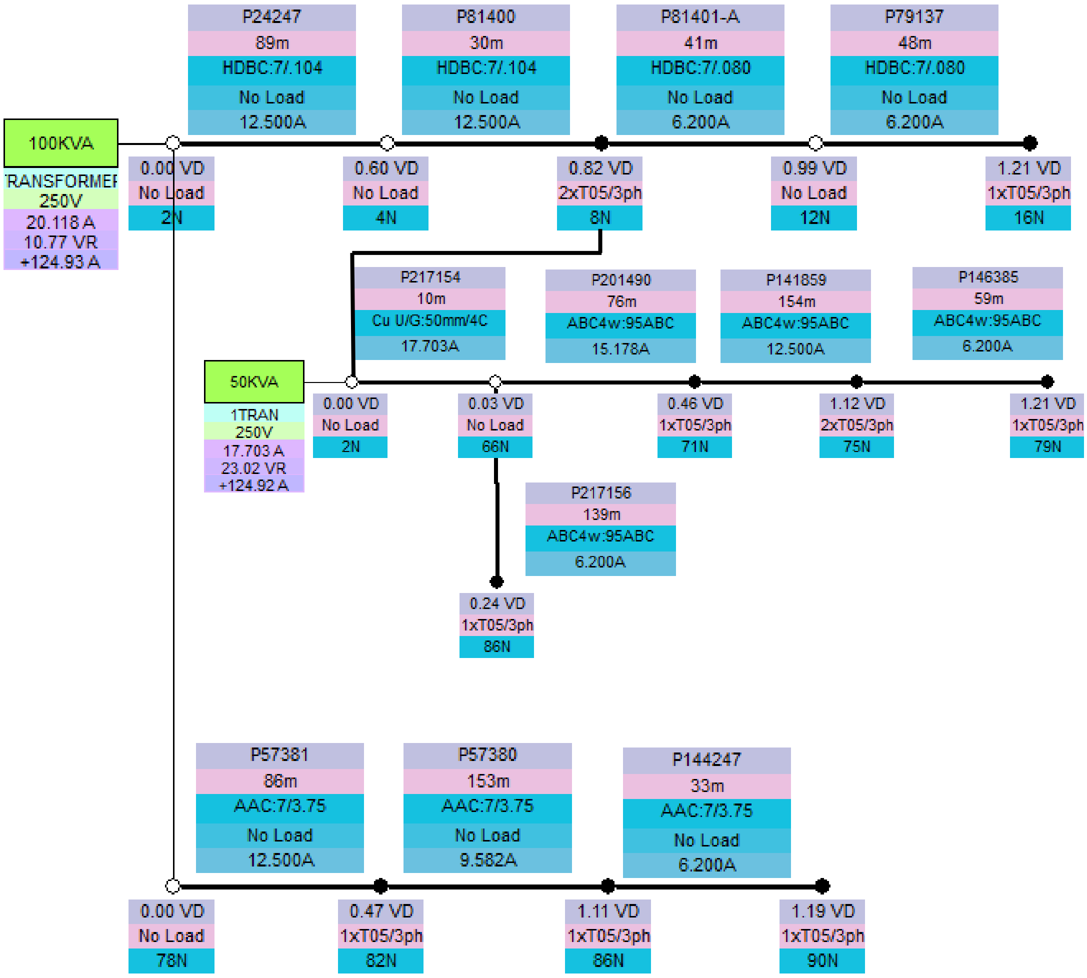

Figure 3. 8 – Model of Network at Minimum Load with Additional PV at Site 1 with IPR installed by User

Figure 3. 8 shows a proposed voltage drop past the new regulator and at the end of the LV feeder of 1.2V during times of low load and peak PV (eg 10 am – 2 pm). This model also shows a peak load of 37A while it is modelled with additional PV connected to the feeder. In this case the PV connected is increased to 62kW and the model shows that the network can support this.

3.1.3 Site 2 Modelling

The modeling of the existing network for the site that has been done by Gridco Systems is shown in Figure 3. 9 and the existing model by the user is shown in Figure 3. 10. Figure 3. 9 shows a voltage drop of 10% while Figure 3. 10 shows a voltage drop of 10V.

From this it has been determined that the optimal location to install the new IPR is shown in Figure 3. 11.

The network has been modelled by Gridco Systems with the new IPR installed in both Peak Load Low PV scenario, Figure 3. 12, and Low Load High PV scenario, Figure 3. 13 and by the user in LV Drop with the new IPR installed in both Peak Load, Low PV scenario, Figure 3. 14, and Low Load High PV scenario, Figure 3. 15.

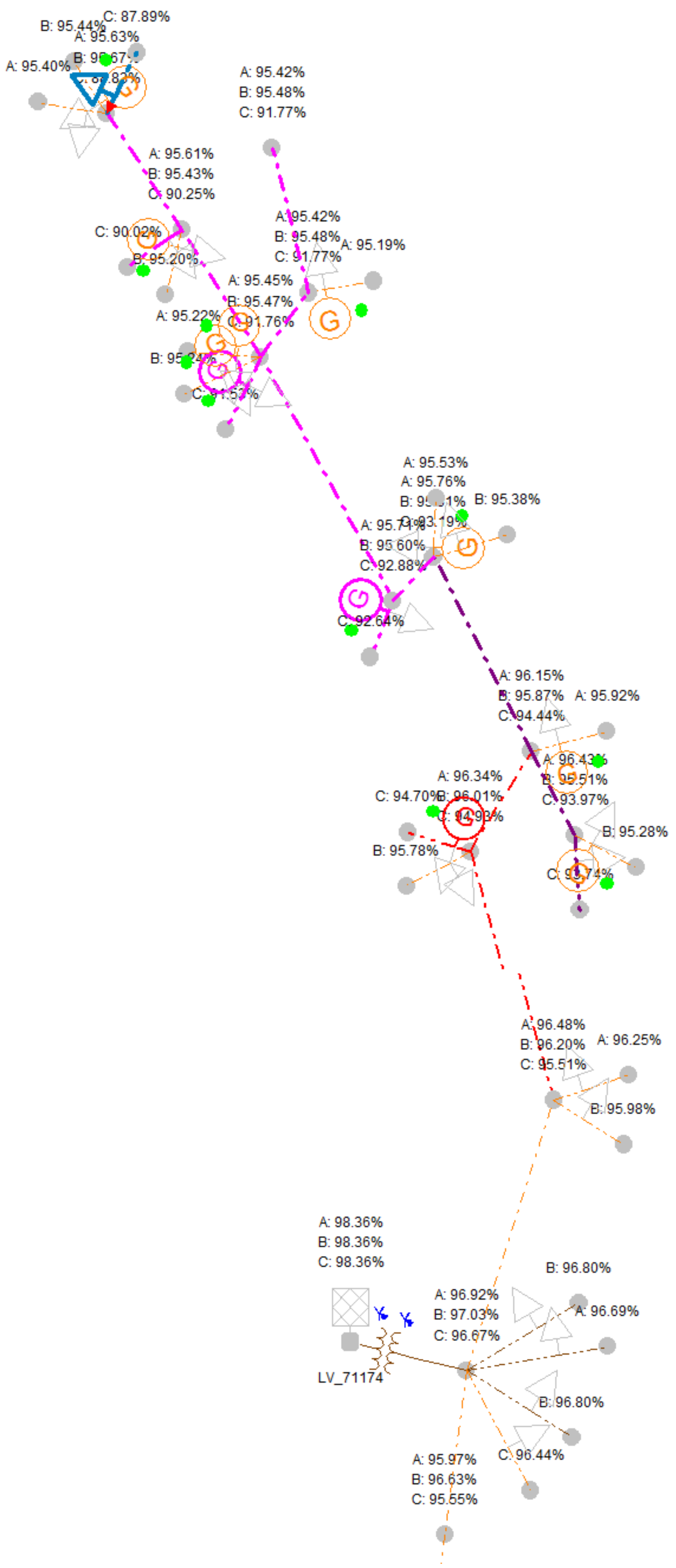

Figure 3. 9 – Model of Existing Network at Site 2 by Gridco Systems

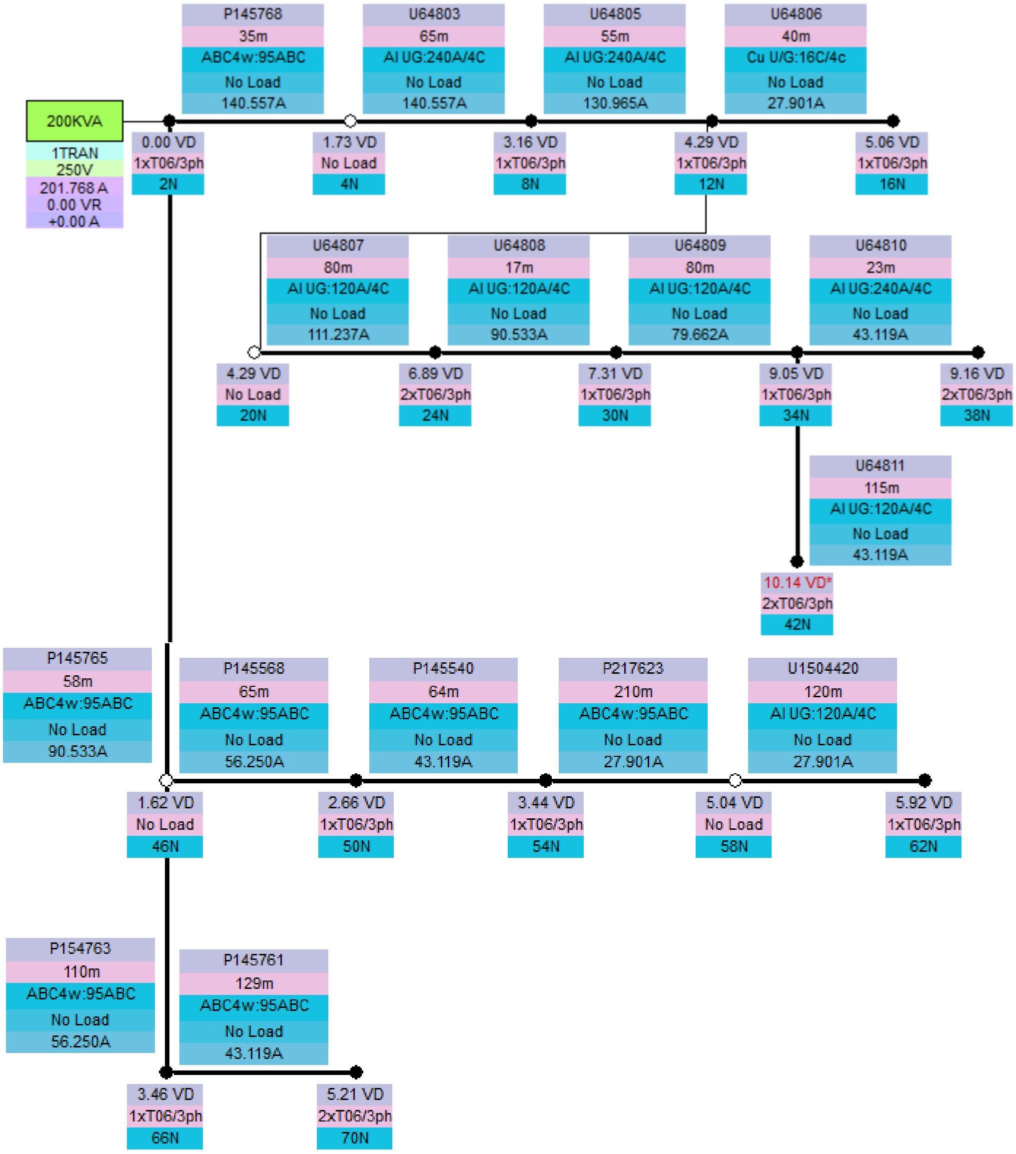

Figure 3. 10 – Model of Existing Network at Site 2 by User

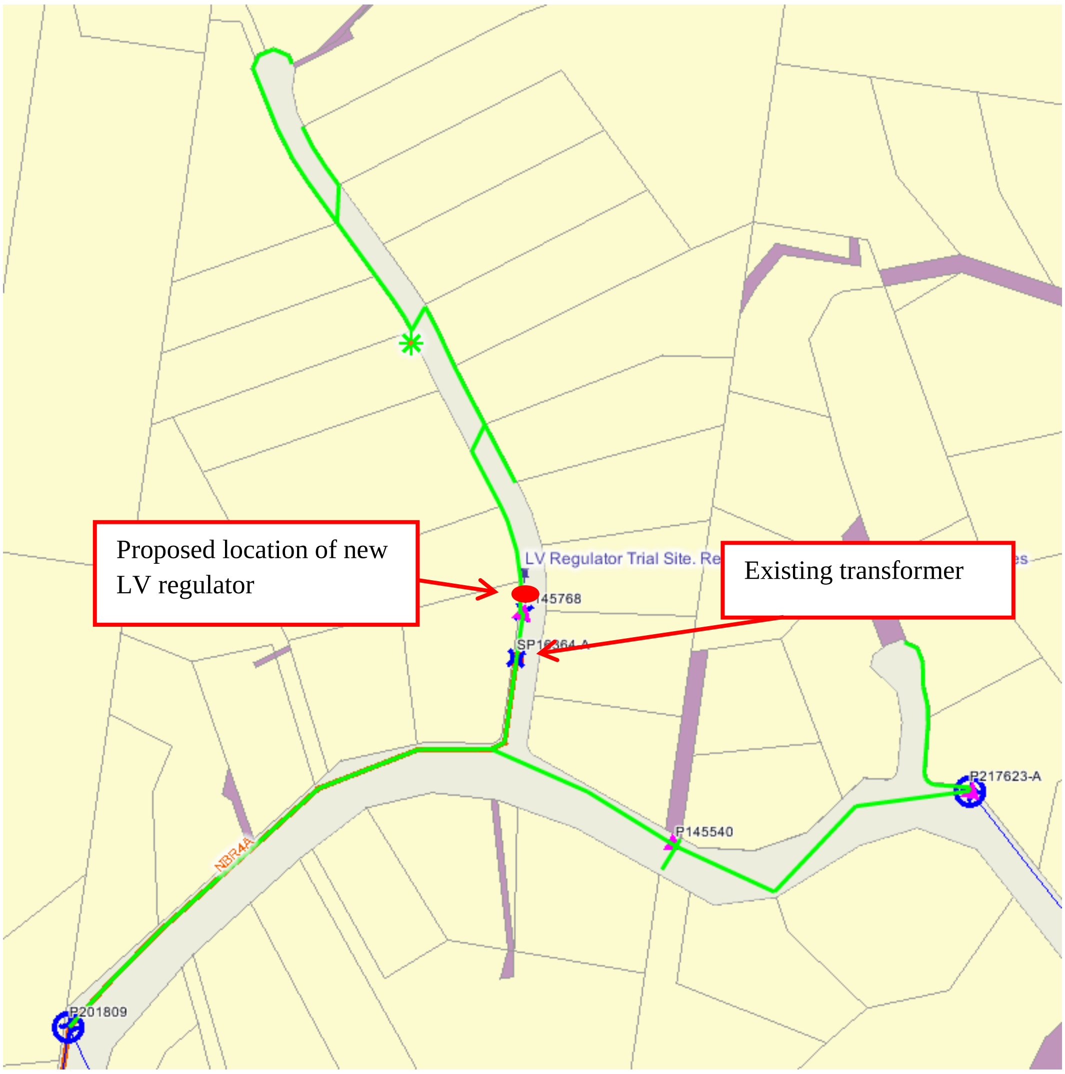

Figure 3. 11 – LV network of Site 2 showing proposed location of IPR by Energex GIS system

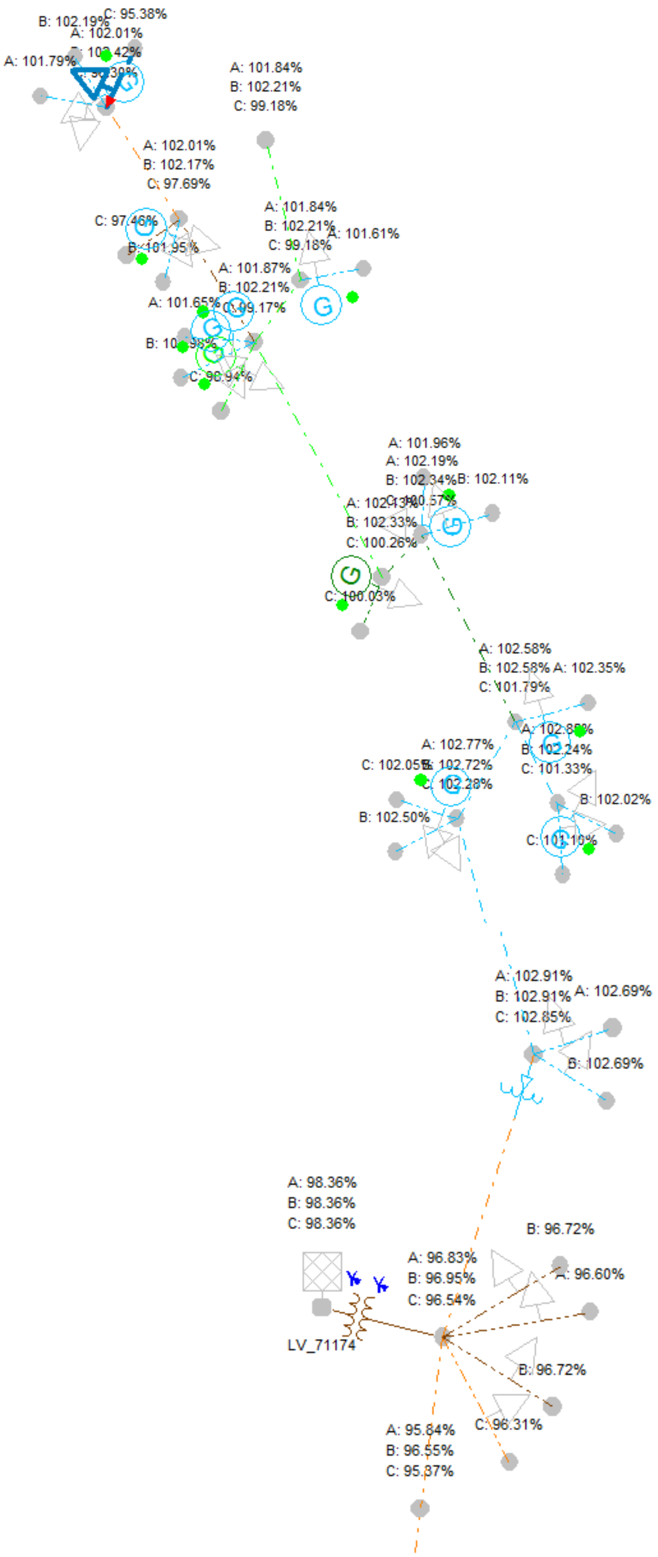

Figure 3. 12 – Model of Network at Peak Load Low PV at Site 2 with IPR installed by Gridco Systems

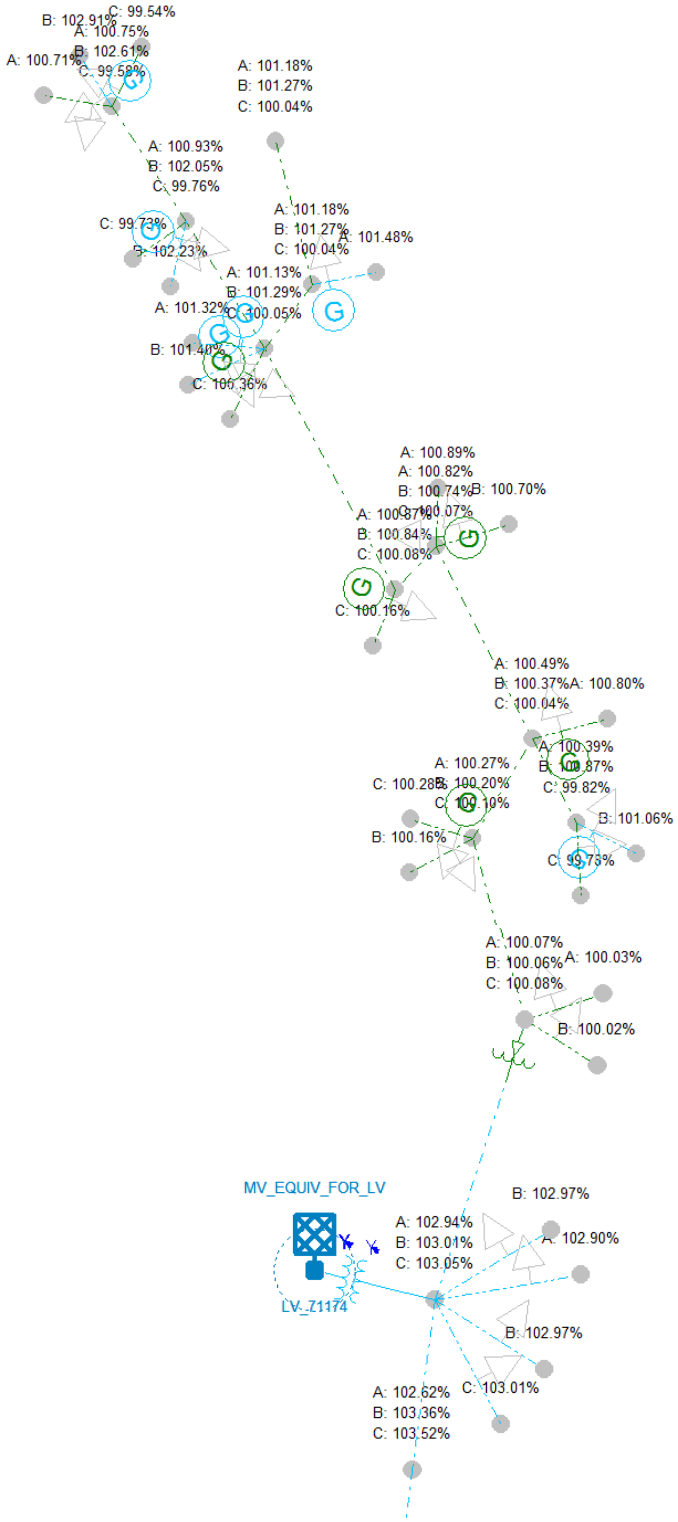

Figure 3. 13 – Model of Network at Minimum Load High PV at Site 2 with IPR installed by Gridco Systems

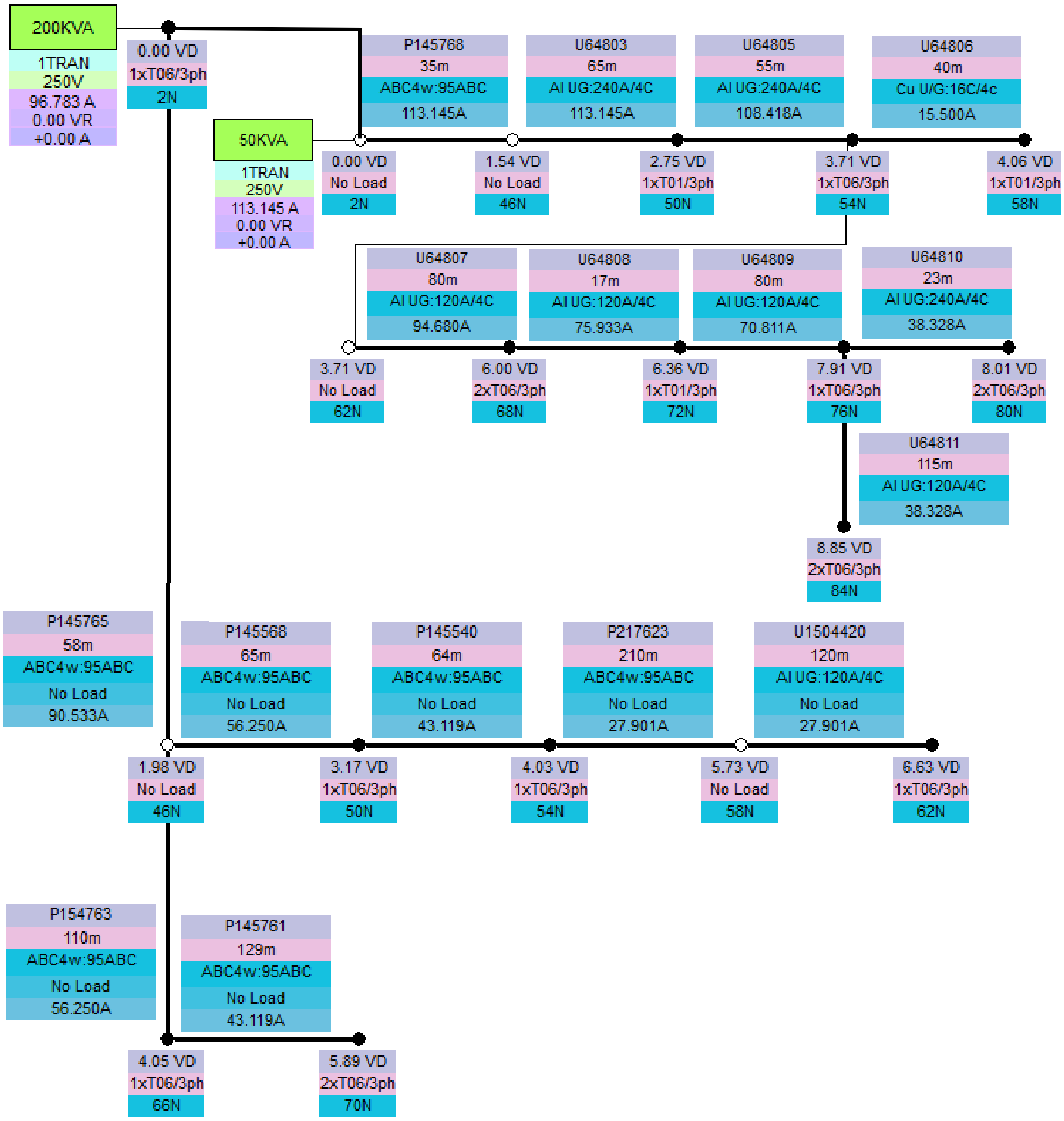

Figure 3. 14 – Model of Network at Peak Load Low PV at Site 2 with IPR installed by User

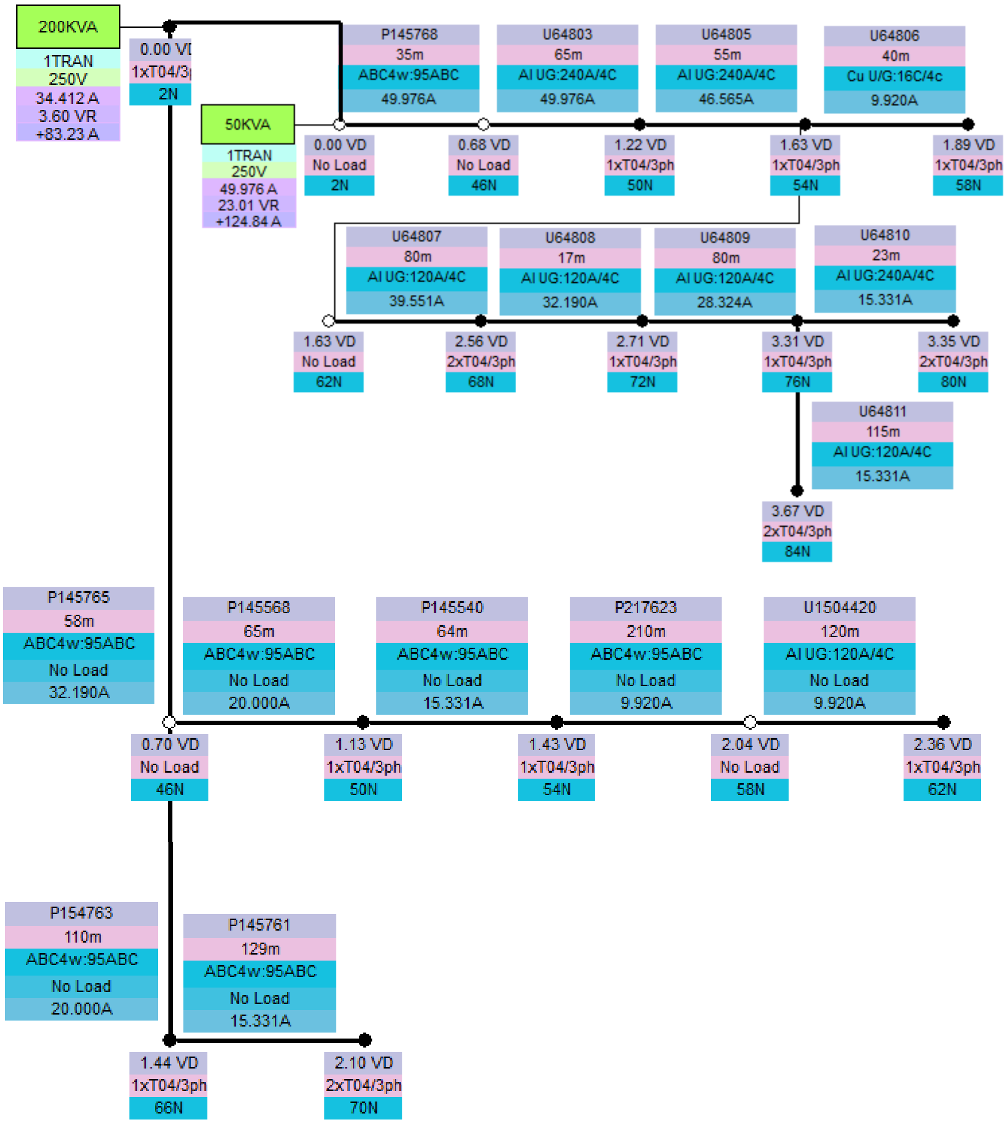

Figure 3. 15 – Model of Network at Minimum Load High PV at Site 2 with IPR installed by User

From the above we see Figure 3. 12 shows a proposed voltage drop past the new regulator and at the end of the LV feeder of 3%. Figure 3. 13 shows a proposed voltage drop past the new regulator and at the end of the LV feeder of 3%. This is when there is minimum load and high PV.

Figure 3. 14 shows a proposed voltage drop past the new regulator and at the end of the LV feeder of 9V during times of peak load and low PV (eg 6 – 8 pm). This model shows a peak load of 210A.

Figure 3. 15 shows a proposed voltage drop past the new regulator and at the end of the LV feeder of 4V during times of low load and peak PV (eg 10 am – 2 pm). This model shows a peak load of 84A while there is 50kW of PV connected.

3.1.4 Site 2 Possible Additional PV Hosting Capacity Model

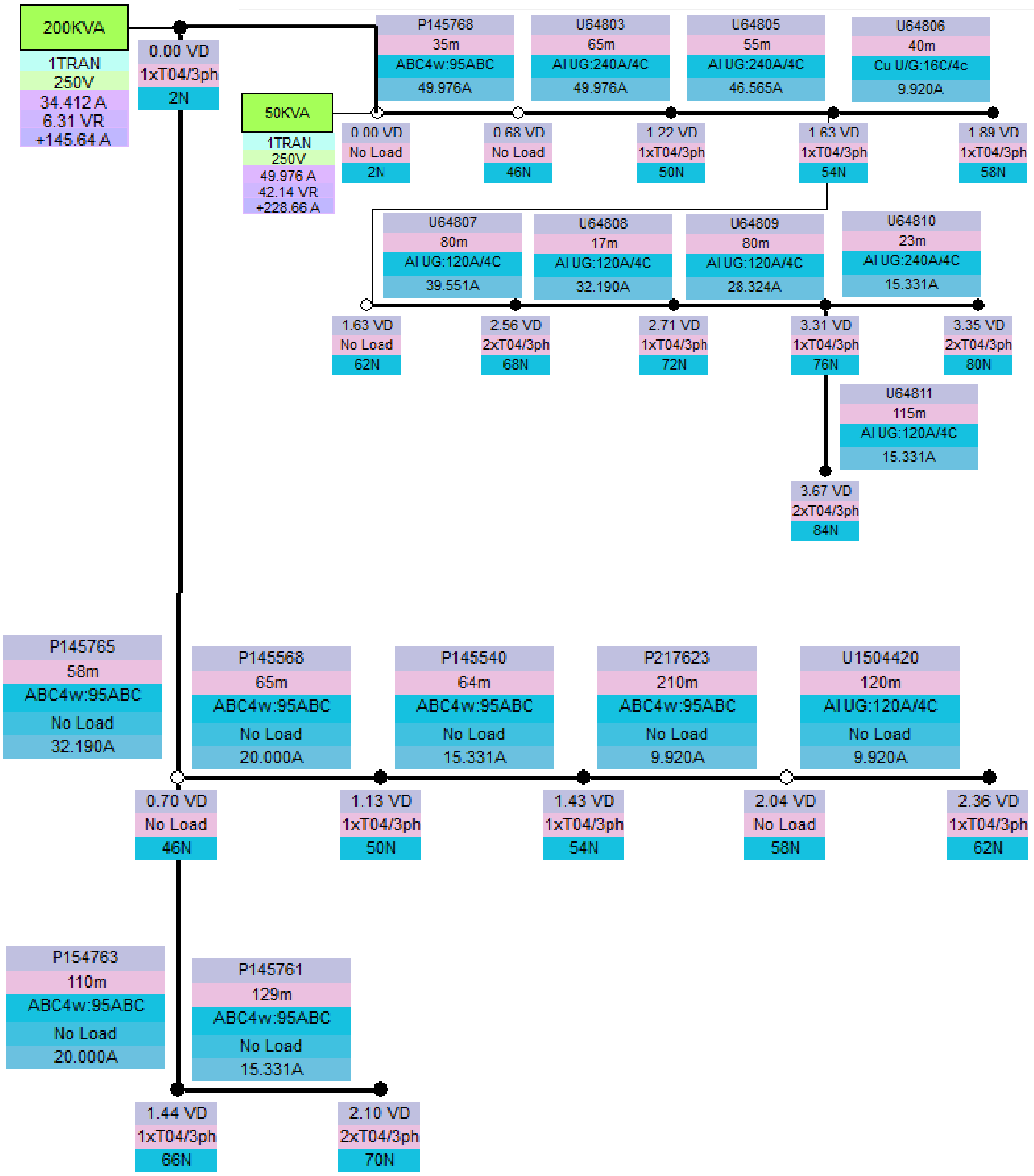

Figure 3. 16 – Model of Network at Minimum Load Additional PV at Site 2 with IPR installed by User

Figure 3. 16 shows a proposed voltage drop past the new regulator and at the end of the LV feeder of 4V during times of low load and peak PV (eg 10 am – 2 pm). This model also shows a peak load of 84A while it is modelled with additional PV connected to the feeder. In this case the PV connected is increased to 95kW and the model shows that the network can support this.

3.2 Data Collection

The design and construction of both sites was completed on time. Two weeks prior to commissioning of site 1, additional power quality data loggers were installed on the LV network. These were left on the network for two weeks after commissioning so that a review could be made on the effectiveness of the LV regulator. There were also other voltage monitors that had been installed on the LV network that would continue to capture the voltage levels of the network. The location of these devices is shown in Figure 3. 17.

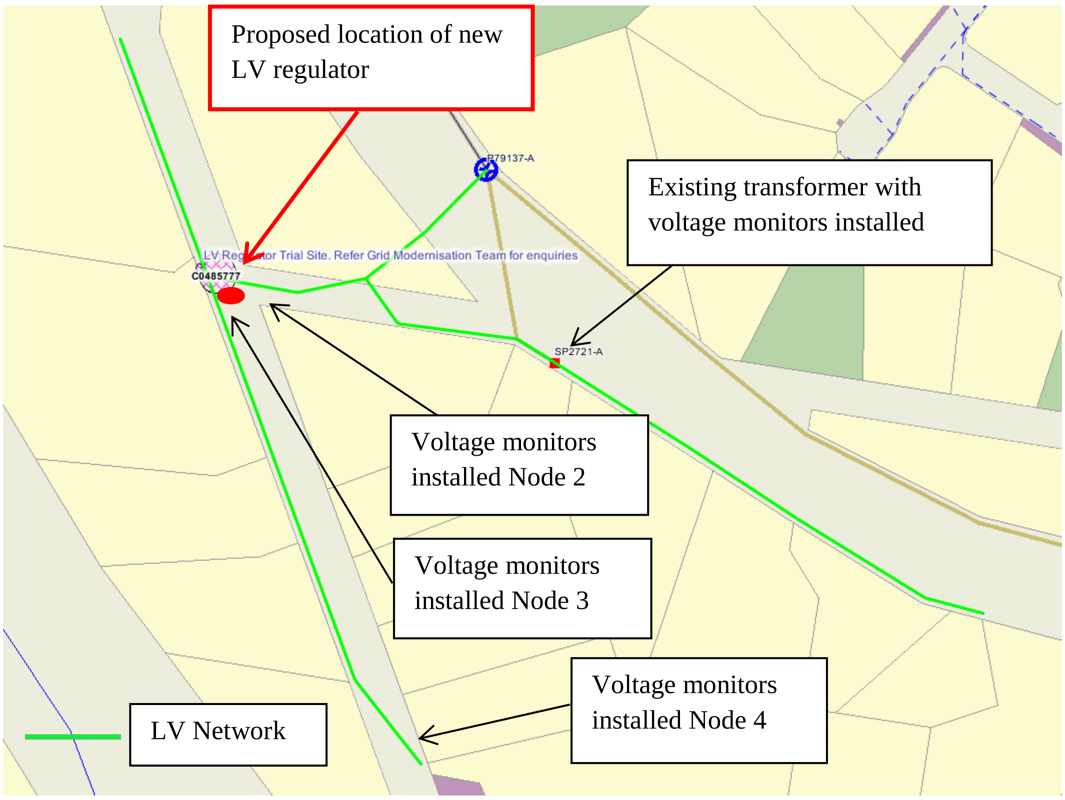

Figure 3. 17 – Location of all voltage monitoring devices at Site 1 by Energex

Site 2 also had a number of voltage monitors installed a month before the IPR was installed and two weeks prior to commissioning additional power quality data loggers were installed on the LV network. These were also left on the network for two weeks after commissioning. The locations of these are shown in Figure 3. 18.

Figure 3. 18 – Location of all voltage monitoring devices at Site 2 by Energex

Screen shots of the voltage data is shown in Appendix C.

Chapter 4. Results and Analysis

As part of the analysis of this project, there is a need to compare the measured data taken from the various points at each site with the models. This analysis has been carried out at each site.

4.1. Site 1

The voltage ranges measured and modelled before the IPR was installed at Site 1 is shown below in Table 4. 1. This table shows that the measured voltage at the transformer ranges between 239V and 250V and at the end of the feeder between 222V and 253V. Using the graphs from Figure 1.3 and Figure 1.4, the maximum variation between the measured voltage at the transformer to the measured voltage at the end of the feeder, is approximately 18V. This maximum variation occurs at approximately 8 pm which is the time of the peak load on the transformer.

The model of the LV network has been completed using LV Drop 8.0.3, as shown in Figure 3. 2, shows a maximum voltage drop of 12V at peak load. This is less than the measured data, however the total load on the transformer is very similar. In this model there should be additional load added to the end of the LV feeder to ensure a similar result.

The model of the LV network that has been completed by Gridco Systems, as shown in Figure 3. 1, shows a maximum voltage drop of 5%, which is 12V, at peak load. This is the same as the model using LV Drop 8.0.3.

Table 4. 1– Voltage Ranges Measured and Modelled at Site 1

Measured	**Min**	**Max**
Transformer	239	250
End of feeder	222	253
LV Drop 8.0.3		
Transformer		250
End of feeder	238	
Gridco Systems		
Transformer		240
End of feeder	233	

After the IPR was installed the data recorded was analysed to determine the effectiveness of the device. This is summarised in Figures 4.1 to 4.3.

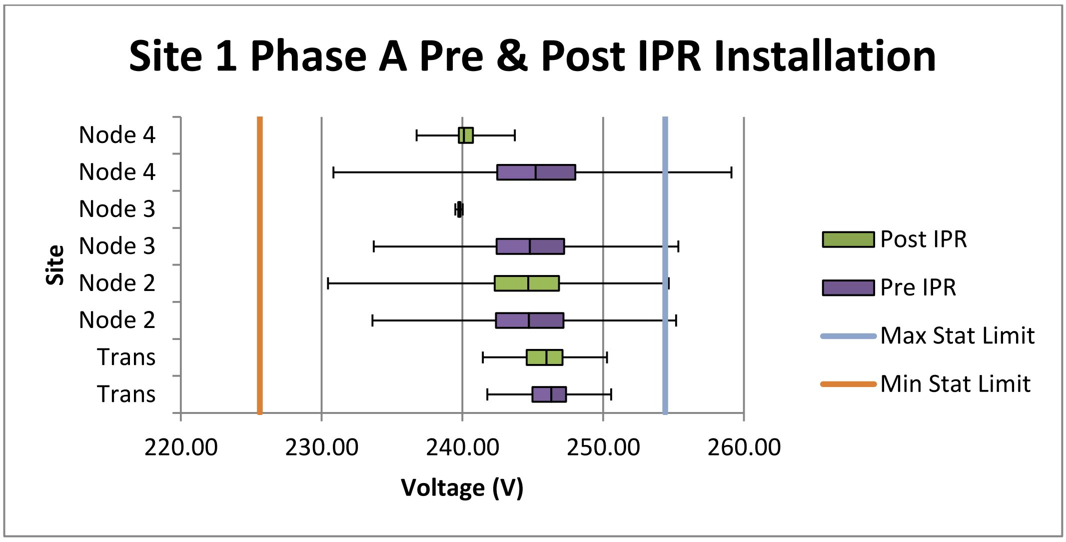

Figure 4. 1 – Site 1 Phase A Pre and Post Installation

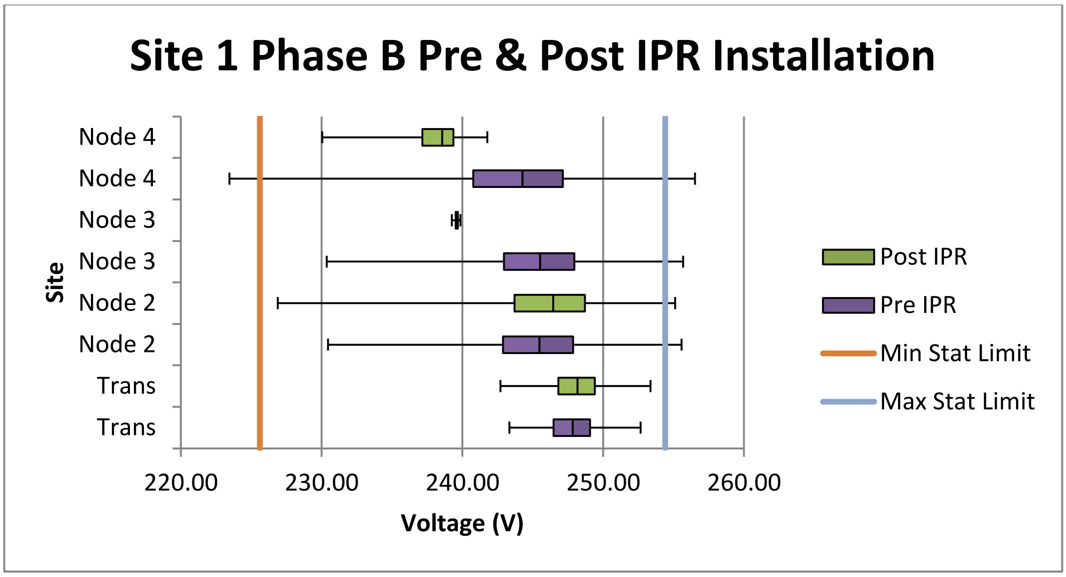

Figure 4. 2 – Site 1 Phase B Pre and Post Installation

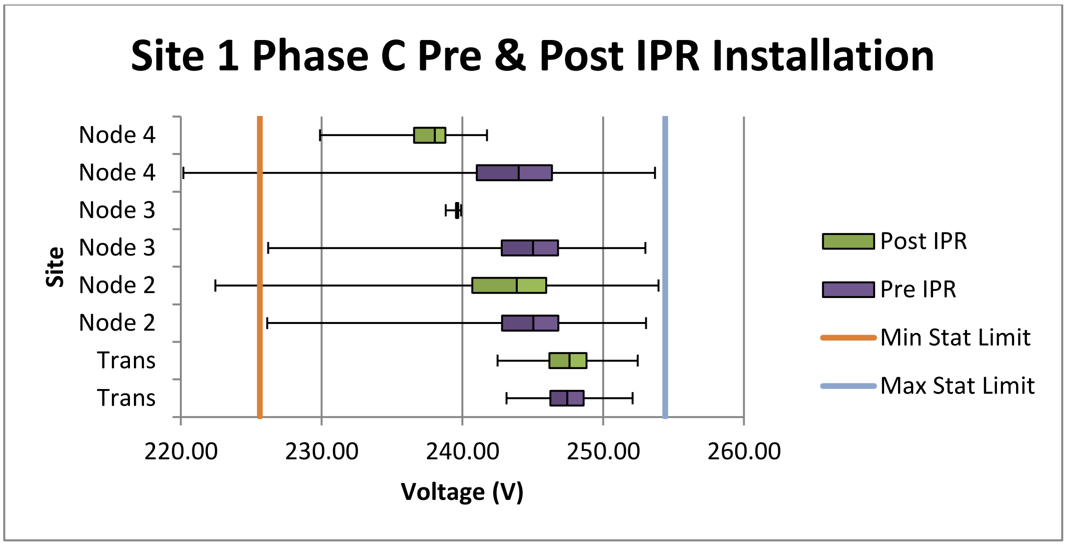

Figure 4. 3 – Site 1 Phase C Pre and Post Installation

Figures 4.1 to 4.3 show the voltage ranges at the transformer and the three node points. The blue vertical line is the maximum statutory limit of 254.4V and the orange vertical line is the minimum statutory limit of 225.6V. The purple results are from the data before the IPR was installed and the green results are from the data after the IPR was installed. The graph shows the maximum and minimum values recorded and the box segment show the 25^{th} 50^{th} and 75^{th} percentiles.

These graphs show that the voltage range at the transformer before and after the IPR was installed is very similar on all three phases. This confirms that the data collected before and after can be compared as the conditions are almost identical.

The data at Node 2 shows a slightly lower minimum on all three phases after the IPR was installed; however the 25^{th} 50^{th} and 75^{th} percentiles are very close to the data from before the IPR was installed.

The voltage range just after the regulator (Node 3) is very tight on all three phases compared to the data before the IPR was installed and this was to be expected.

At the end of the LV feeder (Node 4) the voltage range is well within limits and a tighter voltage range than prior to the IPR installation. The 25^{th} 50^{th} and 75^{th} percentiles on all three phases are now a lot tighter.

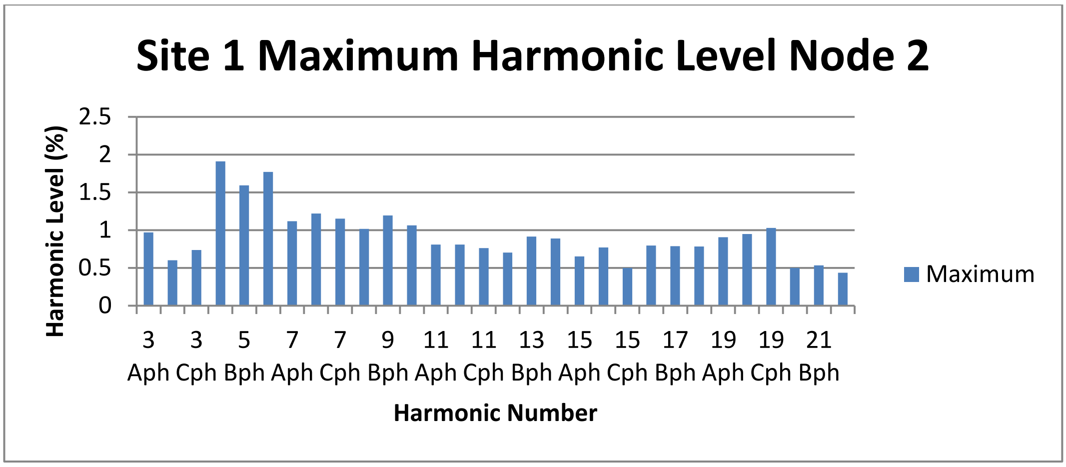

Figure 4. 4 – Site 1 Maximum Harmonic Level Node 2

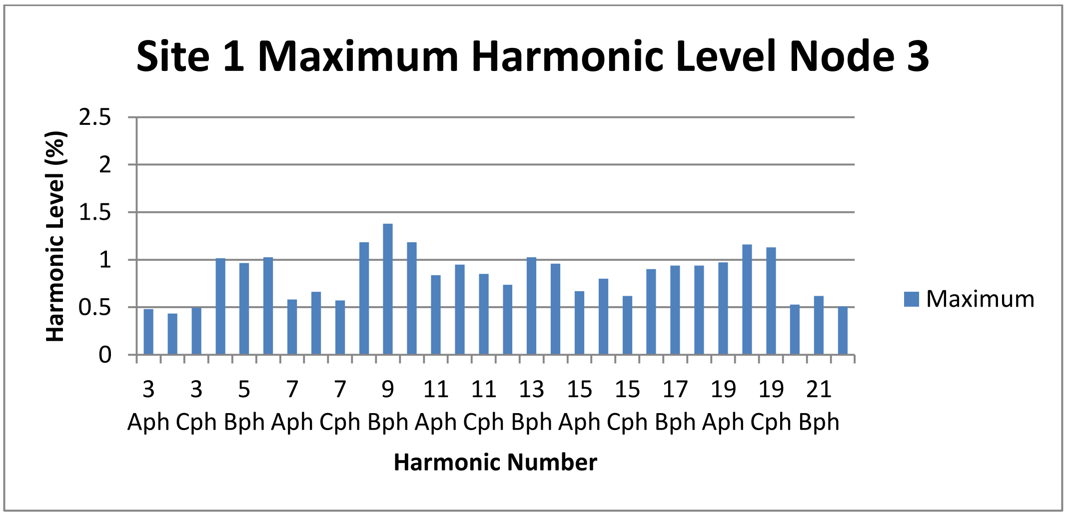

Figure 4. 5 – Site 1 Maximum Harmonic Level Node 3

Although the harmonic level was not of concern at the sites, the data recording equipment was able to capture the levels and has therefore been included as part of the analysis.

Figures 4.4 and 4.5 show the improved harmonic level between Nodes 2 and 3. The level of the 3rd harmonic is halved on A phase, while there is only a minor improvement on B and C phases. The level of the 5th harmonic is reduced on all three phases to approximately 60% of the initial level. The level of the 7th harmonic is almost halved on all three phases while there is a slight increase in the level of the 9th harmonic. From the 11th harmonic and up, there is no discernible change from before the regulator to after the regulator.

4.2. Possible Additional PV Hosting Site 1

The IPR monitors the amount of real power flow and in which direction. This is helpful in showing if there is more PV generating than there is load. This is shown in Figures 4.6 to 4.8 where the blue line is the real power flow that swings from forward to reverse. The two weeks after the installation shows the following:

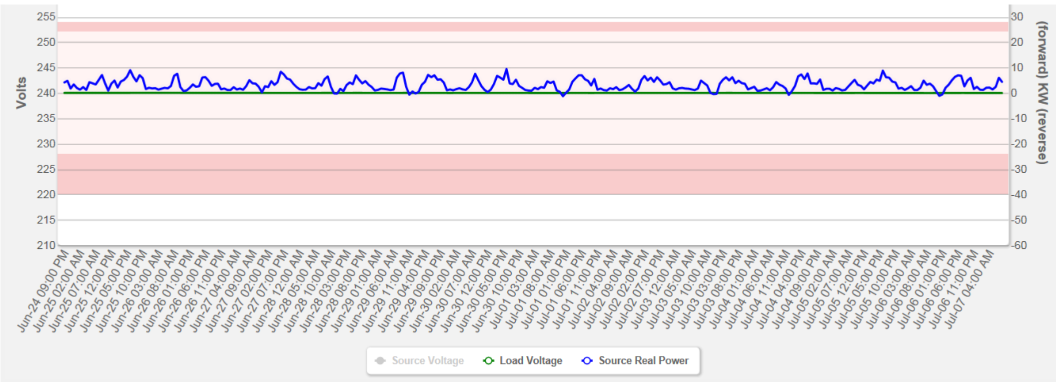

Figure 4. 6 – Site 1 Real Power Flow Phase A

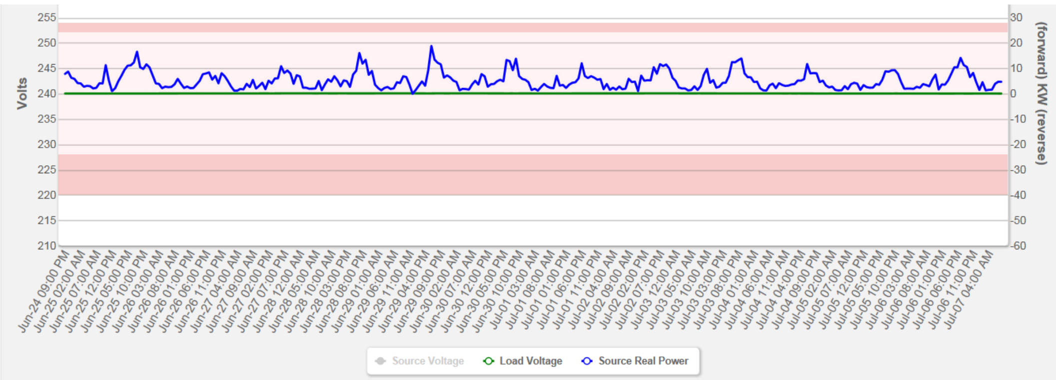

Figure 4. 7 – Site 1 Real Power Flow Phase B

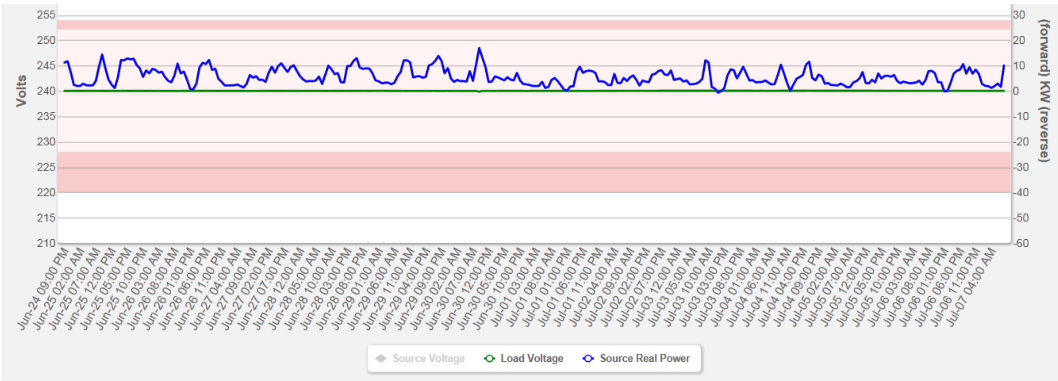

Figure 4. 8 – Site 1 Real Power Flow Phase C

As shown in Figures 4.6 to 4.8 there is minimal real power flow back through the IPR. This is expected as there is only a small amount of PV on this LV network. This data shows that additional PV could be connected to the network.

4.3. Site 2

The voltage ranges measured and modelled at Site 2 is shown below in Table 4. 2. This table shows that the measured voltage at the transformer ranges between 232V and 248V and at the end of the feeder between 232V and 255V. Using the graphs from Figure 1.8 and Figure 1.9, the maximum variation between the measured voltage at the transformer to the measured voltage at the end of the feeder, is approximately 10V. This maximum variation also occurs at approximately 8pm which is the time of the peak load on the transformer.

The model of the LV network has been completed using LV Drop 8.0.3, as shown in Figure 3. 10, shows a maximum voltage drop of 10V at peak load. This is approximately the same as the measured data. Also the total load on the transformer is very similar.

The model of the LV network that was completed by Gridco Systems, as shown in Figure 3. 9, shows a maximum voltage drop of 10%, which is 24V, at peak load. This is significantly more than the LV Drop 8.0.3 model and the measured data.

Table 4. 2 – Voltage Ranges Measured and Modelled at Site 2

Measured	**Min**	**Max**
Transformer	236	248
End of feeder	232	255
LV Drop 8.0.3		
Transformer		250
End of feeder	240	
Gridco Systems		
Transformer		240
End of feeder	216	

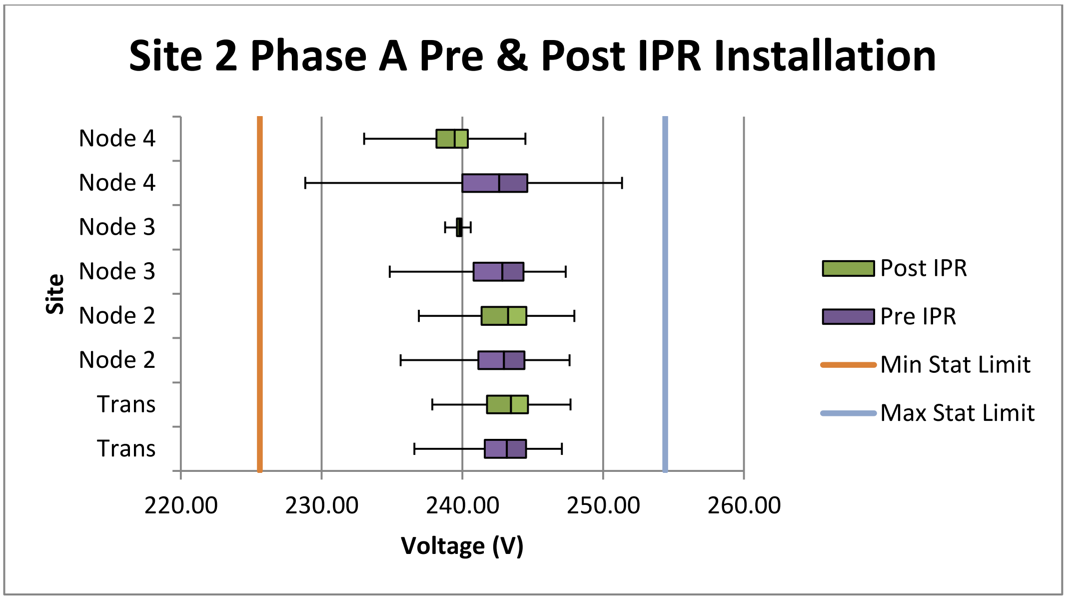

Figure 4. 9 – Site 2 Phase A Pre and Post Installation

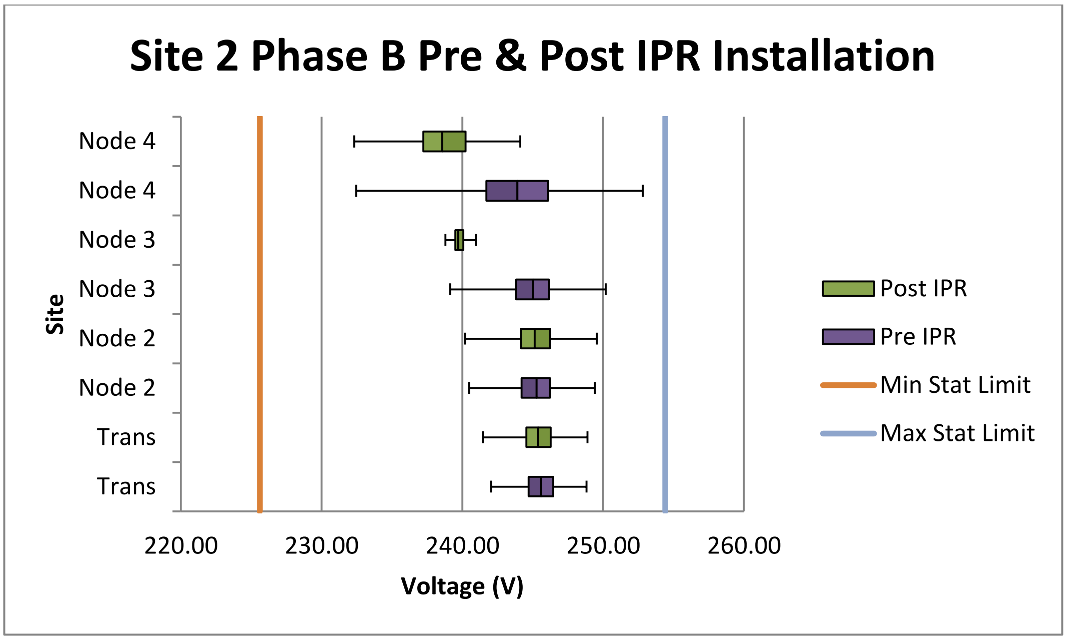

Figure 4. 10 – Site 2 Phase B Pre and Post Installation

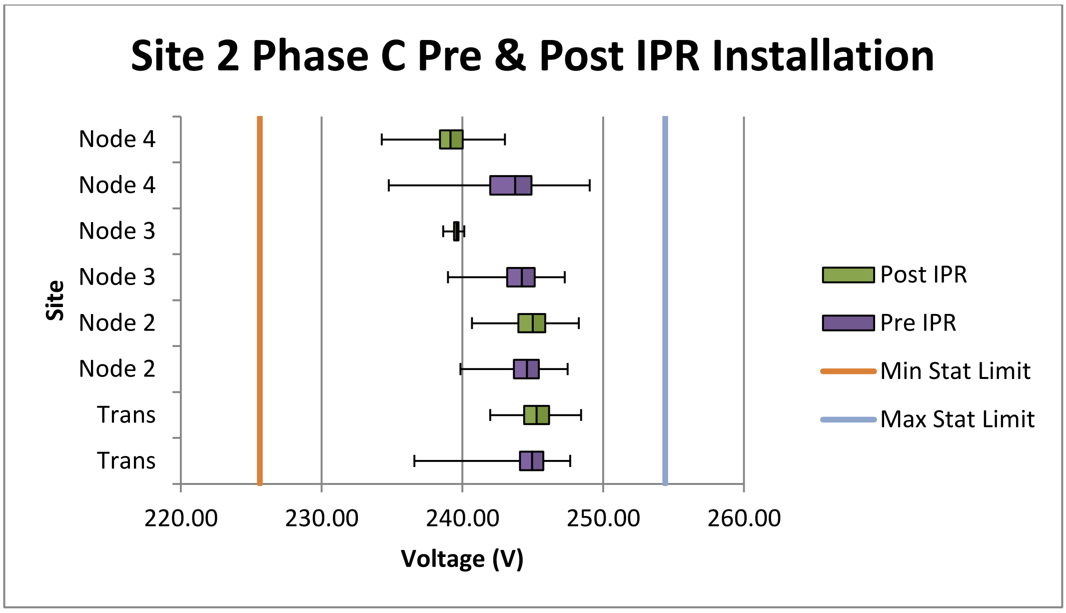

Figure 4. 11 – Site 2 Phase C Pre and Post Installation

Figures 4.9 to 4.11 also show the voltage ranges at the transformer and the three node points. The blue vertical line is the maximum statutory limit of 254.4V and the orange vertical line is the minimum statutory limit of 225.6V. The purple results are from the data before the IPR was installed and the green results are from the data after the IPR was installed. The graph shows the maximum and minimum values recorded and the box segment show the 25th 50th and 75th percentiles.

In the same manner as Site 1, these graphs show that the voltage range at the transformer before and after the IPR was installed is very similar on all three phases. On C phase there was a lower minimum at the transformer, however the 25th 50th and 75th percentiles are still very close. This confirms that the data collected before and after can be compared as the conditions are almost identical.

The data at Node 2 is very similar on all three phases after the IPR was installed; to the data from before the IPR was installed.

The voltage range just after the regulator (Node 3) is very tight on all three phases compared to the data before the IPR was installed and this was to be expected.

At the end of the LV feeder (Node 4) the voltage range is well within limits and a tighter voltage range than prior to the IPR installation. The 25th 50th and 75th percentiles on all three phases are now a lot tighter.

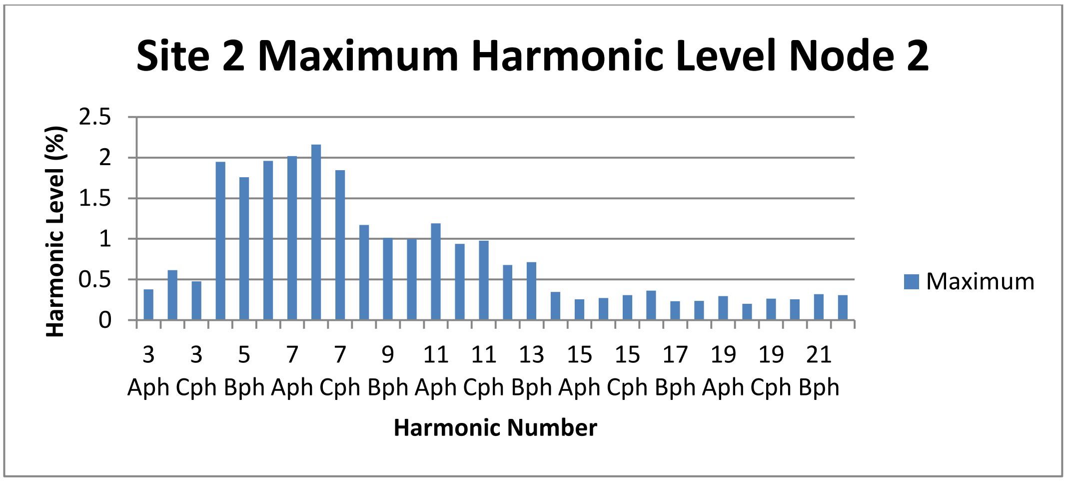

Figure 4. 12 – Site 2 Maximum Harmonic Level Node 2

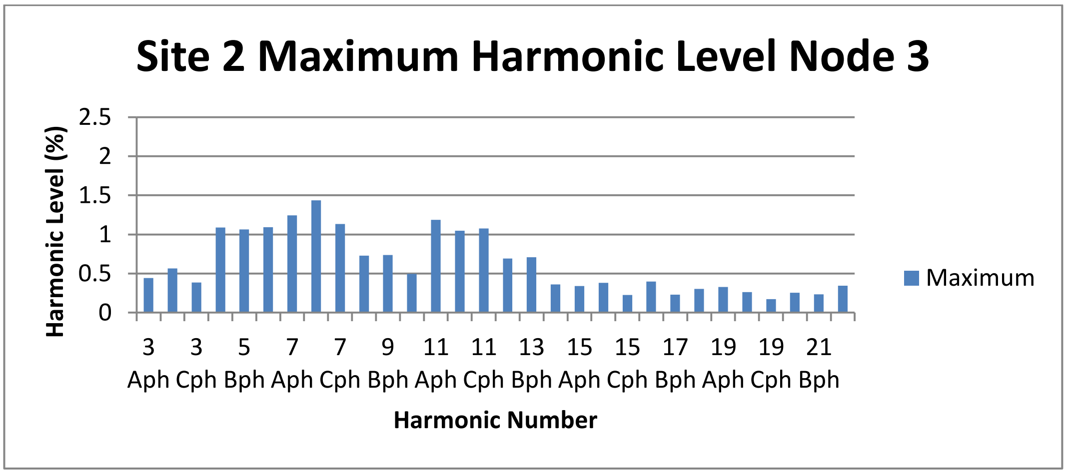

Figure 4. 13 – Site 2 Maximum Harmonic Level Node 3

Figures 4.12 and 4.13 show the improved harmonic level between Nodes 2 and 3. There is no discernible change in the level of the 3rd harmonic on all three phases. The level of the 5th harmonic is almost halved on all three phases of the initial level. The level of the 7th harmonic is approximately 60% of the initial level on all three phases. The level of the 9th harmonic is slightly reduced from the initial level. From the 11th harmonic and up, there is no discernible change from before the regulator to after the regulator.

4.4. Possible Additional PV Hosting Site 2

The same as site 1, the IPR monitors the amount of real power flow and in which direction. This is helpful in showing if there is more PV generating than there is load. This is shown in Figures 4.14 to 4.16 where the blue line is the real power flow that swings from forward to reverse. The two weeks after the installation shows the following:

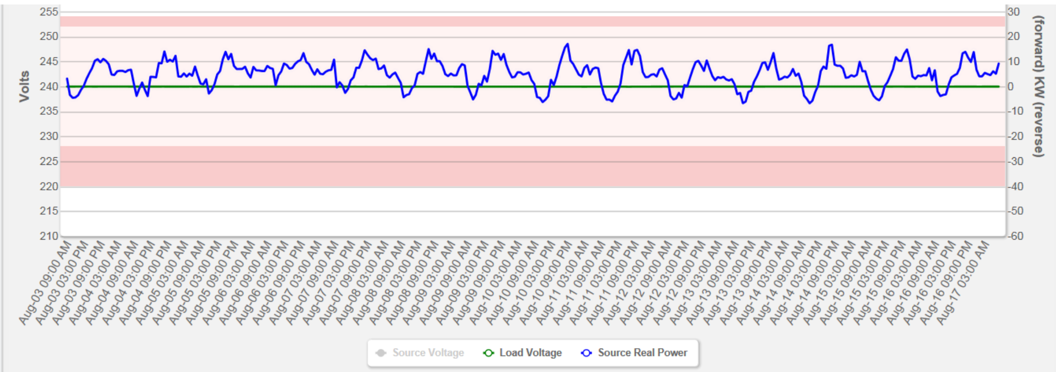

Figure 4. 14 – Site 2 Real Power Flow Phase A

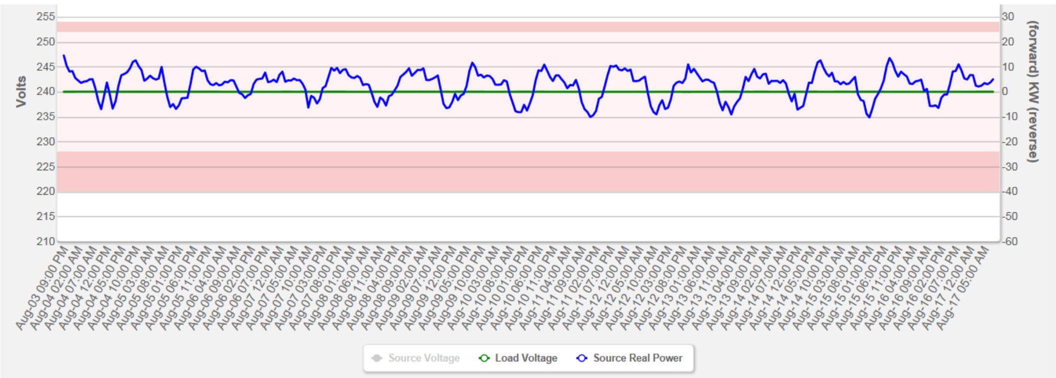

Figure 4. 15 – Site 2 Real Power Flow Phase B

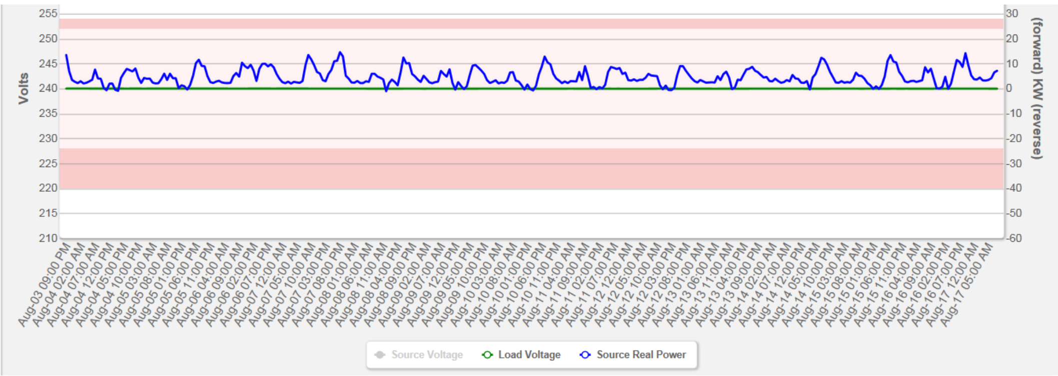

Figure 4. 16 – Site 2 Real Power Flow Phase C

As shown in Figures 4.14 to 4.16 there is approximately 8kW of reverse real power flow through the IPR on phase A and 10kW on phase B. There is almost no reverse real power flow through the IPR on phase C. These results are somewhat expected as there is a significant amount of PV on this LV network, however it was expected to be shared over all three phases.

Chapter 5. Cost Benefit Analysis

As part of the project a cost benefit analysis has been completed to assist in evaluating the IPR. The cost benefit analysis has been broken down into three parts, which are Identify Costs, Identify Benefits and Evaluate Costs and Benefits.

5.1 Identify Costs

The project costs that have been identified have been broken down to the material costs and the labour costs. These costs are as follows:

Material Costs – 80%

Labour Costs – 20%

These costs are per site and are based on the actual costs incurred to install the IPR at each site.

5.2 Identify Benefits

The benefits that have been identified as part of this project include legislative requirements, social expectations, safety considerations and the ethical considerations.

5.2.1. Legislative Requirement

Energex is required to be compliant with the Queensland Electricity Regulation of 240 V ±6%. This project has shown that the IPR is maintaining the voltage within statutory limits at the end of the LV feeders. The benefit of the IPR is it is assisting Energex in continuing to be compliant with the Queensland Electricity Regulation without the need to carry out other rectification works.

5.2.2. Social Expectations

Energex imposes limits on the amount of solar which can be installed on a LV network to mitigate expected network problems. The IPR may be able to increase the amount of PV on a network which means customers who may have had their application rejected could be accepted. Socially, it would be fairer to allow everyone who wishes to install PV to do so, but the network cannot handle that in its current state so those who were first in prohibit those who have come in late by virtue of the network not being able to handle exceedingly high levels of PV penetration without significant and costly upgrades. The modelling that has been completed shows that additional PV can be installed on the network past the IPR. This is a benefit to the community.

5.2.3. Safety

The new IPR's are installed at suitable locations that allow easy access 24 hours per day, seven days a week. This is a requirement when staff need to access the IPR's, they can do so in a safe manner.

Another safety consideration is that there is no maintenance required on the IPR and there is remote communications available to the IPR. The IPR voltage set point can be adjusted remotely which removes the need for personal to go to site.

5.2.4. Ethics

Schermerhorn et al. (2014) defines ethical behaviour as "accepted as right or good or proper in the context of a governing moral code".

The Engineers Australia Code of Ethics (2016) provides the guidelines of professional conduct that need to be adhered too. The key values and principals considered as part of this project are Demonstrate integrity and Promote sustainability.

Demonstrate Integrity includes

- Act on the basis of a well-informed conscience
- Be honest and trustworthy
- Respect the dignity of all persons

Promote sustainability includes

- Engage responsibly with the community and other stakeholders
- Practise engineering to foster the health, safety and wellbeing of the community and the environment
- Balance the needs of the present with the needs of future generations

5.3 Evaluate Costs and Benefits

The evaluation of the costs and benefits is used to ascertain if the project is worthwhile.

The comparison of costs to benefits in this project is difficult to determine as it is challenging to put a dollar figure on the benefits such as maintaining statutory voltage and allowing additional PV connections to the network.

Energex was obligated to augment the network in some way to resolve existing voltage problems. Rather than perform a direct cost/benefit analysis on the IPR option it is sensible to compare the financial cost of the IPR solution with the option of extending the 11kV network and installing a new transformer as discussed in Section 1.3. A Net Present Value (NPV) was calculated using the 11kV upgrade project cost as a basis for comparison. The NPV for the IPR option is shown in Table 5. 1 and includes the costs of replacing the IPR after 25 years. The NPV for extending the 11kV and installing a new transformer is shown in Table 5. 2. This has a higher up front cost but an expected longer life.

As shown in the NPV, the first option has an NPV of 1.09 while the second option has an NPV of 2.38. This shows that the IPR option is approximately 46% of the 11kV extension and transformer option.

As shown in the evaluation of the costs and benefits and the NPV analysis, the installation of the IPR is favoured.

Table 5. 1 – NPV of IPR option

Data	Description	
0.05	Annual discount rate	
-1	Initial cost of investment one year from today	
Yearly expense		
0	1st	Year
0	2nd	Year
0	3rd	Year
0	4th	Year
0	5th	Year
0	6th	Year
0	7th	Year
0	8th	Year
0	9th	Year
0	10th	Year
0	11th	Year
0	12th	Year
0	13th	Year
0	14th	Year
0	15th	Year
0	16th	Year
0	17th	Year
0	18th	Year
0	19th	Year
0	20th	Year
0	21st	Year
0	22nd	Year
0	23rd	Year
0	24th	Year
-0.5	25th	Year
	Description	**Result**
	Net present value of this option	**(1.09)**

Table 5. 2 – NPV of Extending 11kV and Installing a Transformer

Data	Description	
0.05	Annual discount rate	
-2.5	Initial cost of investment one year from today	
Yearly expense		
0	1^{st}	Year
0	2^{nd}	Year
0	3^{rd}	Year
0	4^{th}	Year
0	5^{th}	Year
0	6^{th}	Year
0	7^{th}	Year
0	8^{th}	Year
0	9^{th}	Year
0	10^{th}	Year
0	11^{th}	Year
0	12^{th}	Year
0	13^{th}	Year
0	14^{th}	Year
0	15^{th}	Year
0	16^{th}	Year
0	17^{th}	Year
0	18^{th}	Year
0	19^{th}	Year
0	20^{th}	Year
0	21^{st}	Year
0	22^{nd}	Year
0	23^{rd}	Year
0	24^{th}	Year
0	25^{th}	Year
	Description	**Result**
	Net present value of this option	**(2.38)**

Chapter 6. Augmentation Decision Process

As part of the project an Augmentation Decision Process has been created. This is to assist other planners within the company in determining when it is suitable to use the IPR. The augmentation decision process goes through the key steps in determining when it is suitable to utilise the IPR.

The process is for a voltage complaint project where there are no existing 11kV overhead mains and where there is no LV tie. There is also the consideration of the costs of the business as usual option. If the business as usual costs are greater than the cost of installing an IPR and the project meets the other criteria mentioned, then an IPR solution could be used.

The Augmentation Decision Process is shown in .

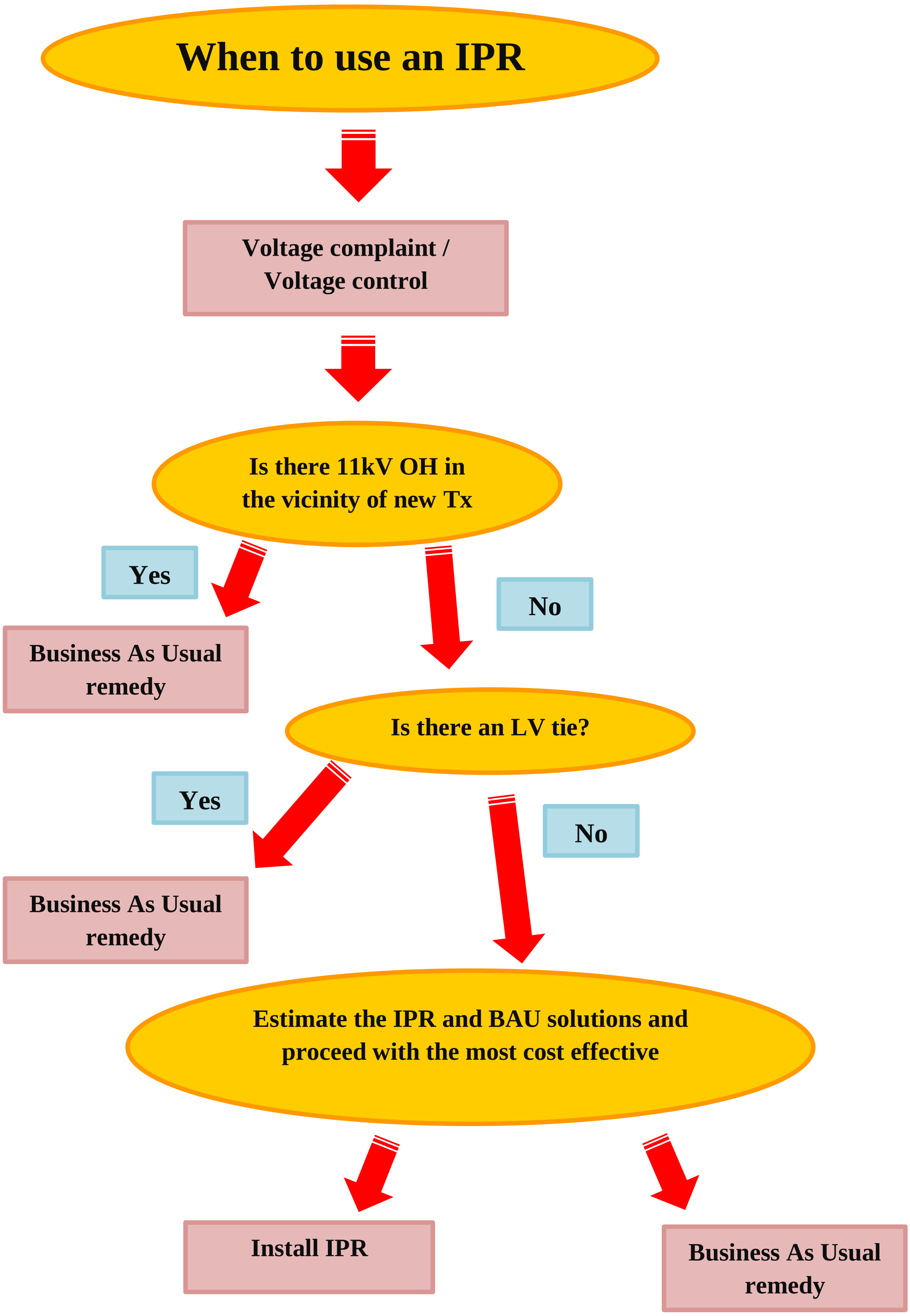

Figure 6. 1 – Augmentation Decision Process

Chapter 7. Conclusion

7.1 Summary of Outcomes

All of the objectives of this project have been accomplished. These include investigate the background on LV networks, voltage statutory limits, PV installation and traditional augmentation methods for voltage issues. This has been completed and can be found in Chapter 2.

The project has reviewed four different types of LV regulation and looked at the benefits of each of these. The types of LV regulation include a distribution transformer with an on load tap changer, a distribution transformer with electronic regulation, a STATCOM device and the Gridco Systems IPR. This review can be found in Section 2.4.

This project has investigated the Gridco Systems IPR as a viable means of addressing LV regulation by means of modelling the network before and after the IPR was installed and comparing it with the data recorded at different node points. The network was modelled for different scenarios including low load with high PV penetration and high load with low PV penetration for the existing network. There was also the scenario of existing low load with additional PV installed. This modelling can be found in Chapter 3.

IPR's were installed at two locations and voltage monitoring devices were installed at a number of locations. The voltage monitoring devices captured the voltage for two weeks prior to the IPR installation and then two weeks after the IPR was installed. The results found and analysis that was completed at both sites from this data can be found in Chapter 4.

An augmentation decision process has also been created to assist others in determining when it is best to use the new IPR or when a business as usual approach should be taken. This is shown in Chapter 6.

7.2 Research Component

The research component of this project has investigated the use of the new IPR on a LV feeder. This has included modelling of the network to allow additional PV installations to be connected. This work has been investigated at two contrasting sites and is shown in detail in Section 3. This work has shown that there is an opportunity of connecting additional PV past the IPR sites while still maintaining statutory voltages.

This will be beneficial to Energex in that the LV network can maintain voltage within statutory limits when additional PV installations are connected and it is less expensive than traditional methods of rectifying some voltage complaints. Also it will benefit the customers in that they will be able to install and connect PV installations on the network.

7.3 Future Recommended Work

It is recommended that further work be carried out on determining the best set point voltage on each IPR. This would need to be done with continued voltage monitoring both before and after the IPR site and especially during different seasons. In summer there may be additional load that would come on at the peak time of 4 to 8 pm, so there is a possibility of the voltage range increasing at this time. Also there may be additional PV operating in spring time during the day when the PV output would be at its highest. There could also be a benefit of changing the set point voltage during the day. This could have a positive impact on the additional PV hosting capabilities. These scenarios would need to be investigated as Energex is required to ensure that the voltage is maintained at all times of the year.

This can be extended to also include additional modelling and testing when extra PV installations could be installed to ensure the voltage is maintained within statutory limits.

7.4 Project Summary

This project was undertaken to assess the Gridco Systems IPR as a viable means of addressing LV regulation. This included modelling of the existing LV network and then modelling the network with the IPR installed. The modelling included the different scenarios that were expected to be seen, that is low load with high PV penetration and high load with low PV penetration, to ensure the IPR would maintain the voltage within limits at all times.

The project has also required the user to liaise with the local council officers to obtain approval in principle prior to design and construction of the IPR devices on the council road reserves. There was also consultation with Energex designers, work group leaders and field workers during the design and construction phase and constant discussions with the Energex project supervisor.

The infield trial of the IPR has so far shown that it will maintain the voltage within statutory limits. The infield trial will continue to assess the IPR under a more extensive range of operating conditions for a complete evaluation before it will become a standard product available for network augmentation.

The results of this project certainly show promise that the IPR can technically achieve the regulation function required whilst proving to be a more economical solution than traditional network remediation options in a select range of circumstances.

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Appendix A: Project Specification

ENG4111/4112 Research Project

Project Specification

For: Shaun Rosendale

Title: Investigation of low voltage regulation opportunities on the distribution network

Major: Power Engineering

Supervisors: Andreas Helwig and Narottam Das

Employer: Energex

Enrolment: ENG4111 – Ext S1, 2016

ENG4112 – Ext S2, 2016

Project Aim: To assess the Gridco Systems Intelligent Power Regulator (IPR) as a viable means of addressing LV regulation

Programme: Issue B 10th April 2016

1. Investigate the background on LV networks including, traditional design methodology, voltage statutory limits, PV installations, traditional augmentation methods for voltage issues.
2. Review and critique the four different types of low voltage regulation, which are a Gridco Systems Intelligent Power Regulator (IPR), a distribution transformer with an on load tap changer, a transformer with electronic regulation and installing a Volt VAR regulator device.
3. Investigating the benefits of each option and look at real scenarios where they could be installed.
4. Assessing past projects that could have used these products and perform a cost benefit analysis to determine if the new product/s would have been more suitable or cost effective than traditional network augmentation methods.
5. Perform analysis of the LV networks before and after the IPR is installed.
6. Calculate the net present value of a traditional LV augmentation project and the new IPR installation.
7. Monitor the voltage after the installation of the IPR and compare to modelled results
8. Create an Augmentation Decision Process to assist the planners in deciding when to use the new product.

If time and resources permit:

9. Investigate a second site and perform analysis of the LV networks before and after the IPR is installed.
10. Monitor the voltage after the installation of the IPR and compare to modelled results.
11. Compare results to first site to ensure results are consistent.

Appendix B: Wilson Transformer OLTC Specifications

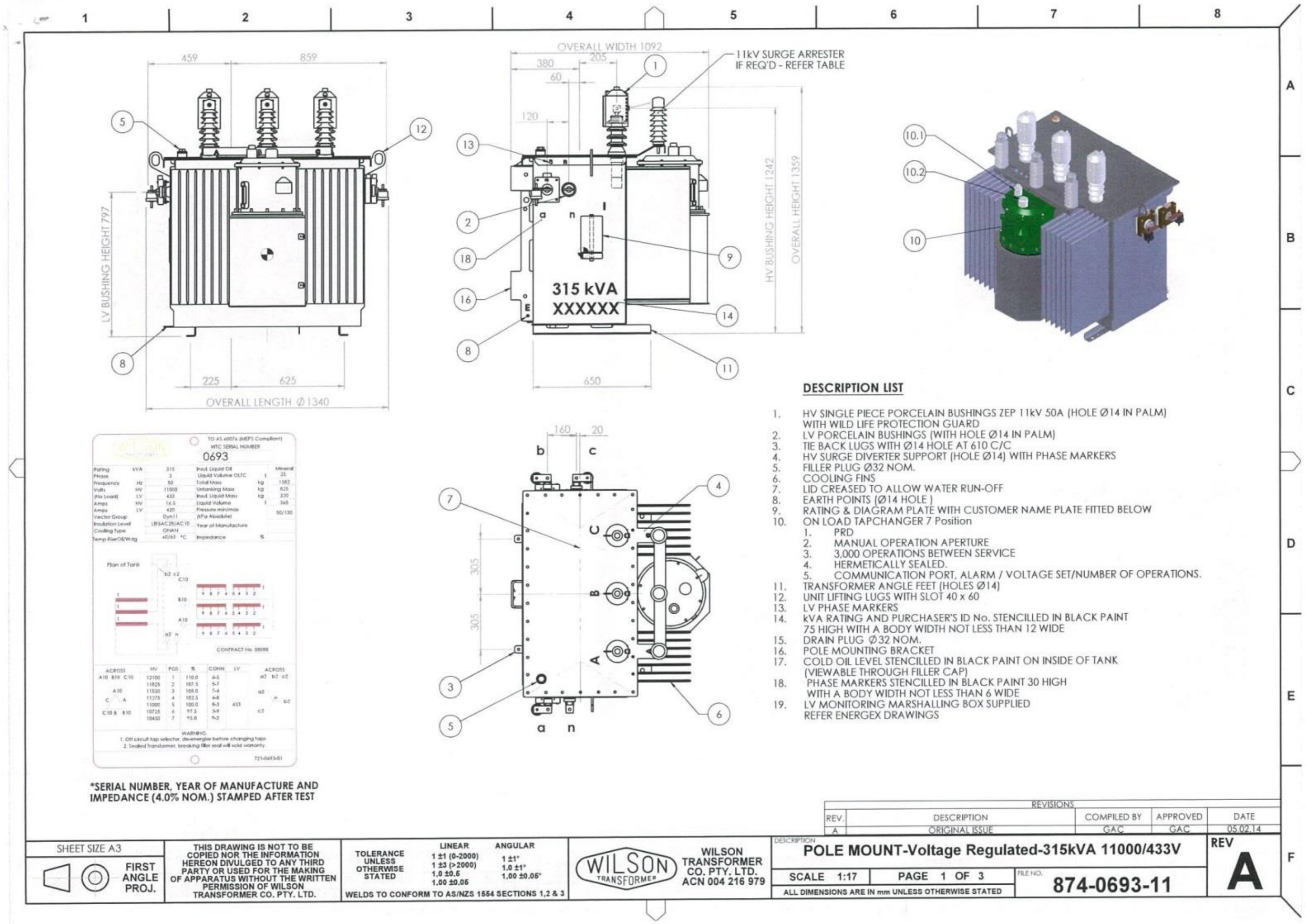

Figure B. 1 – Sheet 1 of 3 - Wilson On Load Tap Changing 315kVA Transformer

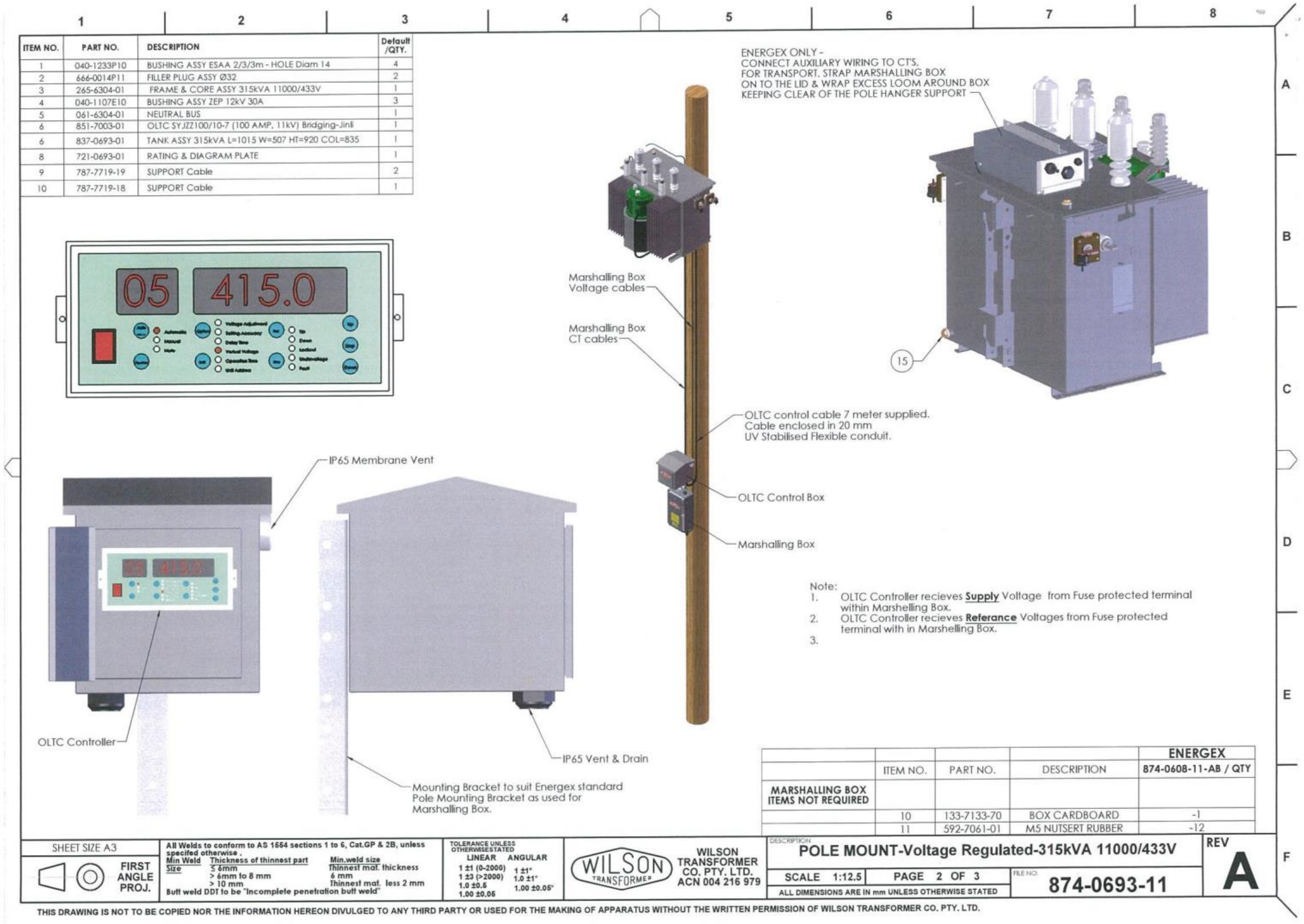

Figure B. 2 – Sheet 2 of 3 - Wilson On Load Tap Changing 315kVA Transformer

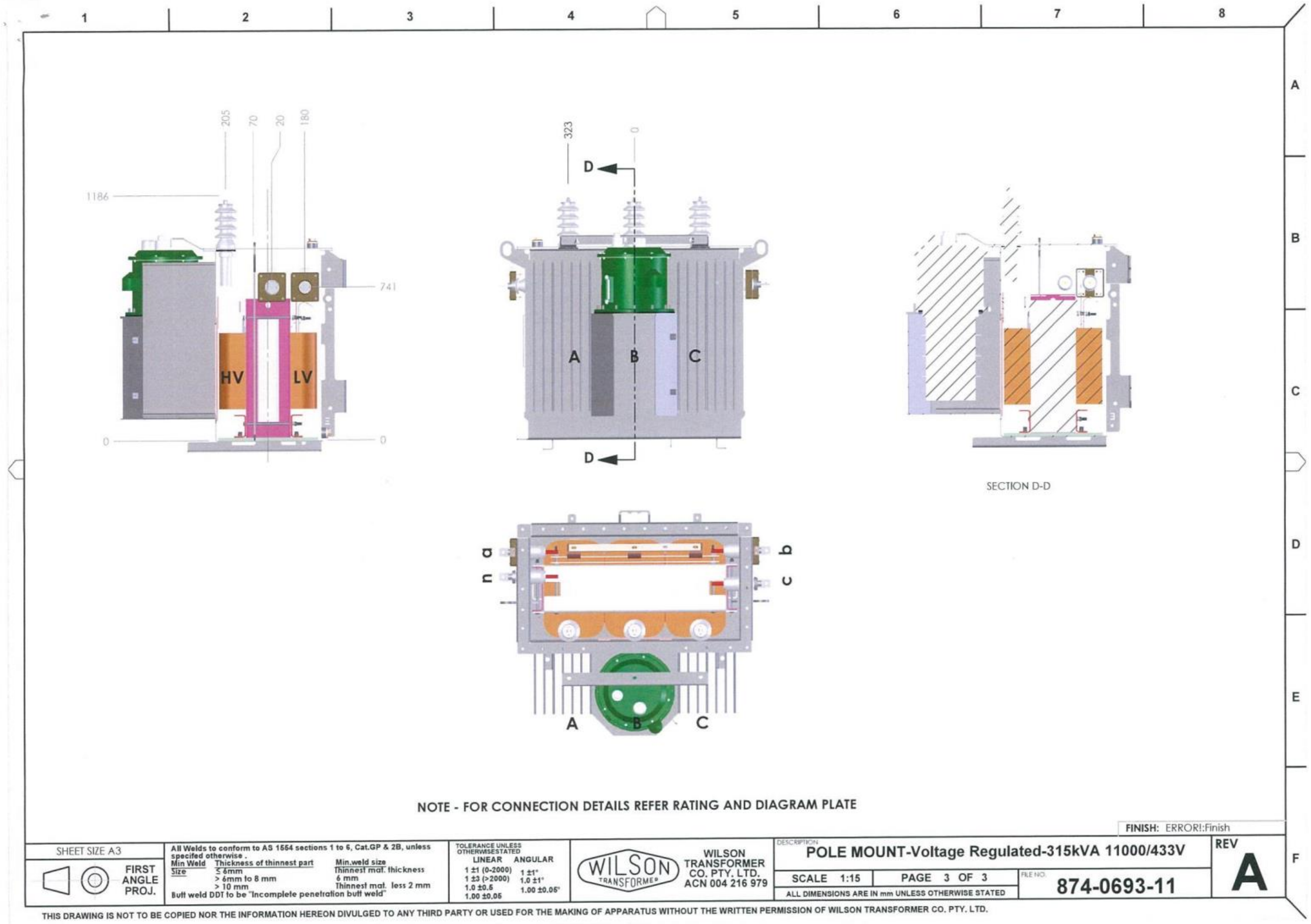

Figure B. 3 – Sheet 3 of 3 - Wilson On Load Tap Changing 315kVA Transformer

Appendix C: Data Collected

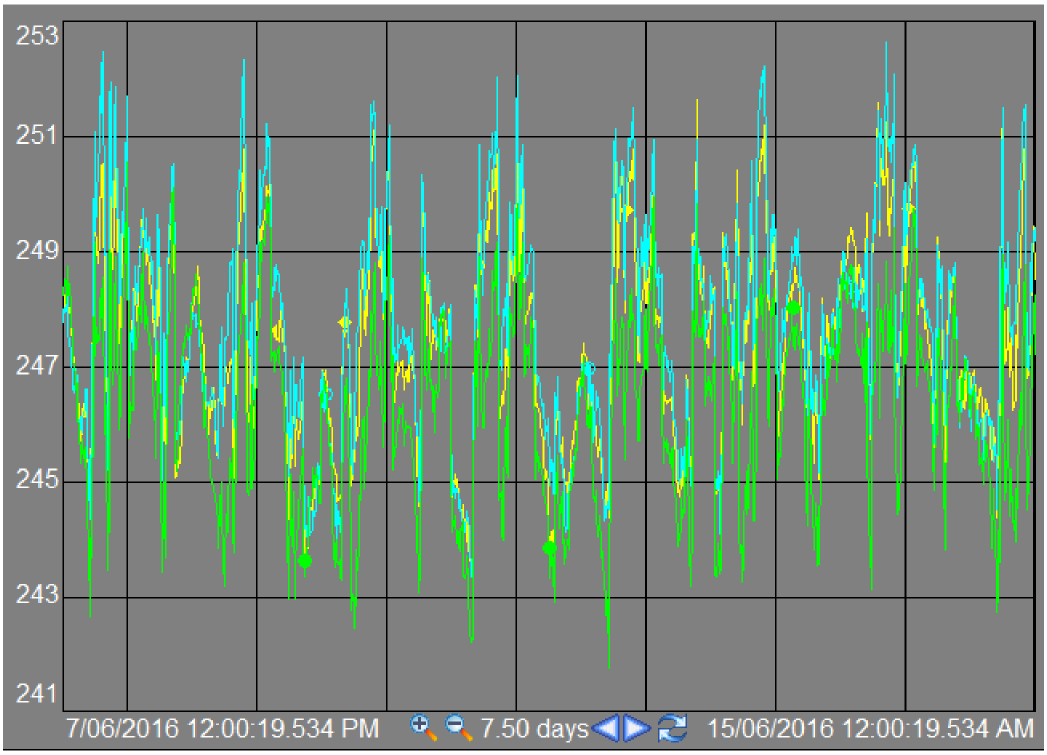

Figure C. 1 - Transformer Site 1 7/06/2016 –15/06/2016 by Energex

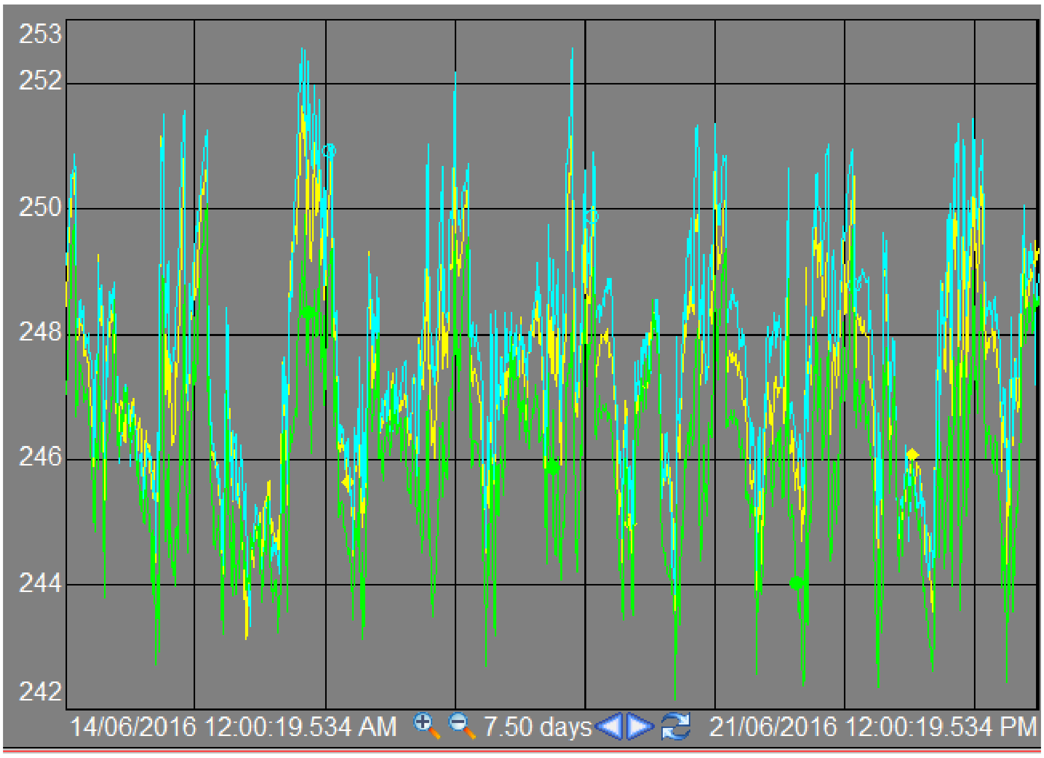

Figure C. 2 - Transformer Site 1 14/06/2016 – 21/06/2016 by Energex

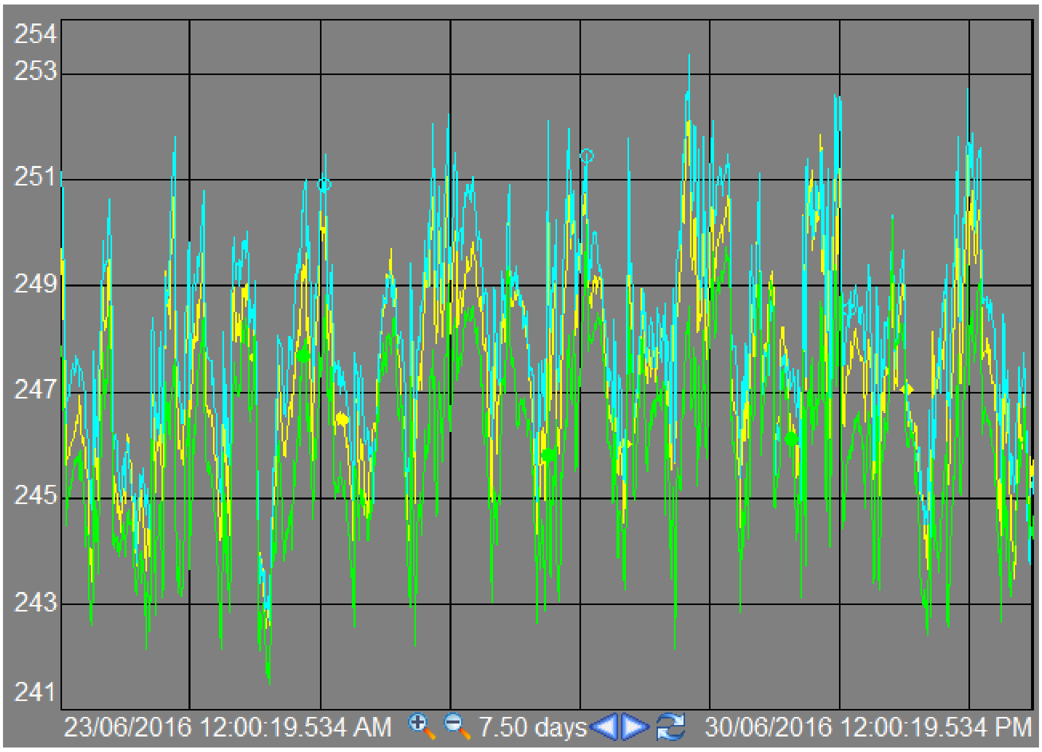

Figure C. 3 - Transformer Site 1 23/06/2016 – 30/06/2016 by Energex

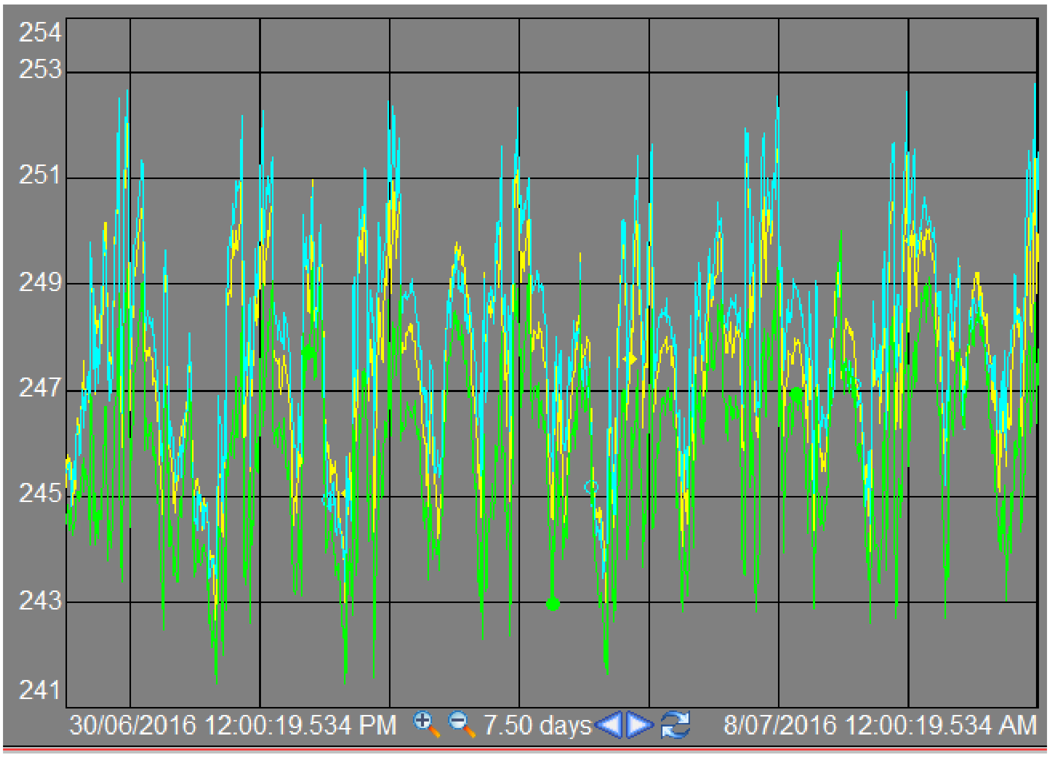

Figure C. 4 - Transformer Site 1 30/06/2016 – 8/07/2016 by Energex

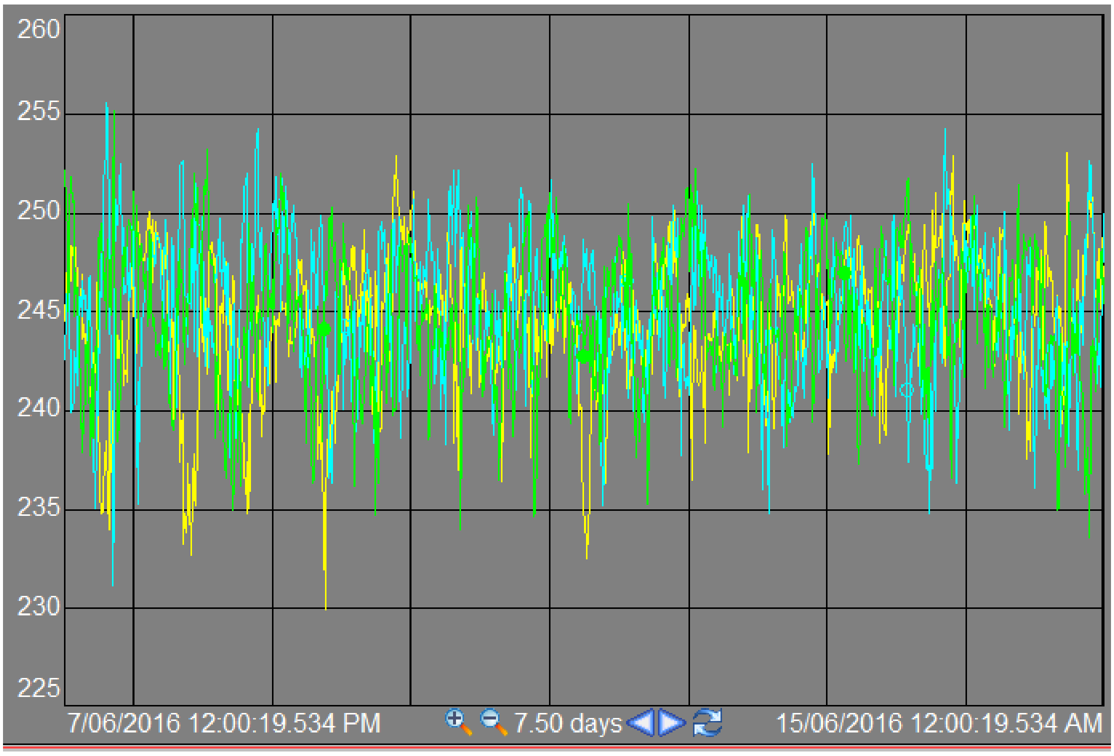

Figure C. 5 - Node 2 Site 1 07/06/2016 – 15/06/2016 by Energex

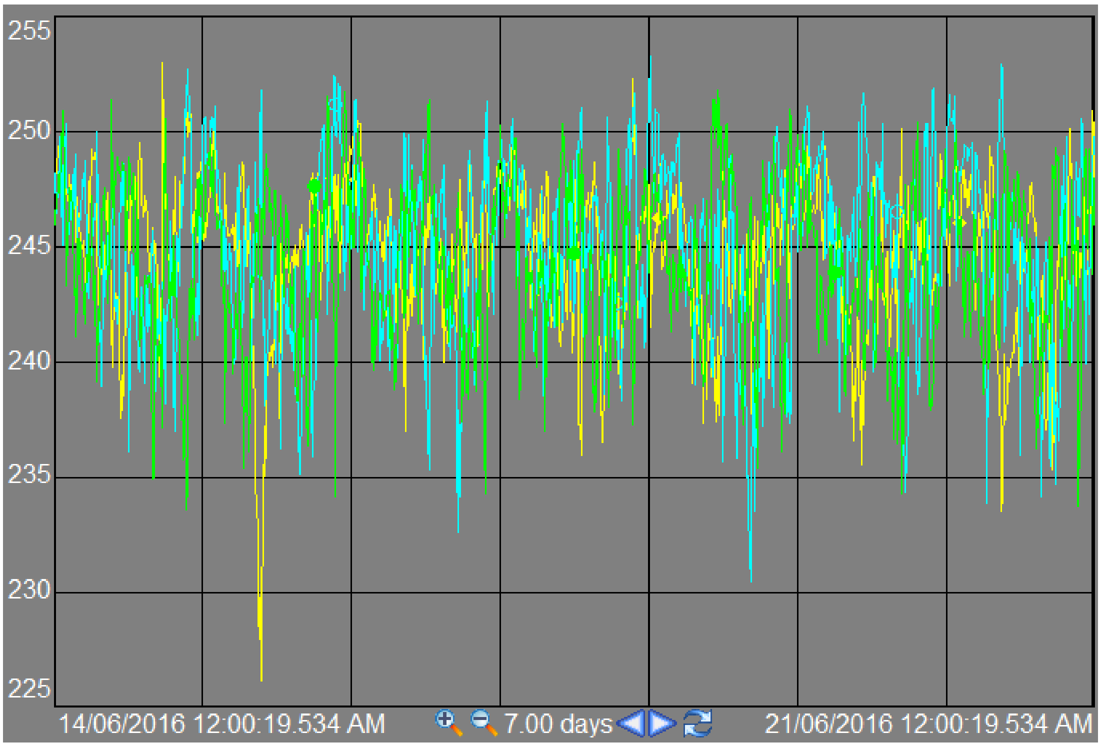

Figure C. 6 - Node 2 Site 1 14/06/2016 – 21/06/2016 by Energex

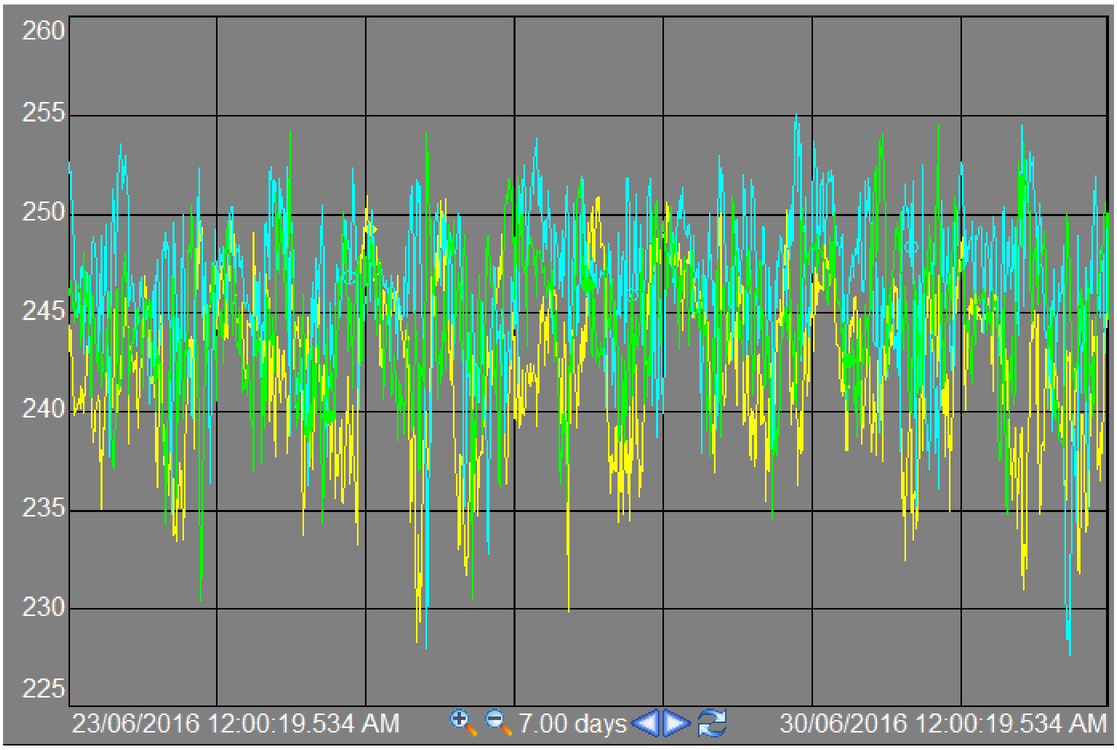

Figure C. 7 - Node 2 Site 1 23/06/2016 – 30/06/2016 by Energex

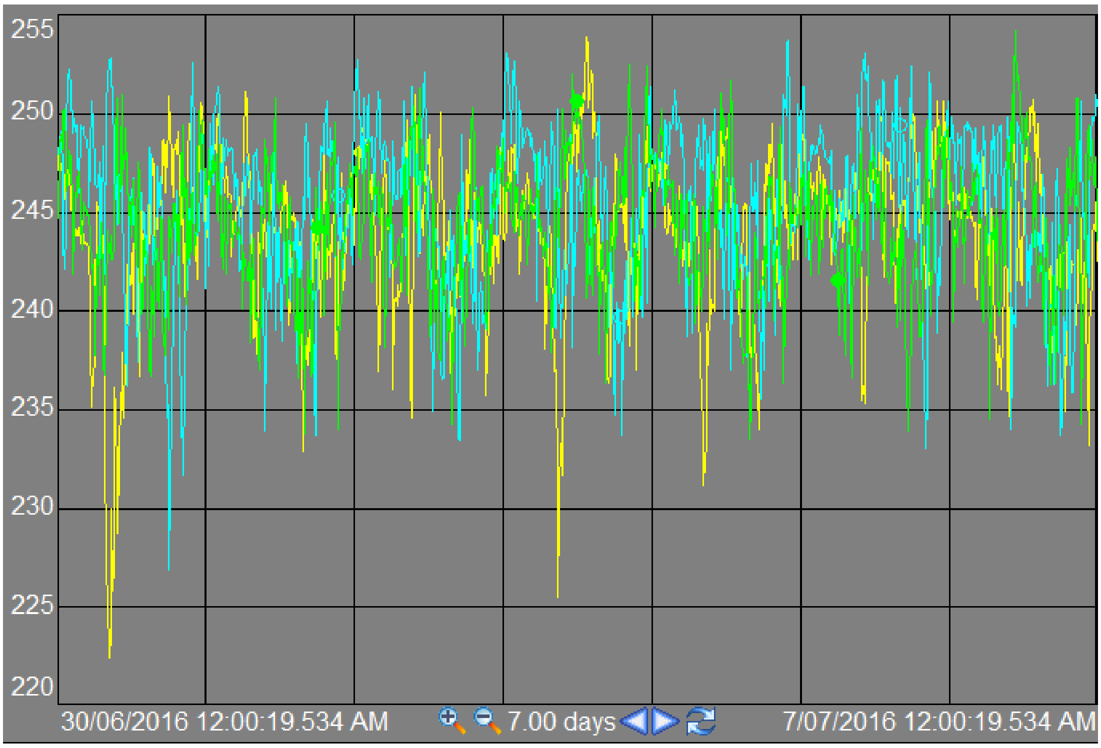

Figure C. 8 - Node 2 Site 1 30/06/2016 – 7/07/2016 by Energex

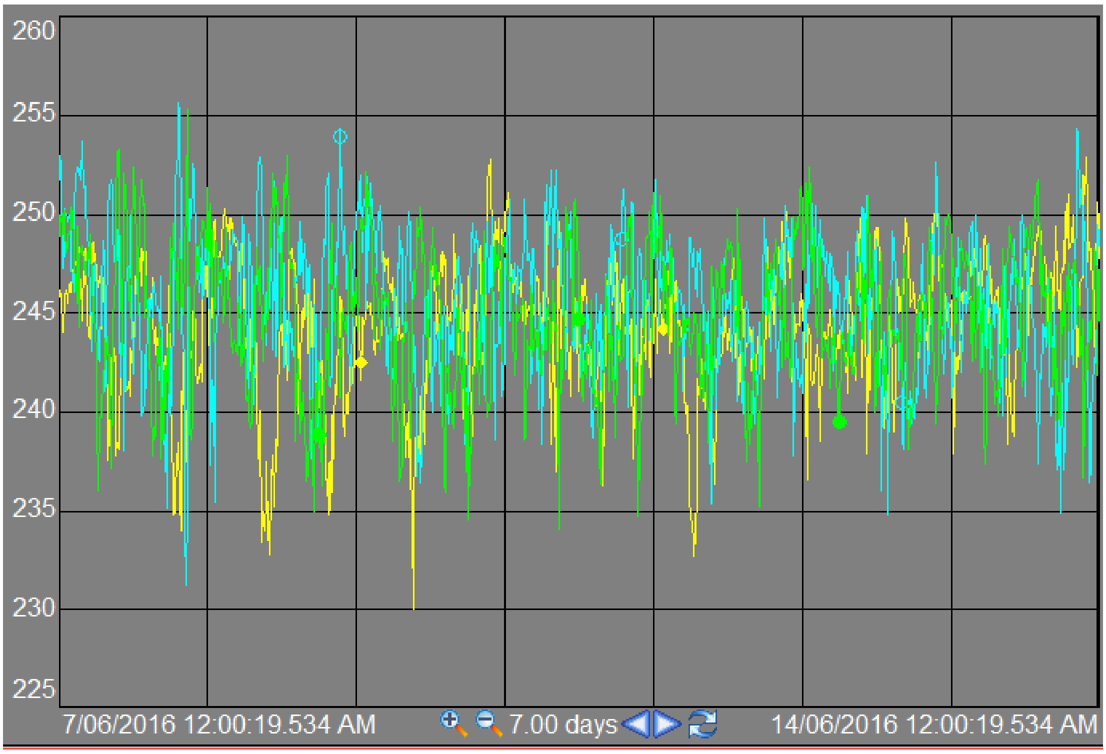

Figure C. 9 - Node 3 Site 1 07/07/2016 – 14/06/2016 by Energex

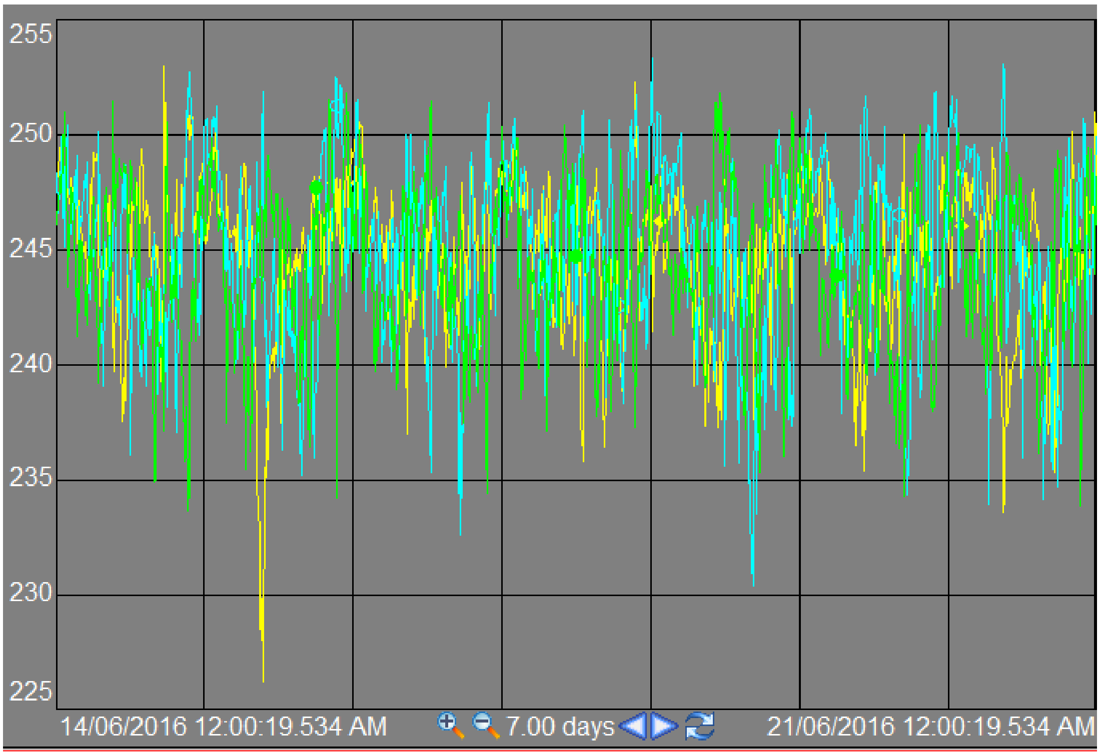

Figure C. 10 - Node 3 Site 1 14/06/2016 – 21/06/2016 by Energex

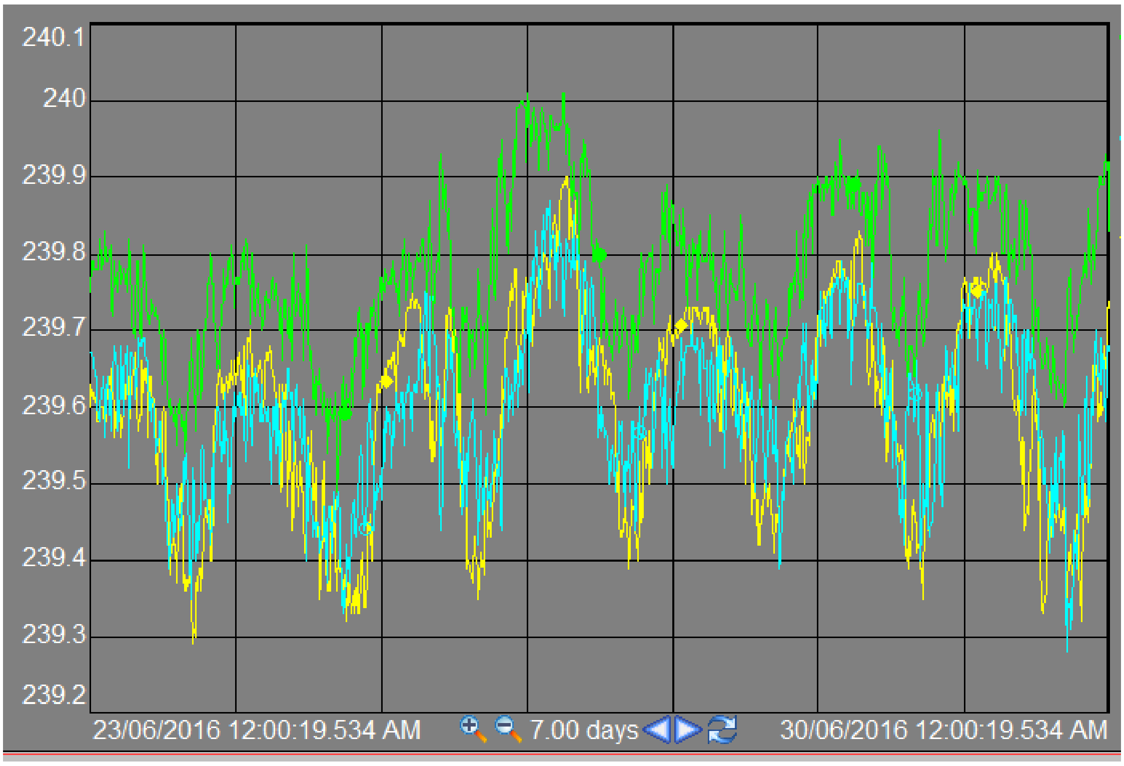

Figure C. 11 - Node 3 Site 1 23/06/2016 – 30/06/2016 by Energex

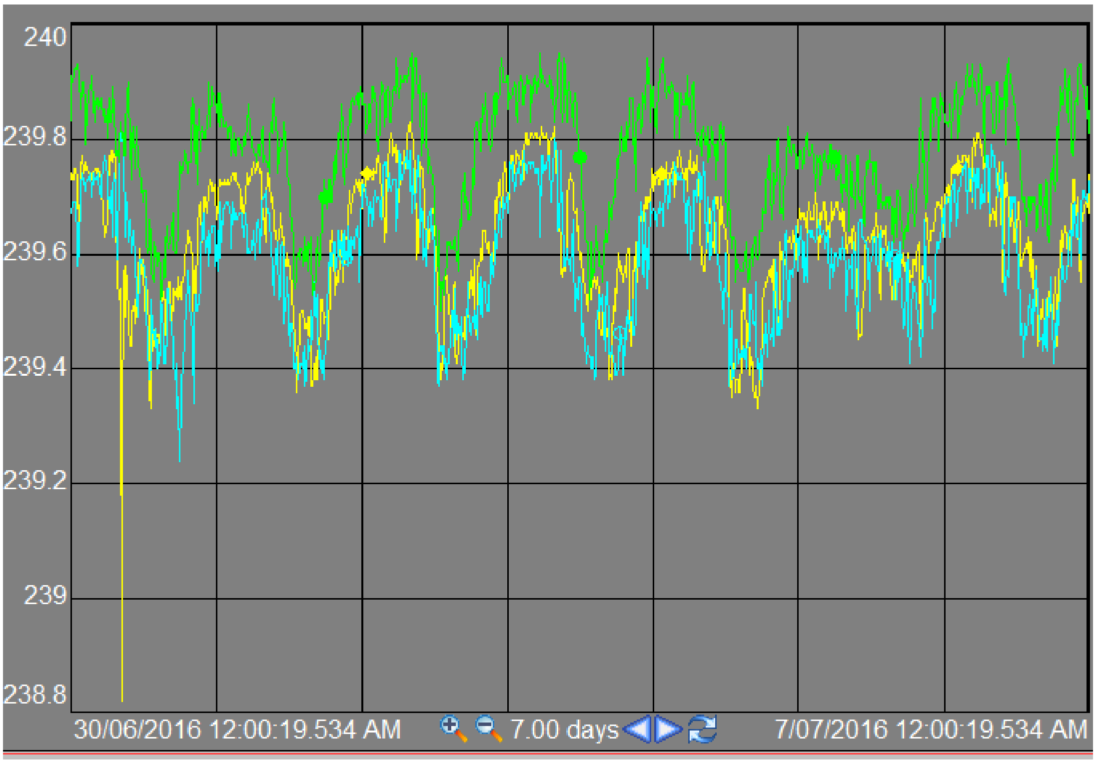

Figure C. 12 - Node 3 Site 1 30/06/2016 – 7/07/2016 by Energex

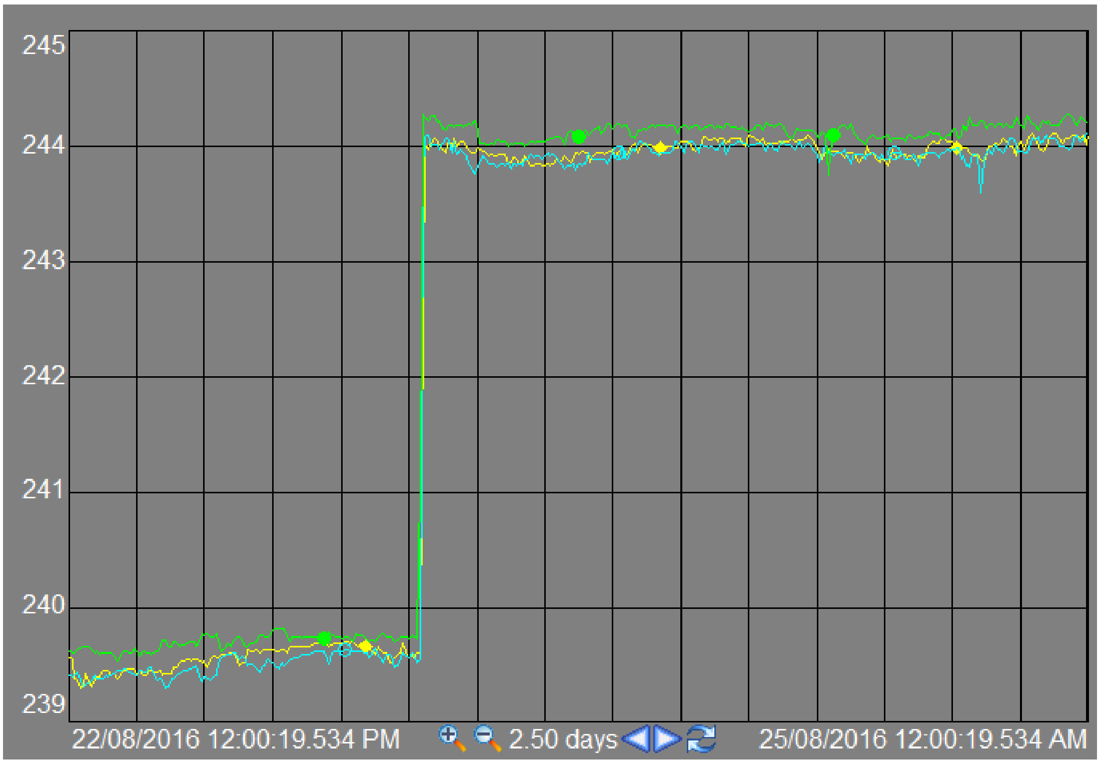

Figure C. 13 - Node 3 Site 1 22/08/2016 – 25/08/2016 by Energex

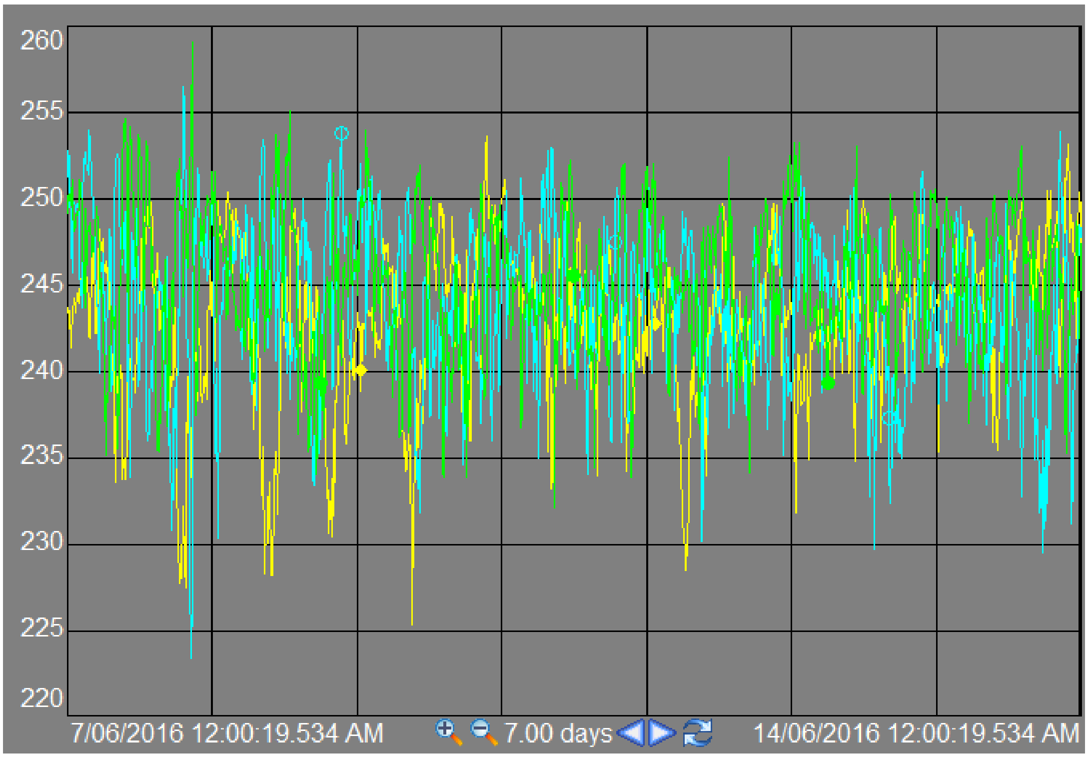

Figure C. 14 - Node 4 Site 1 07/06/2016 – 14/06/2016 by Energex

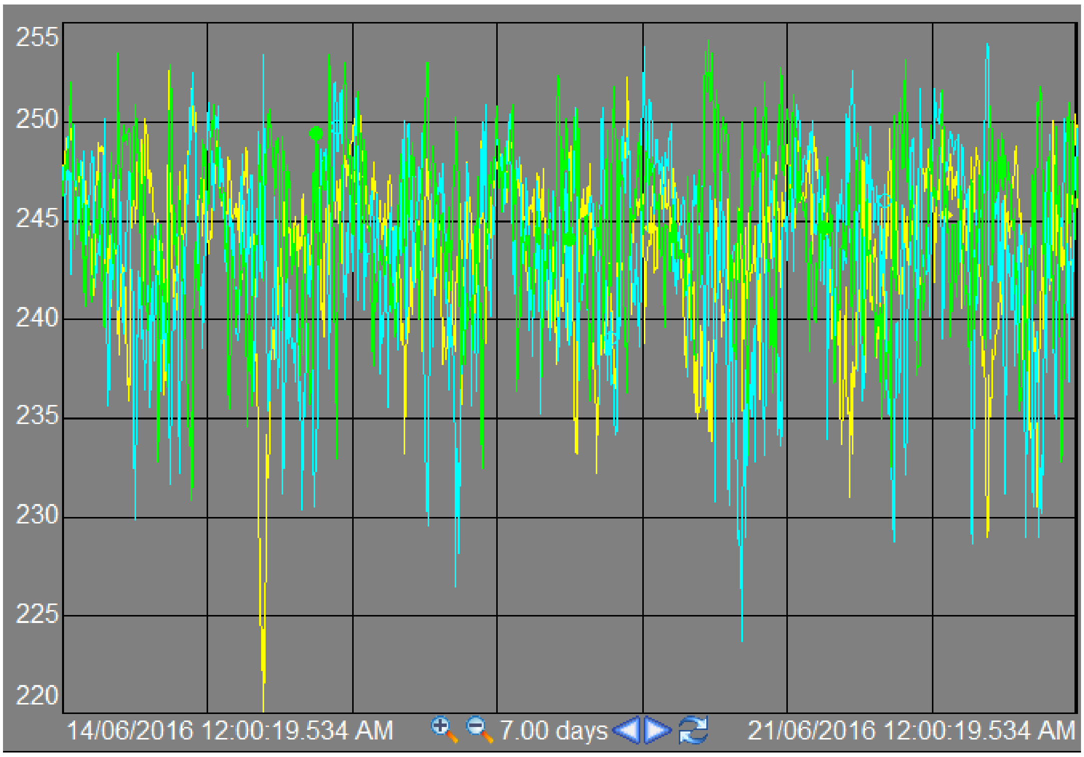

Figure C. 15 - Node 4 Site 1 14/06/2016 – 21/06/2016 by Energex

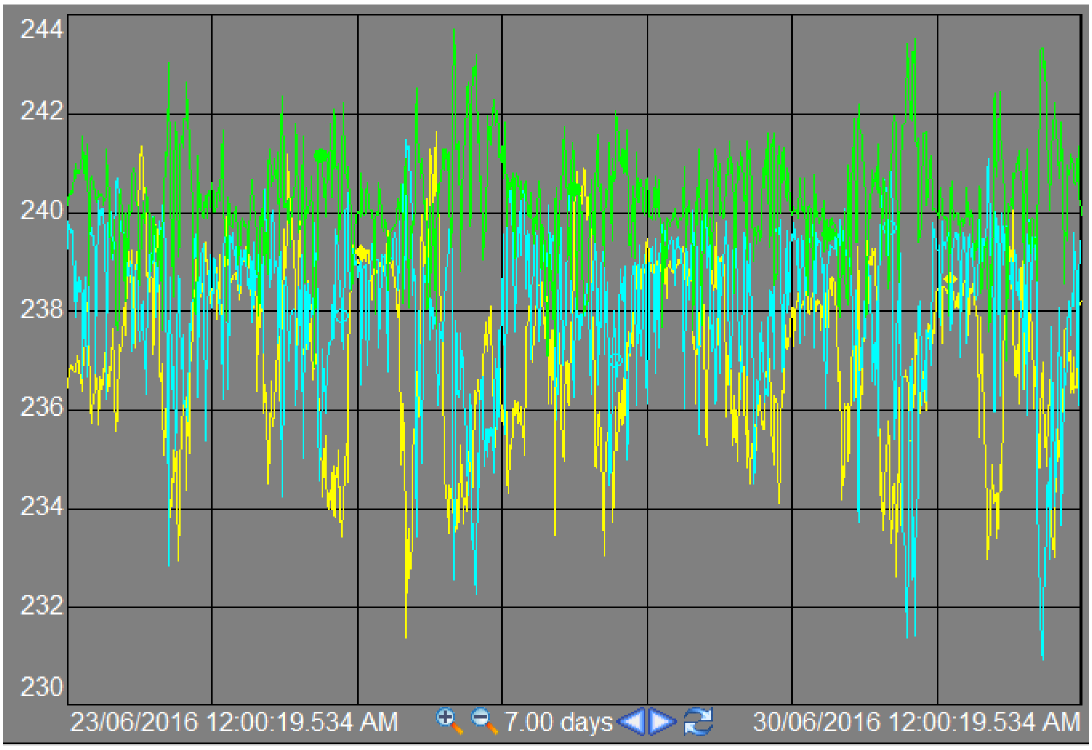

Figure C. 16 - Node 4 Site 1 23/06/2016 – 30/06/2016 by Energex

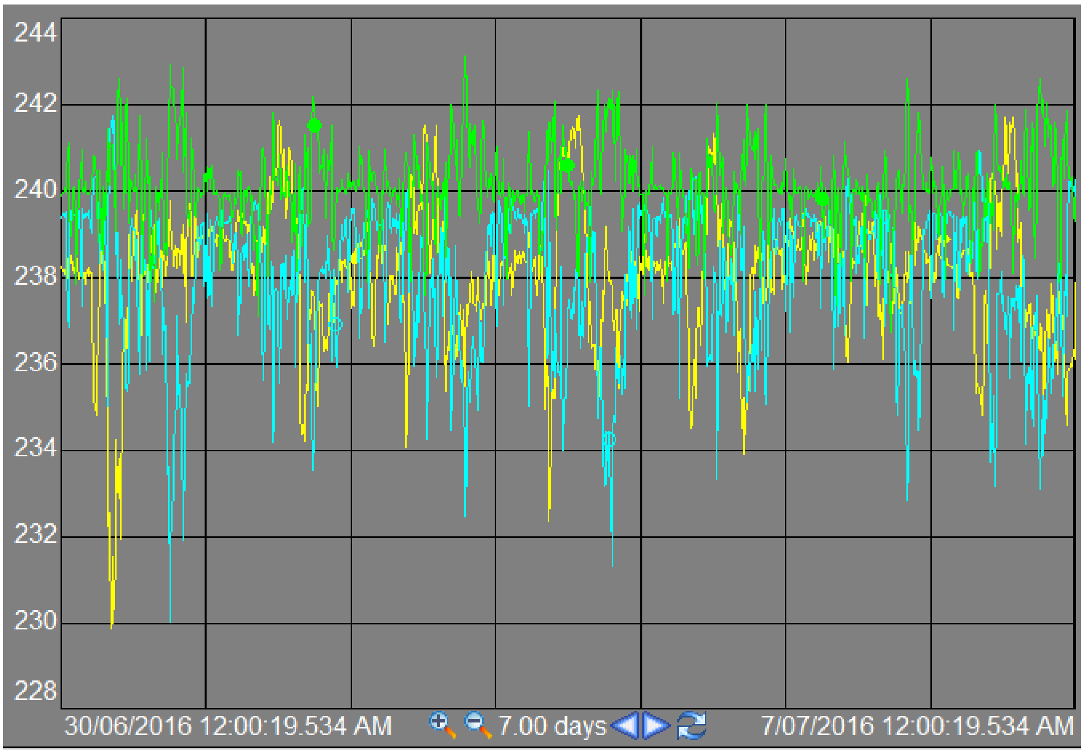

Figure C. 17 - Node 4 Site 1 30/06/2016 – 7/07/2016 by Energex

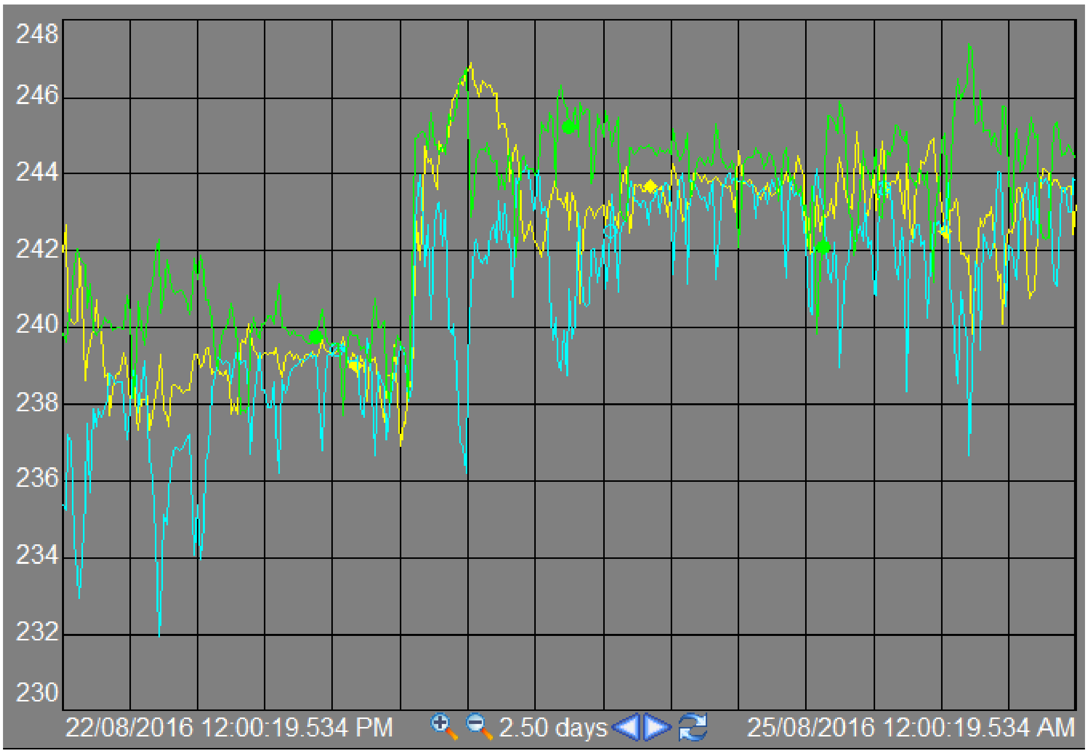

Figure C. 18 - Node 4 Site 1 22/08/2016 – 25/08/2016 by Energex

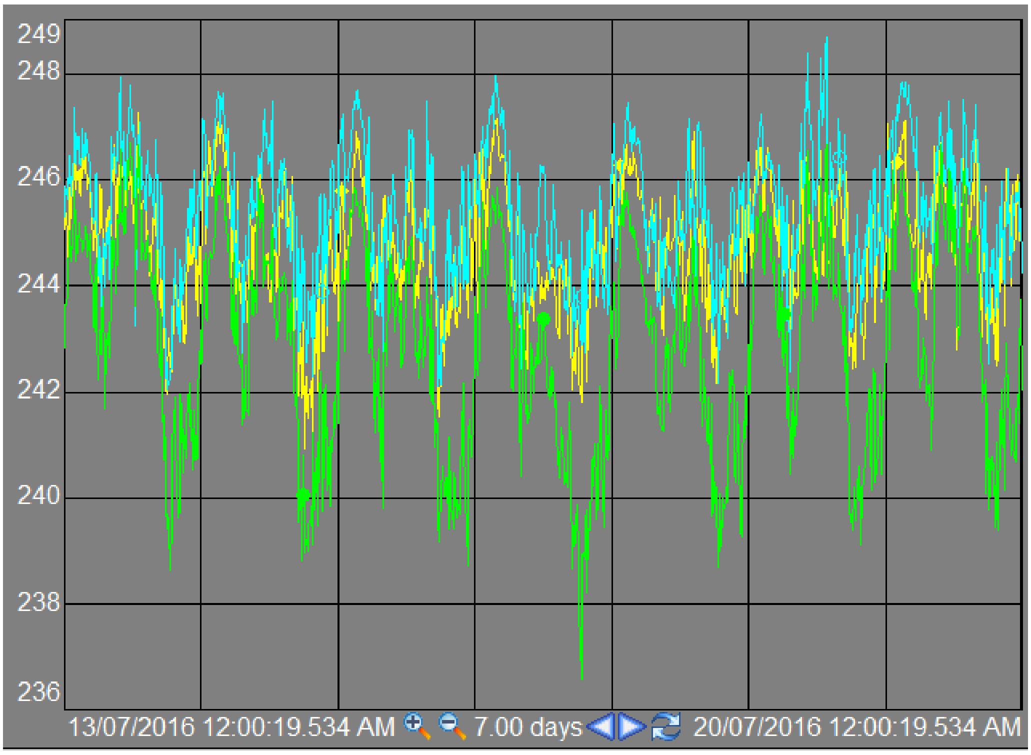

Figure C. 19 - Transformer Site 2 13/07/2016 – 20/07/2016 by Energex

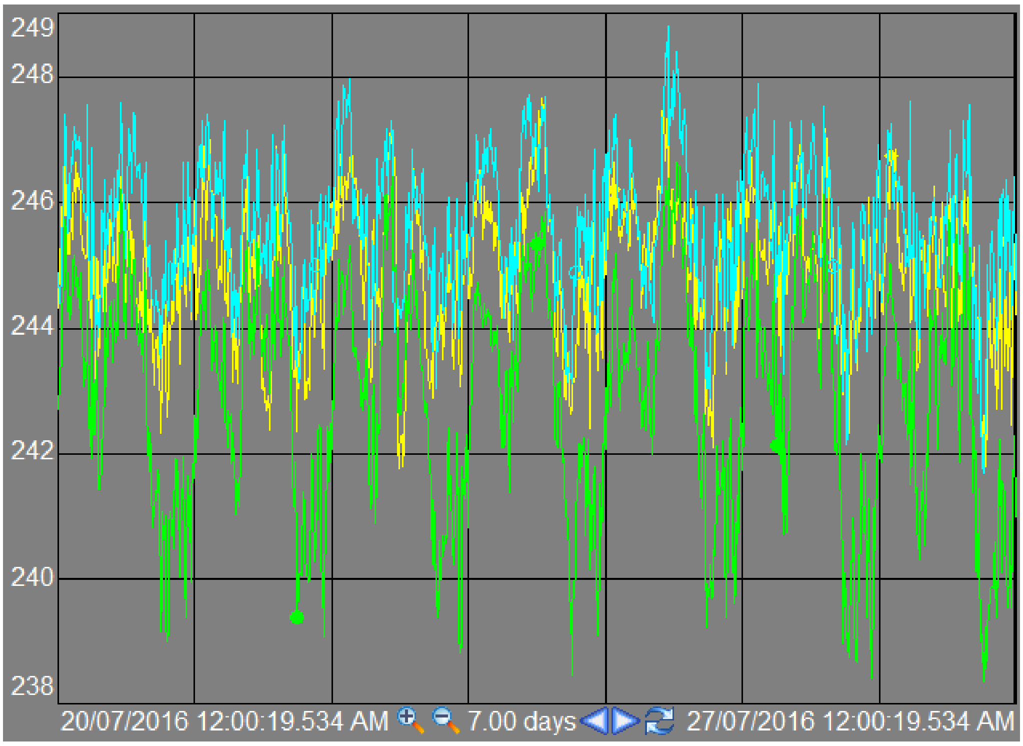

Figure C. 20 - Transformer Site 2 20/07/2016 – 27/07/2016 by Energex

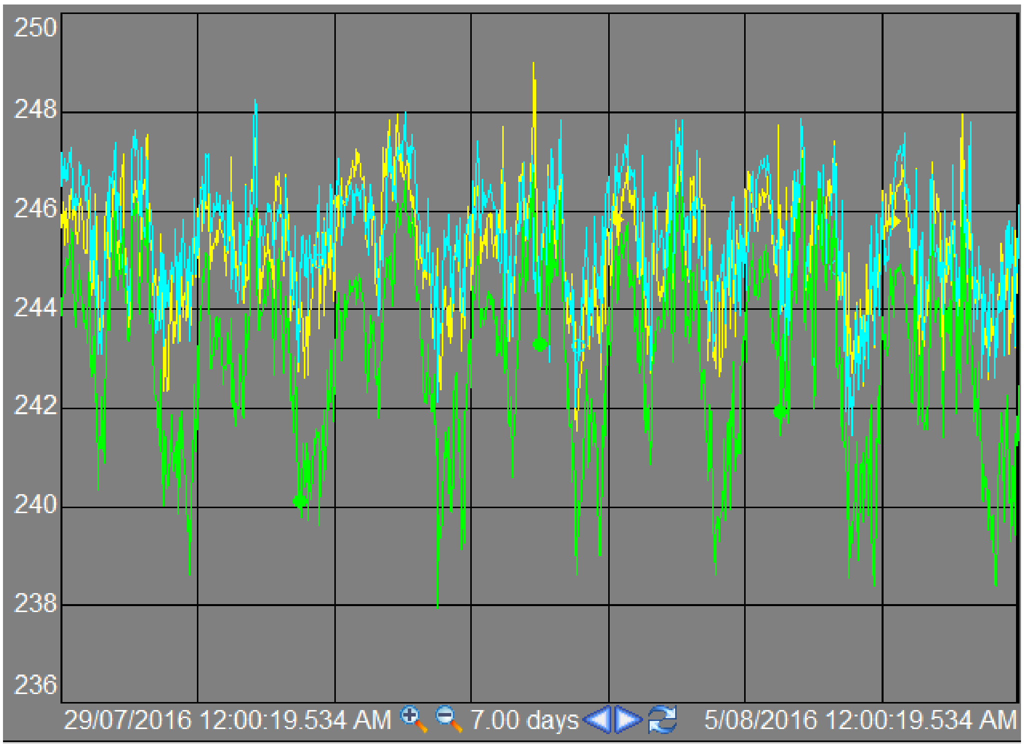

Figure C. 21 - Transformer Site 2 29/07/2016 – 05/08/2016 by Energex

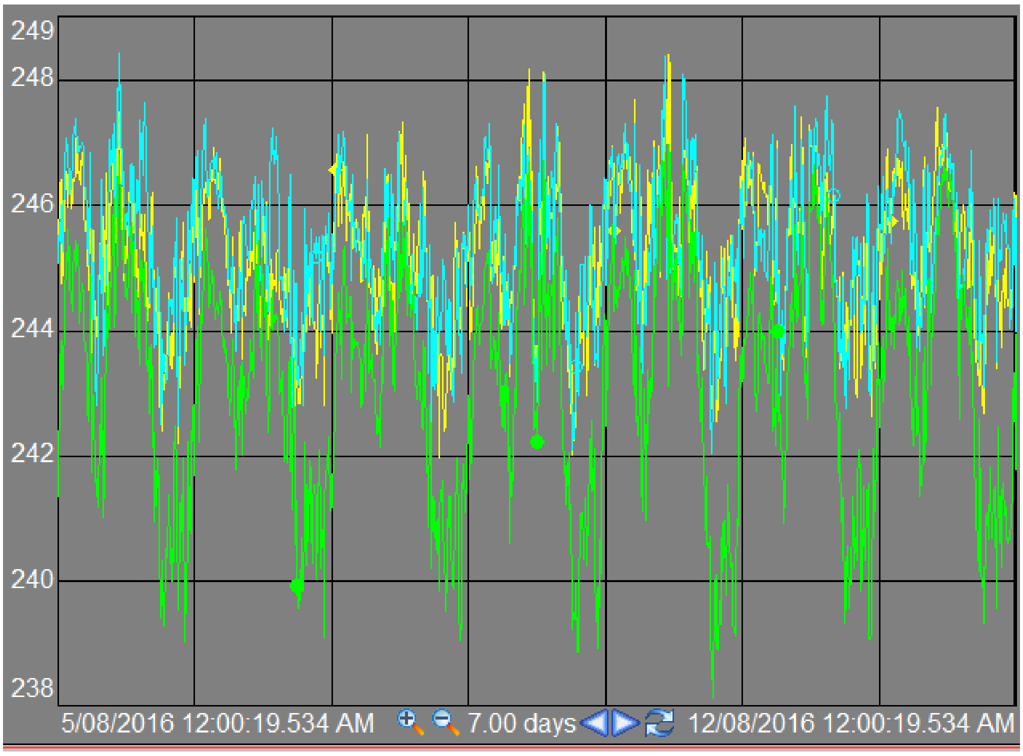

Figure C. 22 - Transformer Site 2 05/08/2016 – 12/08/2016 by Energex

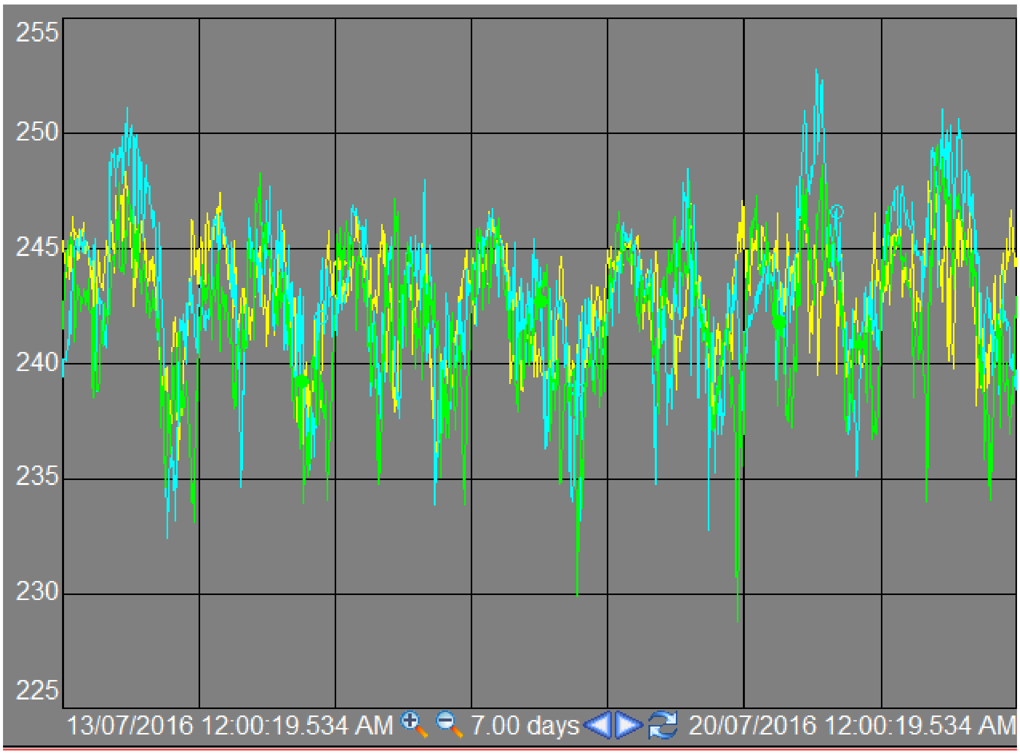

Figure C. 23 - Node 2 Site 2 13/07/2016 – 20/07/2016 by Energex

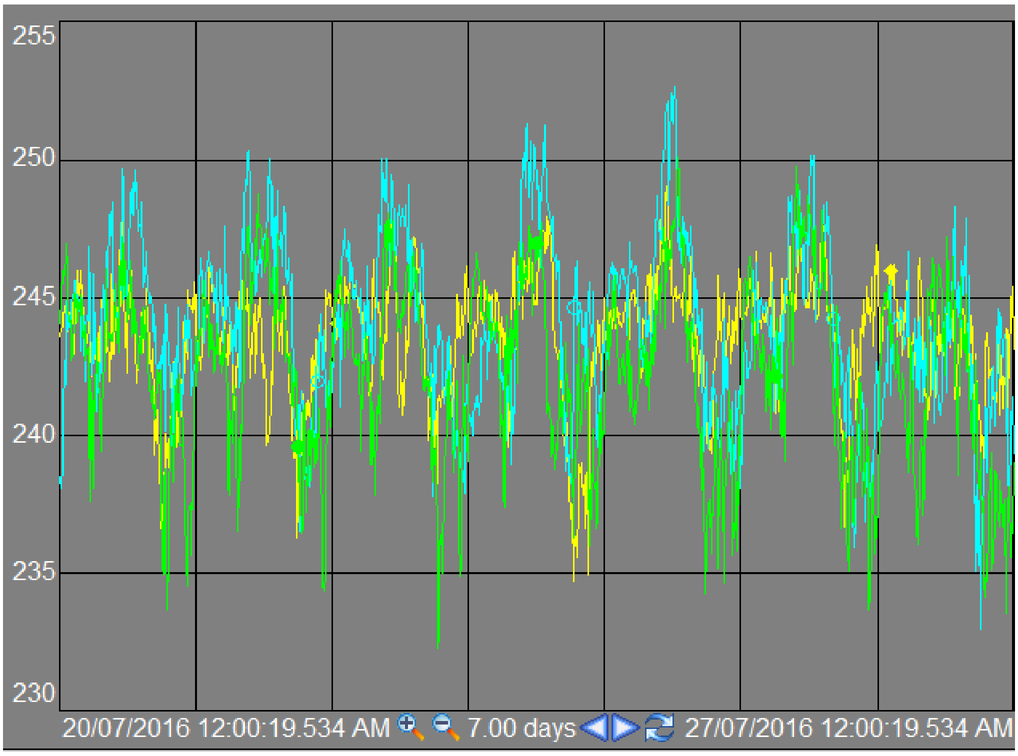

Figure C. 24 - Node 2 Site 2 20/07/2016 – 27/07/2016 by Energex

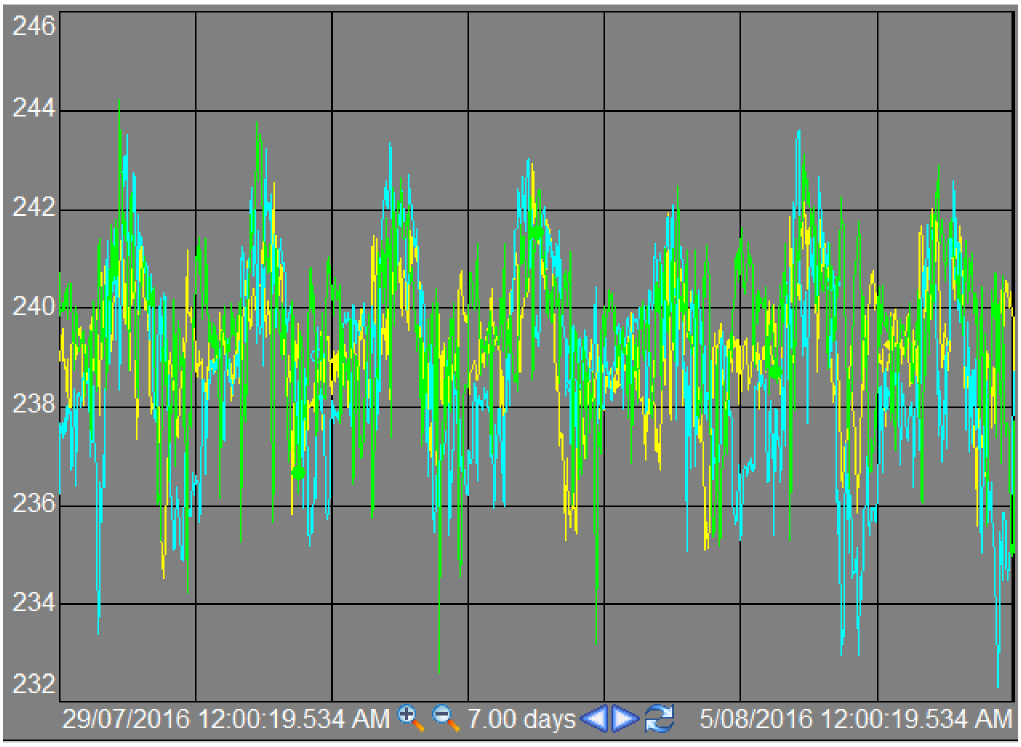

Figure C. 25 - Node 2 Site 2 29/07/2016 – 05/08/2016 by Energex

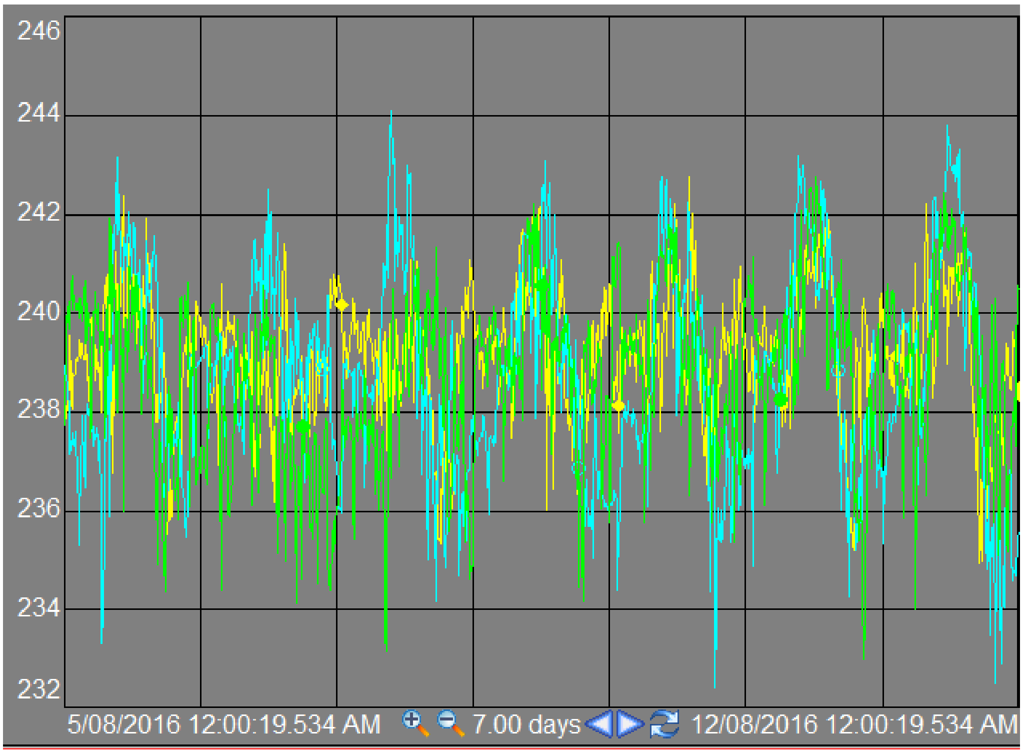

Figure C. 26 - Node 2 Site 2 05/08/2016 – 12/08/2016 by Energex

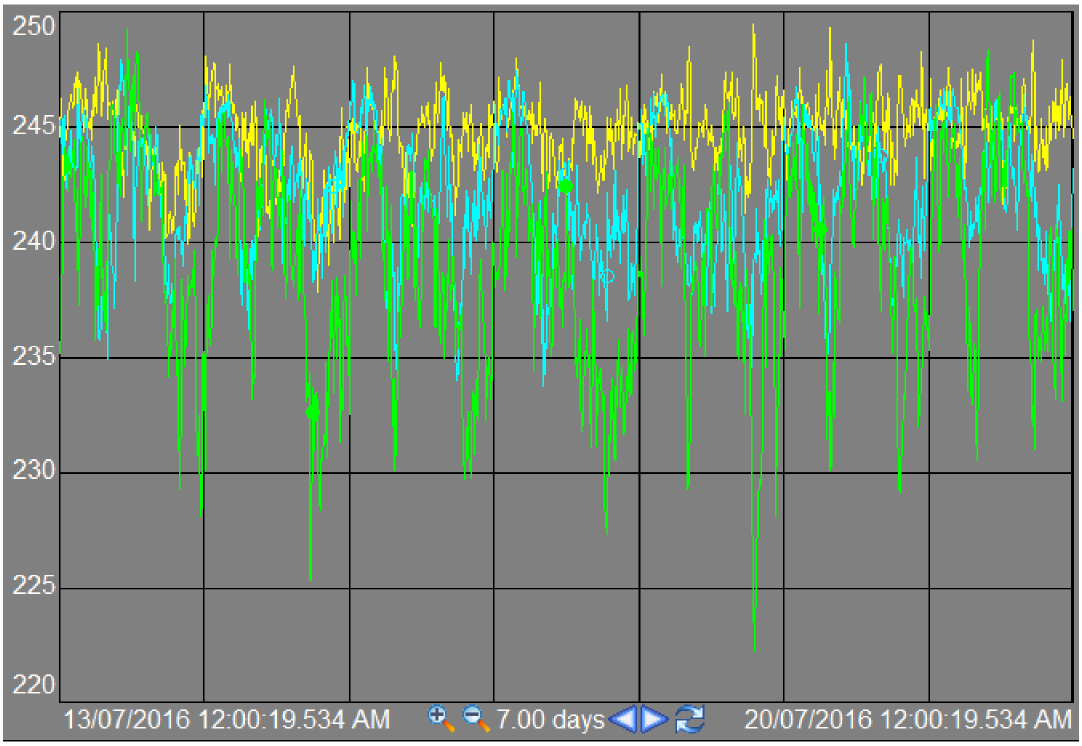

Figure C. 27 - Node 3 Site 2 13/07/2016 – 20/07/2016 by Energex

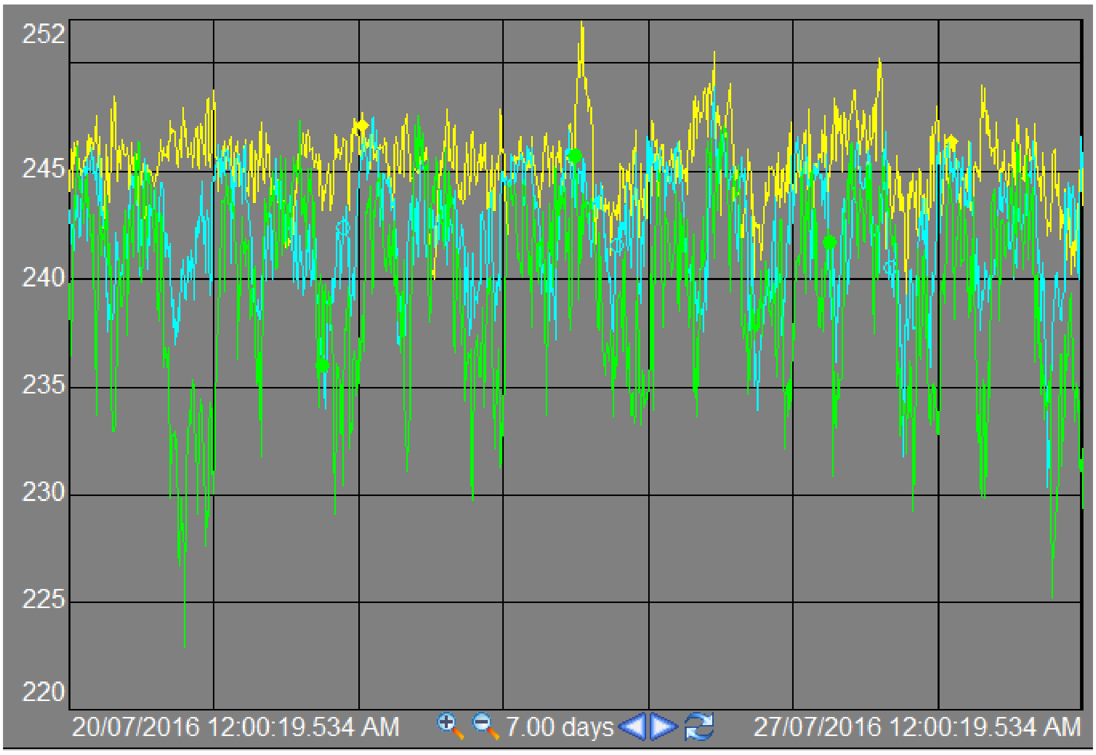

Figure C. 28 - Node 3 Site 2 20/07/2016 – 27/07/2016 by Energex

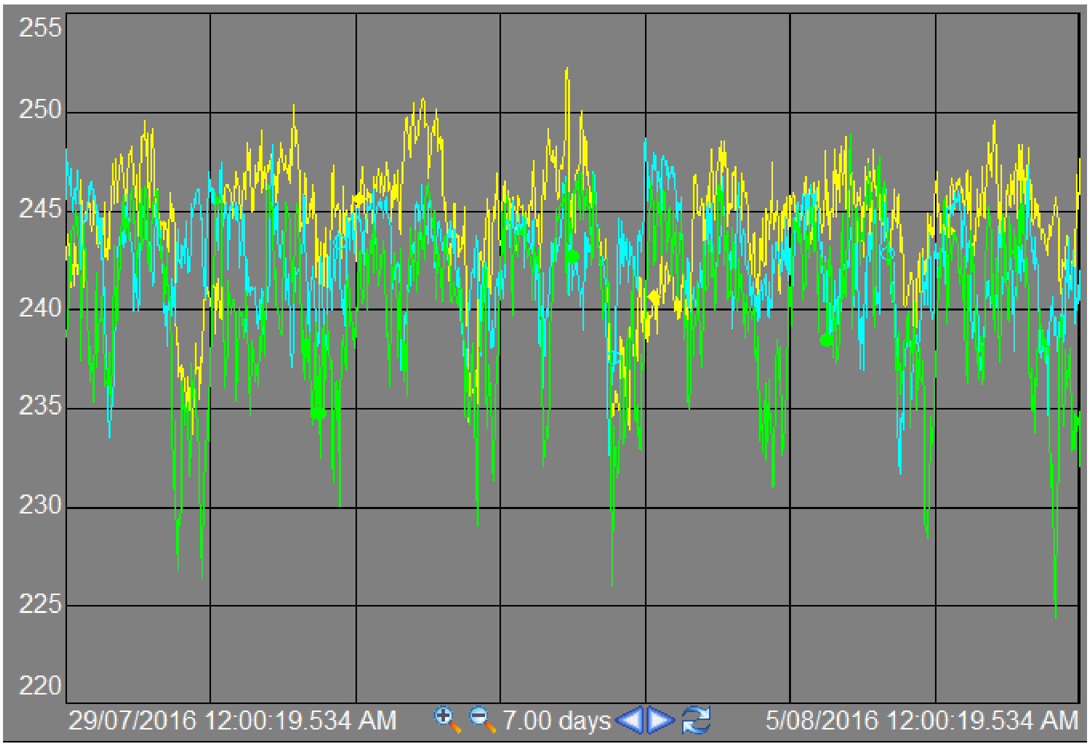

Figure C. 29 - Node 3 Site 2 29/07/2016 – 05/08/2016 by Energex

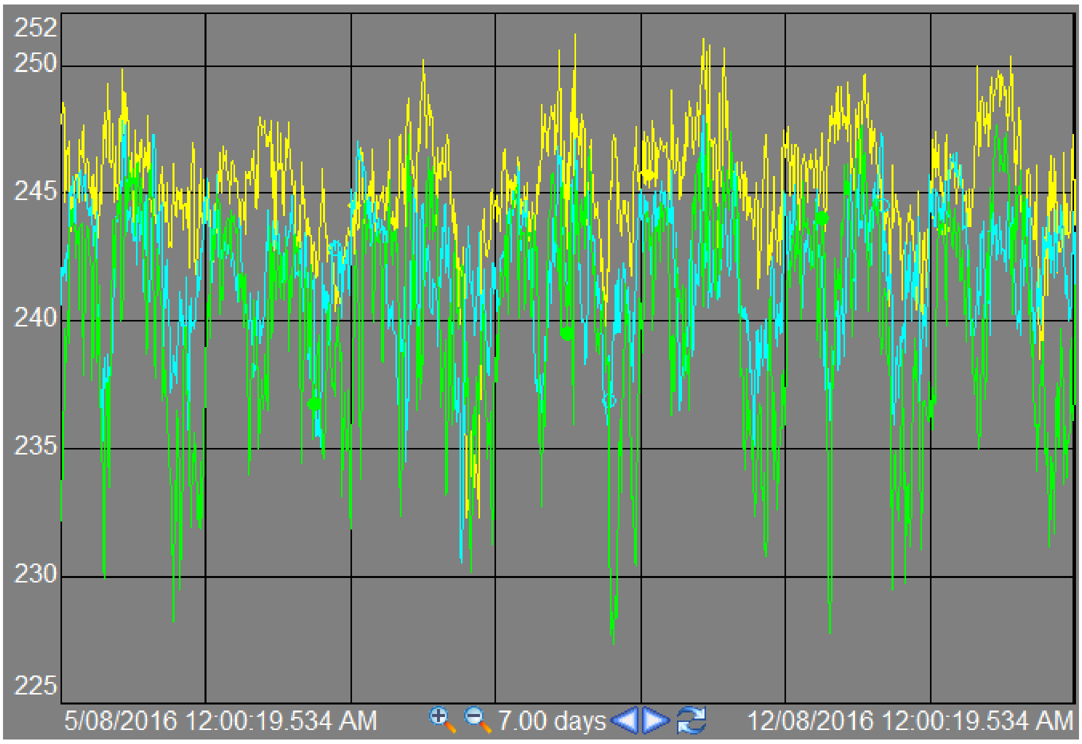

Figure C. 30 - Node 3 Site 2 05/08/2016 – 12/08/2016 by Energex

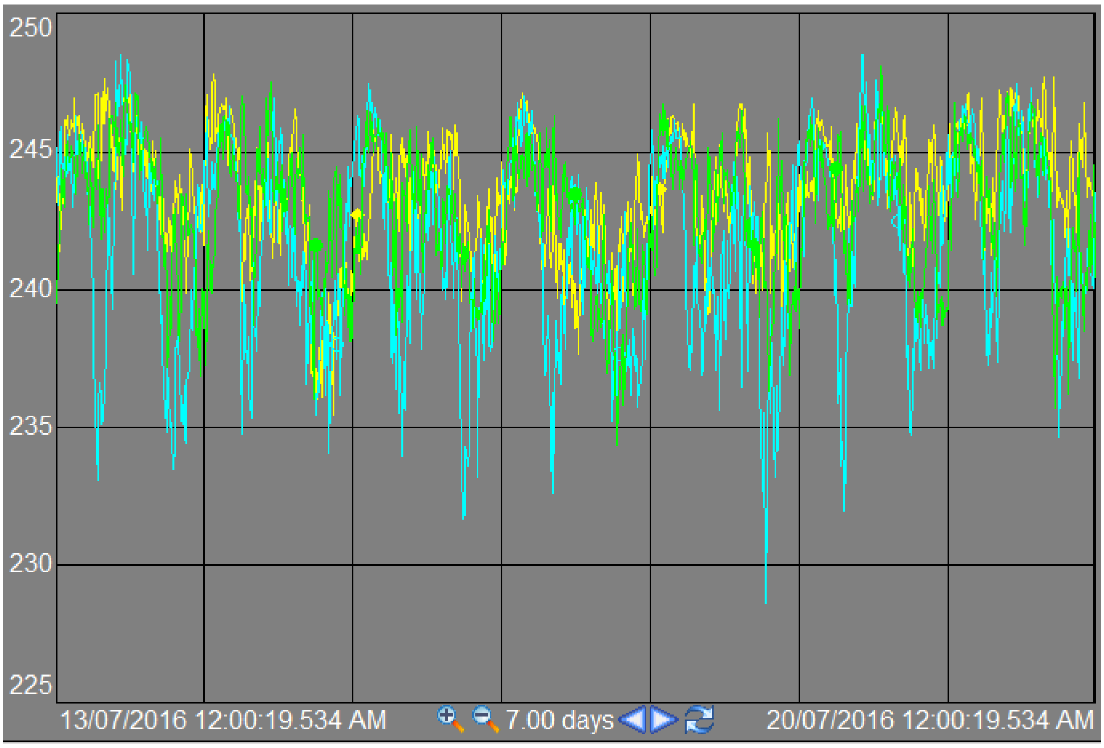

Figure C. 31 - Node 4 Site 2 13/07/2016 – 20/07/2016 by Energex

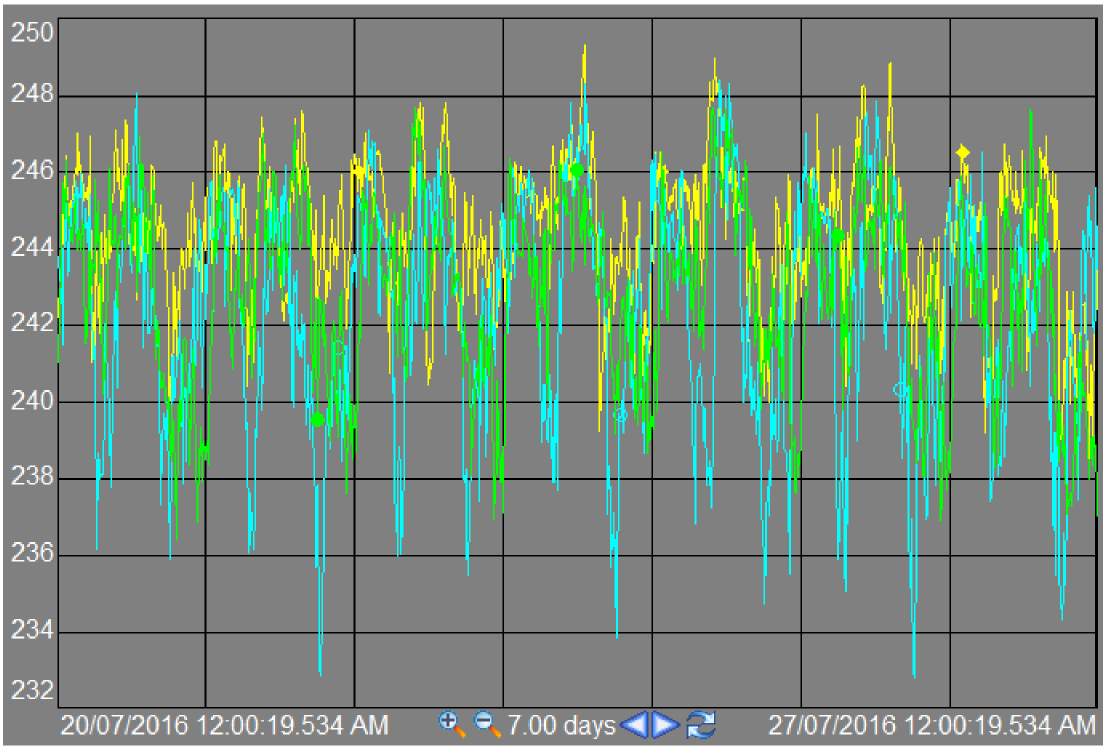

Figure C. 32 - Node 4 Site 2 20/07/2016 – 27/07/2016 by Energex

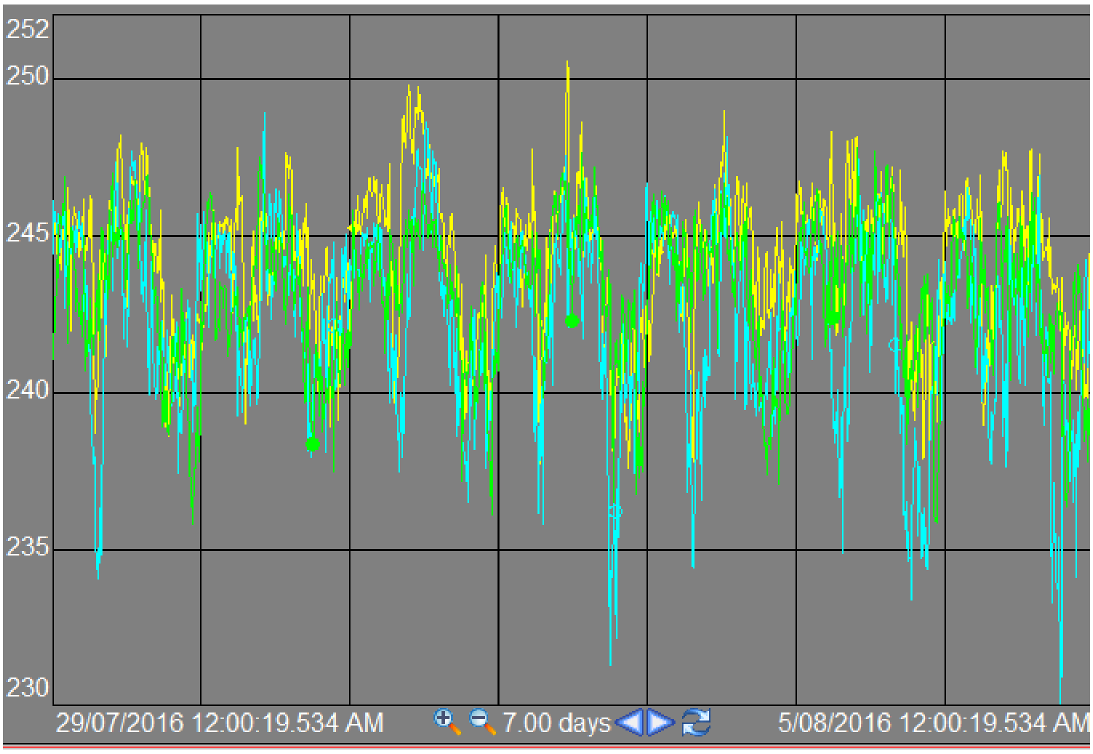

Figure C. 33 - Node 4 Site 2 29/07/2016 – 05/08/2016 by Energex

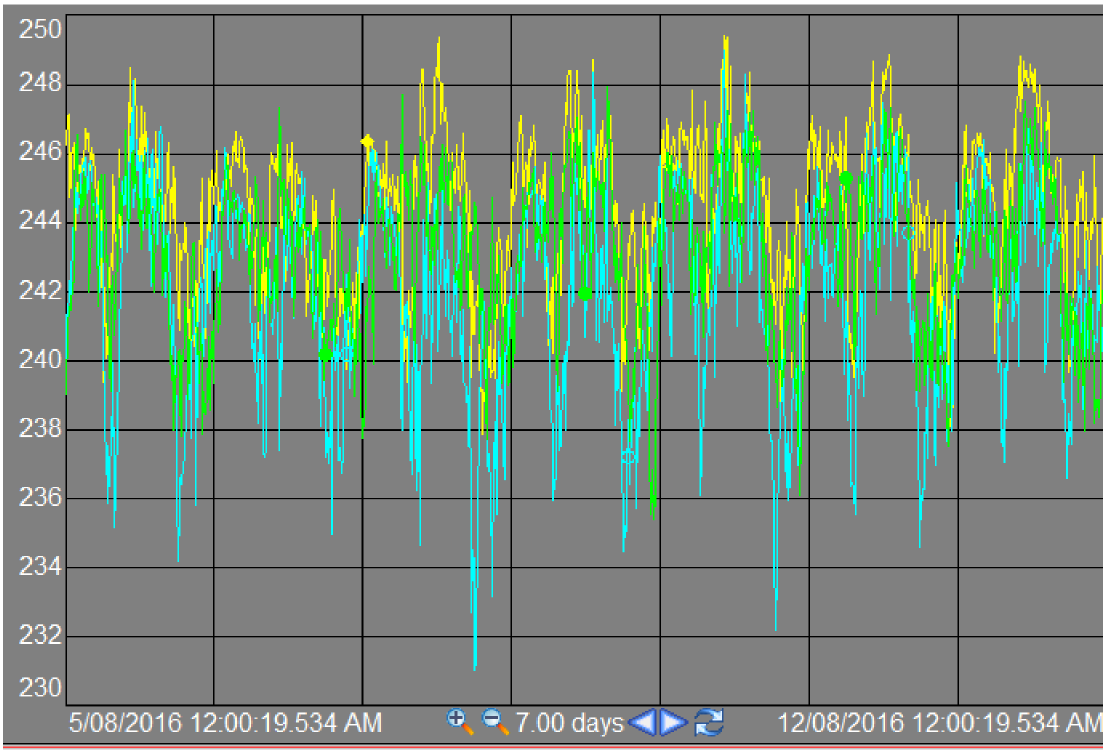

Figure C. 34 - Node 4 Site 2 05/08/2016 – 12/08/2016 by Energex

Appendix D: Risk Assessment

There are risks in everything that we do, however managing risk involves identifying, assessing, controlling, eliminating and minimising the impact of unforeseen events, Loghry, J.D. & Veach, C.B. (2009). A risk assessment is therefore required.

To complete a risk assessment requires understanding the likelihood of something occurring and the consequence of it happening. Using Table D. 1 as the likelihood, Table D. 2 as the consequence and Table D. 3 as the Risk Analysis Matrix, assisted in completing the risk assessment.

Table D. 1 – Likelihood Scale

L Scale Estimated L Likelihood	**Verbal Descriptors** Defined sequence or scenario is the credible combination of events and risk factors / circumstances required to lead to the chosen Consequence (Likelihood estimate must consider the whole scenario including the chosen C)	**Past History / Experience** **[refer to databases and risk registers]**	**Exposure to Risk Factors measured in their effects and exposure time period –** job duration or task time or operational time or lifetime	**Likelihood Estimate can be expressed as a FREQUENCY** per year per climb per hour per km .... **The whole scenario including the chosen C could occur.....**	**Likelihood Estimate can be expressed as a PROBABILITY** 1 in 100 0.01 1 % 1E-02 **The whole scenario including the chosen C could occur.....**
6	**ALMOST CERTAIN** the defined sequence or scenario can and does happen because **ALL** risk events / risk factors are **almost certain** to occur or be present	Whole scenario incl C has been occurring **Almost all the time** in ours or similar organisations / industries	**Extreme EXPOSURE** because **ALL** Risk factors are poorly controlled throughout the **whole** of the time period	**at least daily -** or more often **~ 500 times per year**	**Approx 1 chance in 1 Or very close to every time 100%**
5	**VERY LIKELY** that the defined sequence or scenario can and does happen because **most** risk events / risk factors are **very likely** to occur or be present	Whole scenario incl C has been occuring **very regularly** in ours or similar organisations / industries	**Very high EXPOSURE** because **Most** Risk factors **present** and **not well controlled** during **most** of the time period	as often as **weekly ~ 50 times per year**	**Approx 1 chance in 10 10% of the times**
4	**LIKELY** that the defined sequence or scenario can and does happen because **many** risk events / risk factors are **likely** to occur or be present	Whole scenario incl C has been occurring **regularly** before in ours or similar organisations / industries	**High EXPOSURE** because **many** risk factors **present** but are **only partly controlled** during **much** of the time period	as often as **monthly ~ 10 times per year**	**Approx 1 chance in 100 / 1%**
3	**UNLIKELY** that the defined sequence or scenario can and does happen because **many** risk events / risk factors are **unlikely** to occur or be present	Whole scenario incl C has been occurring **occasionally** before in ours or similar organisations / industries	**Moderate EXPOSURE** because **many** risk factors are **not present** and are **well controlled** during **many** parts of the time period	**as infrequently as once per year**	**Approx 1 chance in 1000**
2	**VERY UNLIKELY** that the sequence can happen because **most** of the risk events / risk factors are **very unlikely** to occur or be present	Whole scenario incl C has been occurring **rarely** in ours or similar organisations / industries	**Low EXPOSURE** because **most** risk factors are **not present** or are **well controlled** during **most** parts of the time period	**as infrequently as once in a 10 years**	**Approx 1 chance in 10 000**
1	**ALMOST NO LIKELIHOOD** that the sequence can and does happen because **almost ALL** of the risk events / risk factors **only** occur or would be present in **exceptional and rare** circumstances	Whole scenario incl C has **almost never** occurred in ours or similar organisations / industries	***Very Low EXPOSURE*** because **ALL** risk factors are **not present** or **ALL** are **well** controlled during **ALL** of the time period	**as infrequently as once in 100 years** or even less	**Approx 1 chance in 100 000 Or even less**

Table D. 2 – Consequence Scale

Nature of Harmful Effects						Response to Harm	
C Scale	Degree of Personal Harm	Examples of Types of Harm	Degree of Non-Fatal Harmful Effects Incapacity Disability Impairment	Duration of Non-Fatal Harmful Effects Discomfort/ Pain/ Disability/ Impairment	Duration of Business Effects Disabling/ Reduced Productivity/ Alternate work/ Lost time	Treatment Required	Required Administrative/ Regulatory Response
6	Multiple Fatalities/ Incurable Fatal Illnesses						
5	Single Fatality/ Incurable Fatal Illness		Irreversible Total				
4	Multiple Serious Injuries/ Illnesses	Quadriplegia/ complete loss of vision/ hearing/ mobility	Irreversible partial >30%	Permanent/ Indefinite/ years	Permanent/ Enduring Approx months	Hospitalisation – In-patient/ long term/ months extensive rehabilitation	
3	Single Serious Injury/ Illness	Amputation/ paralysis of a limb/ severe burns/ loss of vision/ hearing/ mobility loss	Irreversible partial <30%	Long term/ enduring/ days	Long term/ >1 day <1 week	Hospitalisation – In-patient/ short term/days some rehabilitation	External Record & Report Required
2	Minor Injury/ Illness	Cuts/ burns/ strains/ sprains	Reversible partial >30%	Short term/ approx hours	Short term <1 day	Medical/ Outpatient (Doctor)/ limited rehabilitation	
1	Low Level Injury/ Illness	Scratches/ bruises	Reversible partial <30%	Temporary/ approx minutes	Approx minutes	First Aid or less	Internal Record & Report Required

Table D. 3 – Risk Analysis Matrix

		Likelihood					
		1	2	3	4	5	6
Consequence	1	1	2	3	4	5	6
	2	2	4	6	8	10	12
	3	3	6	9	12	15	18
	4	4	8	12	16	20	24
	5	5	10	15	20	25	30
	6	6	12	18	24	30	36

The risks associated for this project were:

If the new IPR was faulty when installed

Likelihood =1, Consequence – 6, Risk Score = 6 (low)

If the project was delayed due to factors outside control, eg, weather

Likelihood =3, Consequence –4, Risk Score = 12 (medium)

Strain from the use of computers for extended periods of time for analysis of data and creating reports.

Likelihood – 3, Consequence – 2, Risk Score = 6 (Low)