Development Of Closed Loop Voltage Control Simulator For Medium Voltage Distribution

N. Z. Dunnett*, A. Maung Than Oo*, T. Gear**

*Faculty of Sciences, Engineering and Health
CQUniversity Australia
**Ergon Energy

***Abstract*— Queensland Distribution Network Service Providers (DNSPs) are required by law to maintain steady state voltages at customer premises within specified limits of currently 240V ± 6%. The utilisation of Automatic Voltage Regulators (AVRs) and distribution transformer Tap Plans have allowed DNSPs to mostly maintain voltages along network feeders within regulatory limits. Two main AVR methods employed for AVRs are a Setpoint bus voltage and Line Drop Compensation (LDC). With a growing influx of the embedded generation, historic voltage management may not be appropriate. This paper presents about the development of a simulator for Closed Loop Voltage Control (CLVC) that utilises real-time data feedback from zone substations and ends of feeders to effectively manage and reduce customer over- and undervoltage issues.**

I. INTRODUCTION

Quality electricity supply is a constantly growing necessity for everyday life in both developed and developing countries. Electrical equipment used today can be sensitive to voltage fluctuations and require electricity utilities to maintain power quality requirements published by regulatory and legislative bodies. Voltage Management is an integral element of Power Quality and it is the role of electricity providers to supply customers with quality electricity.

The main objectives of this project were to:

- Simulate Closed Loop Voltage Control on a distribution network using field-data
- Evaluate the Closed Loop Voltage Control Methodology with current practices at Ergon Energy (A distribution network company based in Queensland, Australia).

The CLVC simulator has been developed to utilise real-time data feedback from zone substations and ends of feeders to more effectively manage voltage regulation and reduce customer over- and undervoltage issues. The results of the simulations have been compared with current practices and recommendations have been made regarding the best voltage management procedures and whether CLVC should be further developed for integration into the network.

At present, AVRs on distribution feeders are configured to respond when the network voltage floats outside of a given band for a given duration. The set point, bandwidth and time delay settings of the Zone Substation AVR are set to maintain the voltage at the bus.

Tap Plans for distribution transformers on feeders are prepared by Distribution Planning. Bucking and boosting the voltages along network feeders on the distribution transformers helps maintain voltage regulation.

DNSPs have utilised LDC to increase the voltages at the Zone Substation during heavy loads and reduce the voltages during light loads. LDC at Zone Substations was not always effective due to:

- Different load profiles on adjoining feeders which can lead voltages to floating outside of regulatory limits on some feeders
- Not knowing the feeder impedances exactly due to multiple emanating feeders, the continuous addition of new loads and feeder augmentations

II. BACKGROUND

A. Voltage Regulation Methodology

A number of contributing factors influence the overall distribution voltage regulation including:

- Zone Substation busbar voltage
- Feeder loads
- Line regulation – dependant on line impedance and load type

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- Transformer regulation – dependant on transformer impedance and load
- Distribution transformer tap settings
- Voltage Unbalance
- LV System characteristics

Ergon Energy is one of many Distribution Network Service Providers who are continually improving voltage management throughout its network. Ergon Energy's Network Monitoring Program involves expanding the number of monitoring devices to over 2000 [1], with the ultimate vision shown in Figure 1.

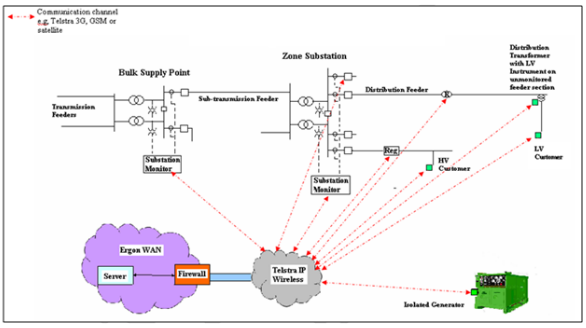

Figure 1 Network Monitoring Overview [1]

Various methods have been utilised for the purpose of maintaining voltage regulation, including:

- Substations placed nearest to load centre
- Capacitors and Reactors
- On Load Tap Changing (OLTC) transformers and voltage regulators
- Distribution transformer Tap Plans

B. Conservation Voltage Reduction

Conservation Voltage Reduction involves reducing feeder voltages to reduce energy consumption. It has been trialled by many utilities and its benefits have been debatable. Voltage reduction would be most effective on constant impedance loads as the power drawn decreases proportionally with the voltage squared.

A Distribution Efficiency Initiative found voltage reduction is largely not practiced due to skepticism, but where it was practiced a 1% reduction in voltage results in, on average, a 0.8% reduction in energy consumption [2].

Kirshner and Giorsetto in reference [3] found that residential energy savings were 0.76% for each 1% reduction in voltage; commercial and industrial loads had reductions of 0.99% and 0.41%, respectively (but the correlations between load class and energy reduction were fairly small).

C. Smart Grids

A Smart Grid is the concept of an optimally operated electric power system that employs communications, control systems and other technologies. The existing grid is 'struggling to keep up' [4] with modern concerns including reliability, efficiency, economy (reliance on power and technology), affordability, security (against potential grid attacks) and environment/climate change.

An array of technologies will be used to implement a Smart Grid, some of which are in place now. The term 'Smart' would mean there is intelligence behind the system that would perform system checks, immediately respond to problems, predict problems that may occur and provide feedback etc. It would need to be interactive with customers and industry alike and allow seamless integration of new technologies such as generators and equipment.

The results from this Dissertation's Closed Loop Voltage Control Simulator are potentially a step toward the Smart Grid.

III. METHODOLOGY

A. Site Selection and Data Acquisition

Boyne Residential 66/11kV (BORE) and Tully 132/22kV (TULLY) Zone Substations (ZSs) were selected for monitoring. These substations are owned by Ergon Energy in Queensland, Australia. The feeders emanating from the substations have different characteristics and load profiles such as Urban, Short Rural and Long Rural. Power Quality (PQ) Meters have been strategically placed at the ends of feeders to acquire one-minute-average phase voltage data for the study.

SCADA was available to collect ZS Secondary Bus Voltages, Total Current and either OLTC Tap Position or Primary Bus Voltages. Ergon Energy provided over one week of field data for both sites which was used in this study as the Raw Data.

Figure 2 gives an overview of the typical distribution network and where the measuring points were located.

B. Defining the Model

Loads of electrical equipment are rated at nominal voltage i.e. 240V. The load, though, can vary with supply voltage in such a way that the load can be modelled as constant impedance, power, current or a mix of all three.

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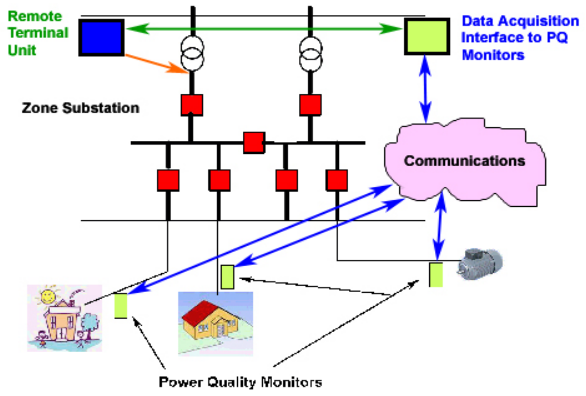

Figure 2 Data Collection Overview

Distribution loads are predominantly constant impedance and power whereas constant current loads are a minority, but can sometimes be used to represent the aggregate behaviour of the two [5]. With the data available, it was assumed that the load is a 50/50 mixture of constant impedance and power and can be modelled as a constant current load, meaning a 1% increase at the substation bus will incur a 1% voltage increase at the feeder end.

A full study of feeder loads would benefit the CLVC application in the future. Despite this assumption, the feedback loops would provide actual system voltages to react upon enabling the controller to calculate the next step.

C. Software Specifications

The software program selected to build the Closed Loop Voltage Control simulator tool was National Instruments (NI) LabView. Other packages would have also produced appropriate simulations for the controller. NI LabView was chosen due to its fast and powerful graphical coding techniques given the time frame to complete the dissertation. NI LabView provides a very flexible environment for handling data.

Importing and integrating the field data with the software was a major component of the dissertation. One-minute-average PQ Meter Voltage Data from field devices was collected in Microsoft Access as part of a Voltage Interval table. 1-minute-average SCADA Bus Voltage/s and Current Data was collected using the Microsoft Excel interface to PI software used by Ergon Energy. SQL Code was developed to compile all data relevant to the simulations into a Comma Separated Values (CSV) text file for utilisation in NI LabView.

Program outputs included graphical and numerical comparisons of Raw Data with the CLVC Data.

D. Program Structure and Settings

Figure 3 shows the program structure of the CLVC Simulator tool. In NI LabView, each file is referred to as a Virtual Instrument (VI), consisting of a Block Diagram containing graphical source code and a Front Panel for the user interface.

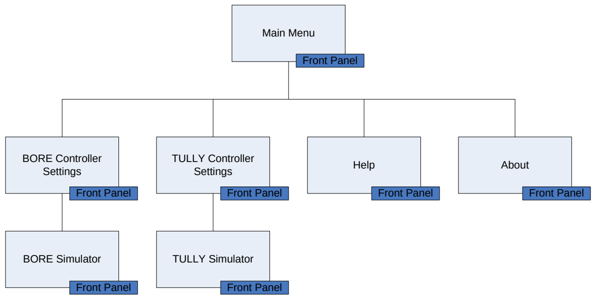

Figure 3 Program Structure

Default controller settings for each Zone Substation included High-, Medium- and Low Voltage (HV, MV, LV) Bases, OLTC Tap Step (1.25%), Low Voltage and First House Protection (FHP) Upper and Lower Limits. The Controller Settings Front Panels allow the user to change specific settings prior to running a simulation.

Low Voltage Limits were 240V +6%/-1%, allowing for a 5% planned LV drop from the distribution transformer to point of supply during heavy load conditions of 5%. FHP Limits were calculated using equipment specifications:

FHP_Upper=PointOfSupplyVmax-DistTxNominalBoost+DistTxTapBuck+DistTxLosses LightLoad
FHPUpper=1.06-0.0434+0.025+0.0074=1.049pu

FHPLower=PointOfSupplyVmin-DistTxNominalBoost+DistTxTapBuck+DistTxLosses HeavyLoad
FHPLower=0.99-0.0434+0.025+0.0296=1.012pu

E. Simulator Operation

The Simulator VIs were configured to operate with a Stacked Sequence Structure with four frames, analogous to movie film. Frame 0 contains all initialisation of variables and items to be displayed on the Front Panel. Frame 1 reads in the stored Controller Settings.

Frame 2 reads in all Raw Data from the site, located in the compiled CSV file, discussed in Section 3.3. For TULLY, the simulator tap is known. For BORE, it is calculated using the following formula.

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Raw Data Tap= (11kV pu-66kV pu)/(Tap Step)

Frame 3 operates the Closed Loop Voltage Control algorithms. For the purpose of rapid results, an Event Structure has been implemented to speed up the simulator and run the one-minute-average data through every millisecond.

On timeout, the following occurs:

1) Raw Data for that minute is read and stored
2) Per unit values are calculated and the current raw tap is found. Maximum and Minimum phase voltages from each PQ Meter are determined and stored.
3) The new collated per unit data is appended using the constant current model if the Simulator Tap differs from the Raw Tap.
4) An array is constructed for each of the possible OLTC transformer taps detailing expected voltages from the model.
5) If **Mode 0 Normal Operation** was chosen, a statistics array is created for each tap scenario. The first check results in a binary 1 or 0 if FHP limits are met or not. Secondly, the percentages of feeder end voltages that are expected to be in-band are calculated. The final check calculates the average deviation from upper and lower LV Limits of 0.99pu and 1.06pu (0 indicates all are in-band).
6) The code now reduces the new statistics array to find a ‘Best Tap’. Once found, the Simulator can perform one action – Tap Up, Tap Down or Do Nothing.
7) The entire process is repeated for each minute-average-data.
8) If **Mode 1 Greenhouse Gas Contribution Savings Operation** was selected, the third check is replaced by the average value of feeder end voltages. This means that the resulting selected tap would meet FHP, have the highest percentage of feeders in-band but with the lowest voltages to initiate Conservation Voltage Reduction.
9) All data can be exported to CSV text files. Graphs are generated to compare values of CLVC results with the original data, including Bus Volts, Tap Position, Feeder End Volts and Histograms.
10) Annual extrapolated savings of kWh, indirect CO_2 emissions and cost for purchased electricity are displayed alongside total minutes sampled and number of tap changes made.

A section of the Front Panel Display is shown in Figure 4.

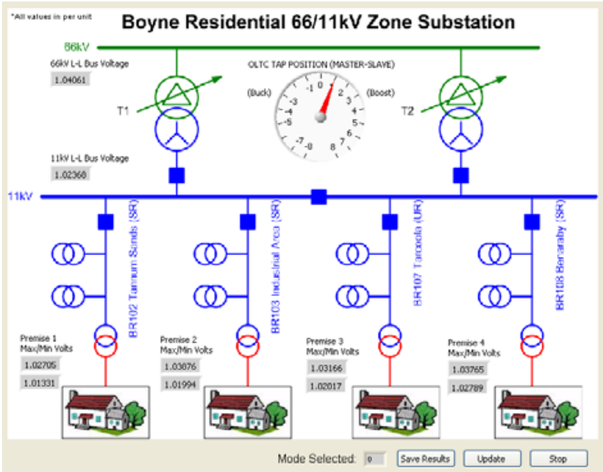

Figure 4 BORE Simulator VI Front Panel Display

IV. RESULTS

A summary of BORE Raw Data and CLVC Mode Results have been provided in Table 1.

Raw Data is the recorded data from the current network using the following AVR settings: Setpoint of 101%, Bandwidth of 1.8%, LDC Off, Time Delay of 30 seconds and Sequentially 10 seconds or minimum time.

TABLE 1 SUMMARY OF BORE RESULTS

Boyne Residential Zone Substation (BORE) Summary of Simulations			
Time Period: 25/04/09 12.54am to 04/05/09 6.30pm			
	Raw	Mode 0	Mode 1
Minutes Sampled	13800	13800	13800
Distribution Mean	245.06	244.97	241.90
Distribution Median	246.96	246.96	244.08
Distribution Skewness	-10.64	-10.66	-10.74
Distribution Standard Deviation	22.35	22.27	22.46
Out of Band Feeders	2.98%	1.27%	0.20%
Tap Change Count	425	70	752
Extrapolated Yearly Tap Changes	16187	2666	28641
Annual Tap Change Decrease	N/A	83.53%	-76.94%
Extrapolated Annual Savings (kWh)	N/A	-11616.7	339813
Annual Greenhouse Gas Savings (t CO2)	N/A	-10.15	296.76
Annual Electricity Cost Savings	N/A	-$1,743	$50,972
Annual Savings	N/A	-0.04%	1.22%

Figures 5 to 7 represent feeder voltage distributions for the different BORE modes in 1-volt interval histograms and cumulative ogives. They highlight the percentage of site voltages within band (0.99pu to 1.06pu) and outside compliance levels.

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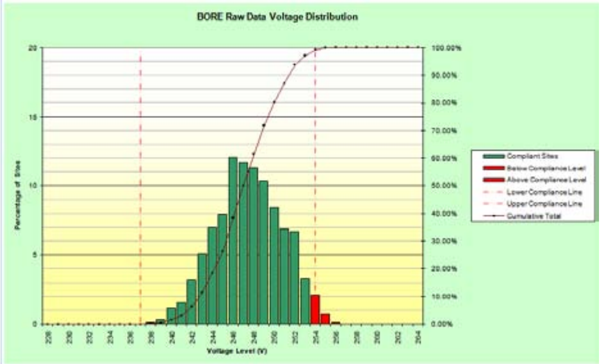

Figure 5 BORE Raw Data Voltage Distribution

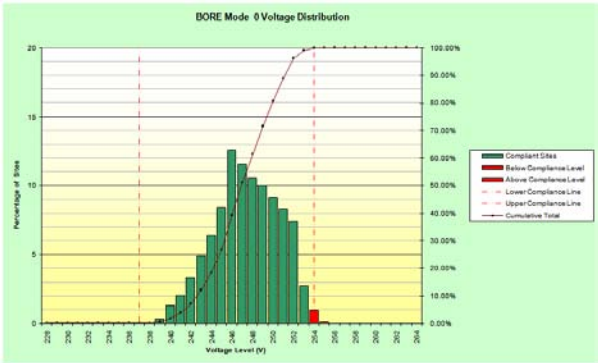

Figure 6 BORE CLVC Mode 0

(Normal Operation) Voltage Distribution

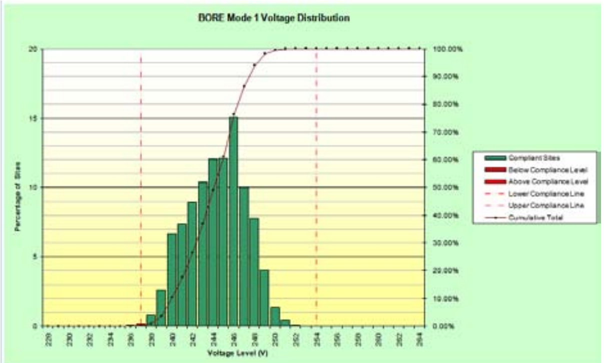

Figure 7 BORE CLVC Mode 1

(Greenhouse Gas Saving) Voltage Distribution

4.1 Feeder Voltage Comparison

From the results, the Raw Data Voltage Distribution has 2.98% of voltages out-of-band. Mode 0 reduced the out-of-band voltages to 1.27%. The voltages have become more tightly compacted which is evident by the decrease of standard deviation from 22.35V to 22.27V.

Mode 1 has further reduced the out-of-band voltages to 0.20%. At the same time the mean has been reduced from 245.06V to 241.9V showing conservation voltage reduction. These results show that CLVC has effectively selected better tap positions in order to control out-of-band voltages.

4.2 Savings Comparison

Mode 1 has contributed to an annual extrapolated savings of 1.22%, $50,972 of purchased electricity and 297 tonnes of indirect CO2 emissions.

The installation of 42 voltage regulators as part of Ergon Energy's Capital Expenditure Plan could be delayed as a result of implementing CLVC. Taking a unit cost of $100,000 and difference between cost to borrow and work of 10%, it is possible to save $420,000 for every year of delay.

It was also calculated that $17445 could be saved by delaying the frequency of Distribution Transformer Tap Plan Reviews from four to six years.

Further studies would be required to price the implementation of a real-world CLVC system, although a positive return on investment is possible over the medium term.

4.3 Maintenance Considerations

Savings of more than 80% of tap changes were apparent with Mode 0. On the other hand, Mode 1 increased the number of operations by almost 80%. If the number of tap changes were halved, the yearly number of Zone Substations requiring maintenance would be halved resulting in potential savings of approximately $52198.

Further studies were performed as part of the dissertation to implement a bandwidth for Mode 1 so that all taps resulting in average voltages less than 1.01 per unit were considered equally viable in the third check. This resulted in a decrease to 0.74% savings but only 5.41% increase in the number of operations compared to the Raw Data.

V. CONCLUSION

The main objectives of the project were met. Not only are voltage management improvements apparent, but also the savings in capital expenditure and indirect greenhouse gas emissions.

The results prove that CLVC has merit and should be considered as an option for future voltage management on Zone Substations, particularly those with different feeder profiles. With the growth of

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communication networks and the broadband era, there is great potential for successful implementation.

Recommendations are to perform a follow-up study, collecting data from a ZS site over the summer peak load period. The CLVC controller should be developed further to include additional metering points along the feeders that could effectively improve methods for Voltage Management. A real-world controller and communications should then be considered.

Overall this research project has provided the authors with a challenging study on Voltage Management, improving knowledge in an area of interest. Successful outcomes with CLVC are possible in the near future and it is believed that this research paper has provided a foundation for further development.

VI. REFERENCES

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