Implementation of Closed Loop Voltage Control for Medium Voltage Distribution

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***Abstract*—Queensland legislation requires Distribution Network Service Providers (DNSPs) maintain a steady state voltage of 240V ± 6% at customer premises. With use of sensitive electronic equipment and embedded generation, traditional voltage management solutions may no longer be appropriate. This paper proposes Closed Loop Voltage Control (CLVC) that utilises real time data feedback from substation Supervisory Control and Data Acquisition (SCADA) and Power Quality (PQ) meters to dynamically set the optimal Zone Substation (ZS) OLTC transformer tap. The algorithm acts to reduce 'out of limits' voltages at PQ meter locations and hence provide tighter voltage regulation at the network extremities. A software GUI was developed to test CLVC on a distribution network in Regional Queensland, Australia. The OLTC transformer was switched to manual mode and tap actions were initiated on SCADA based on real time CLVC.**

Keywords-Voltage Management; Closed Loop Control, Voltage Regulator; Distribution; Power Quality; Conservation Voltage Reduction

I. INTRODUCTION

In [1], Dunnett developed a Closed Loop Voltage Control (CLVC) simulator for Medium Voltage distribution. This steady state voltage regulation method utilises real time network data to effectively manage customer 'out of limits' voltages.

Simulated results with CLVC at Boyne Island (BORE) Zone Substation in regional Queensland found that CLVC could reduce the 'out of limits' voltages from 2.98% to 1.27% and tighten the voltages spread with a decrease in standard deviation of 22.35V to 22.27V. The CLVC concept had merit so a 'proof of concept' trial was initiated.

The objectives of this CLVC investigation were to

- Design and develop a real time Closed Loop Voltage Controller
- Perform a 'real world' CLVC test with a manual AVR override
- Calculate and trial new LDC settings
- Assess the value of CLVC and investigate future implementation issues

A. *Automatic Voltage Regulator*

Current practice is to utilise an OLTC transformer Automatic Voltage Regulator (AVR) for local control of the bus voltage. Setpoint voltage or Line Drop Compensation (LDC) settings on the AVR in conjunction with distribution transformer tap plans ensure that feeder voltages are in limits most of the time.

Referring to Figure 1, the AVR initiates a tap change when the network bus voltage V_B floats outside the voltage bandwidth BW for a given time delay TD. The set point, bandwidth and time delay settings are adjustable.

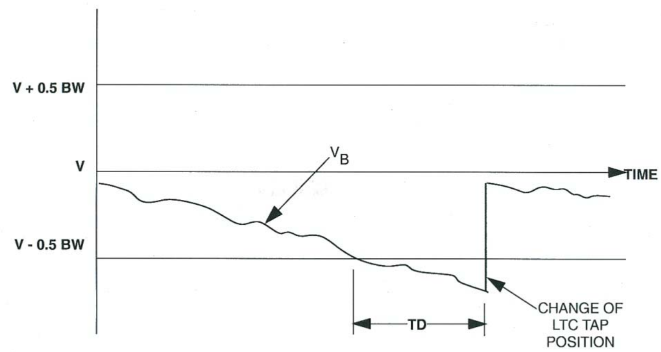

Figure 1. AVR Tap Up Action [2]

B. *Line Drop Compensation*

Line Drop Compensation is an optional AVR setting that, in effect, increases the bus voltage at heavy load and decreases the bus voltage at light load to maintain a consistent voltage at a load centre. It can be difficult to set and maintain accurate LDC settings with load growth and feeder augmentation. LDC is also less effective if there are differing load profiles on adjacent feeders [3].

C. Distribution Tap Plans

Normal distribution transformers have five (or seven) off-load tap settings on the load side as follows:

A	B	C	D	E
-5%	-2.5%	0%	2.5%	5%

The role of distribution planners is to formulate tap plans that determine the optimal fixed taps for parts of the network.

D. PQ Meters

Queensland regional DNSP Ergon Energy has installed EDMI Mk10 Power Quality meters (as shown in Figure 2) at strategic locations on its distribution network. As a guideline, 1 PQ meter is installed in each line section on the same distribution transformer tap. The PQ meters are located on the LV side of pole top and pad mount distribution transformers.

Figure 2. EDMI Mk10. PQ Meter 1821 in the field

PQ meter data is sent to the Ergon Energy Wide Area Network (WAN) over the Telstra IP Wireless network at up to 1 minute average voltages. Ergon Energy configures and schedules PQ meters with 'EziView' software and stores data in SQL databases. A PI Excel tool enables the PQ group to access stored SCADA substation data.

E. Closed Loop Voltage Control

Current voltage regulation practice involves fast acting, automatic, 'closed loop' control with local equipment. By contrast, in Figure 3, CLVC acquires data from PQ meters at strategic locations to set the optimal zone substation tap for the entire network. To complete the loop, a tap signal is sent to the Remote Terminal Unit (RTU).

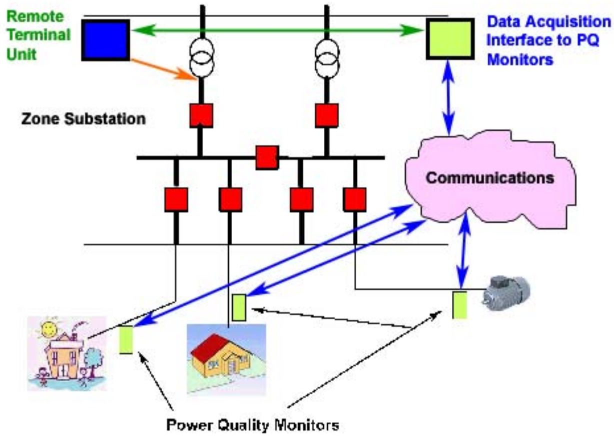

Figure 3. Closed Loop Voltage Control Concept

F. Conservation Voltage Reduction

Conservation Voltage Reduction (CVR) was also tested as part of the CLVC trial. A Voltage Reduction Energy Conservation trial at Ergon Energy [4] found that a reduction of 248V to 228V (8.4%) achieved energy savings of at least 5.3%. Reference [5] states that a Smart Grid that utilises Volt-VAR control or CVR could save 1 to 2% in energy with continual optimisation of the distribution network voltage.

To date, CVR has been considered impractical for its inability to provide tight control and resultant under voltage issues at the network extremities. But substantial energy and indirect Greenhouse Gas savings could be achievable which is becoming more critical as energy costs rise dramatically.

G. Distribution Management System

In the future, DNSPs will migrate to a Distribution Management System (DMS). The DMS will enable utilities to supervise, control, optimise and manage the operation of the distribution networks. In conjunction with Advanced Metering Infrastructure (AMI), the DMS will enable the future electrical 'Smart Grid'. The eventual goal is to integrate CLVC into the DMS software that is rolled out in the near future.

II. CLVC TEST METHOD

A. Site Selection and Data Acquisition

Yeppoon ZS 66/22/11kV (YEPP) zone substation on the central Queensland coast was chosen for the CLVC test for its SCADA visibility, PQ meters and differing feeder load profiles (urban and short rural). The substation is owned and operated by regional DNSP Ergon Energy.

Figure 4. PQ Meters on Yeppoon Distribution Network

The 11kV Yeppoon distribution network in Figure 4 (in blue) had 7 PQ meters installed at strategic locations prior to the CLVC test. Each PQ meter acquired 1 minute average phase A, B and C voltages. SCADA substation data (bus voltage, current, OLTC transformer tap position) was accessible in real time with a PI Excel interface.

B. CLVC Model

The CLVC controller acts to minimise the differences of 'out of limits' voltages from the specified limits, in the shortest possible time. There are a fixed number of outcomes (17 possible taps; 8 buck, 8 boost and neutral) and a predictable relationship between the voltage at the bus and end of the radial feeder.

Distribution electrical loads are predominantly constant power and impedance with a ratio of 60-40 to 40-60 [6]. The CLVC controller assumes that loads are, on average, 50-50 and can hence be modelled as constant current e.g. a 1% bus voltage increase corresponds to a 1% end of the feeder voltage increase.

For each tap CLVC calculates: (1) Binary values to indicate if a tap complies with First House Protection (FHP) limits, (2) Predicted voltages at PQ meter sites then the proportion of PQ meter sites within CLVC limits, (3) Sum of differences of 'out of limits' voltages from CLVC limits and (4) Preferred OLTC transformer tap and 1 resultant tap action (up, down or no change)

C. Software Specifications

National Instruments (NI) LabVIEW software was utilised to develop a Closed Loop Voltage Controller to perform a 'real world' test. The CLVC simulator provided in [1] was utilised as a basis for this work with kind permission of the author.

An intuitive Graphical User Interface in Figure 5 was developed for the Controllers to observe the network and run CLVC. The GUI has indicator lights for bus variation warnings, 'up to date' data and tap lock. Network data is updated on the panel in real time and a tap dial and traffic light indicate tap actions.

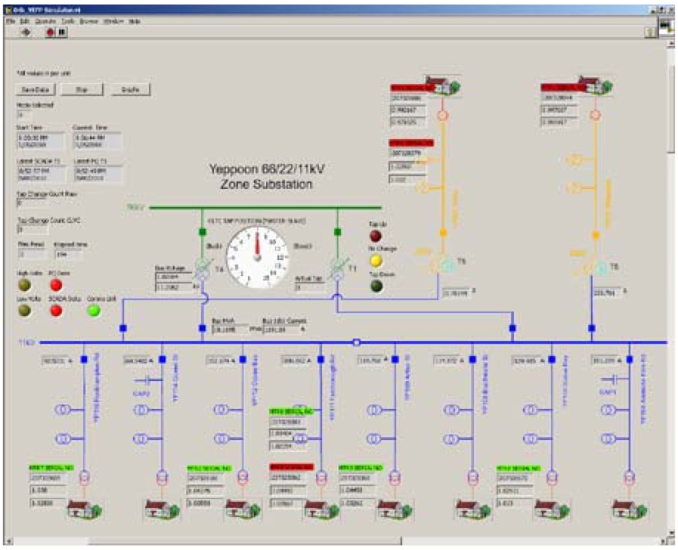

Figure 5. Closed Loop Voltage Control Front Panel

D. CLVC Settings

The default CLVC settings were:
HV Base = 11kV
LV Base = 240V
Tap Step = 1.25%
First House Protection (FHP) limits were found:
FHP Upper Limit = PointOfSupplyVmax - DistTxNominalBoost + DistTxTapBuck + DistTxLossesLightLoad = 1.06 - 0.0434 + 0.025 + 0.0074 = 1.049pu
FHP Lower Limit = PointOfSupplyVmin - DistTxNominalBoost + DistTxTapBuck + DistTxLossesHeavyLoad = 0.99 - 0.0434 + 0.025 + 0.0296 = 1.012pu

The adjustable CLVC regulation limits were set to 240V and 252V i.e. +5%. This allows for up to 5% voltage drop in the Low Voltage (LV) network from the PQ meter to the customer. These limits are 1% tighter than legislation to allow for minor excursions prior to CLVC correction.

For reference, the AVR settings at the zone substation OLTC transformer were:
Setpoint - 1.01pu
Bandwidth - 1.8%
LDC – Off
Time Delay – Initial 30s, Subsequent 10s or min

E. CLVC Source Code

The LabVIEW CLVC graphical source code consists of a Stacked Sequence of structures. Code was written to poll the SQL PQ and local SCADA servers each second. Updated data was then written to Comma Separated Values (CSV) text files in a defined format and file location.

In each CLVC iteration, the code waits and checks for a new CSV text file. The latest data is read from file and stored to defined variables in the code. Next, voltages at all PQ meter sites were predicted for each possible tap using a constant current model. Statistics were then calculated and stored in TABLE I.

TABLE I. INITIAL TAP SELECTION STATISTICS ARRAY

Stats

8	1	1	0
9	1	0.7	0.00128335
10	0	0.3	0.00812086
11	0	0	0.0190959
12	0	0	0.0315959
13	0	0	0.0440959
14	0	0	0.0565959
15	0	0	0.0690959
7	1	1	0
6	1	0.7	0.001525
5	0	0.3	0.00718751
4	0	0	0.0184042
3	0	0	0.0309042
2	0	0	0.0434042
1	0	0	0.0559042

In TABLE I, column 1 lists all taps, columns 2 stores a 1 or 0 to indicate if voltages are within FTP limits, column 3 lists the proportion of PQ meters sites inside CLVC limits and column 4 lists the sum of differences of 'out of limits' voltages from the CLVC regulation limits.

The CLVC tap selection algorithm eliminates taps in the statistics table until the optimal tap is left. Step (1) deletes taps with a 0 in column 2, step (2) deletes taps without the highest value in column 3 and step (3) deletes taps without the lowest value in column 4.

F. CLVC Test

The CLVC tests were performed in the Ergon Energy Southern Control Room in Rockhampton, Australia. The YEPP ZS 66/11kV OLTC transformer was switched to manual mode with SCADA. A separate PC ran CLVC in real time data on the corporate server. The CLVC GUI directed the trained Network controllers to initiate tap actions as required in substation SCADA.

A buzzer and traffic light on the GUI indicated when a CLVC tap action up (top red), down (bottom green) or do nothing (middle yellow) should occur. Yellow warning lights also alerted the controller to a loss of data, 'out of limits' voltages and drastic bus value variation.

After an actual or proposed tap change, the tap locked until all PQ meter and SCADA values in the CLVC algorithm updated. A 180 second wait occurred after each tap change to allow the average voltage data to update and stabilise. With looser regulation, overshoot and excessive tap changes were avoided.

G. Test Results

The online CLVC tests were conducted in Mid April 2010 on the Yeppoon 11kV distribution network in regional Queensland. PQ meters on the 240V LV network prior to line regulators were included in the CLVC algorithm (total of 5). Voltages at these sites are affected if a tap change occurred at the bus.

Normal baseline data without CLVC was collected for 5 similar evenings in the previous week. The tests occurred with evening peak load (from 3:15PM to 10:15PM) to coincide with control room shifts. The CLVC results are outlined in TABLE II.

TABLE II. YEPPOON ZS (YEPP) DATA FOR VALID CLVC PQ METER SITES

	Normal Data	CLVC Test Data
Test Minutes	2140	428
Mean	244.16	246.05
Median	245.67	247.6
Skewness[a]	-0.61	-0.53
Standard Deviation	5.11	4.54
Out of Limits -Statutory	0.60%	0.00%
Out of Limits - CLVC	21.01%	17.88%
Tap Change Count	38	22

a. Pearson mode skewness γ is defined in (1)

$$\gamma = \frac{\mu - \bar{x}}{\rho} \quad (1)$$

The charts in Figure 6 and 7 represent the collated PQ meter voltages in 1 Volt histograms and cumulative ogives for normal and CLVC operation.

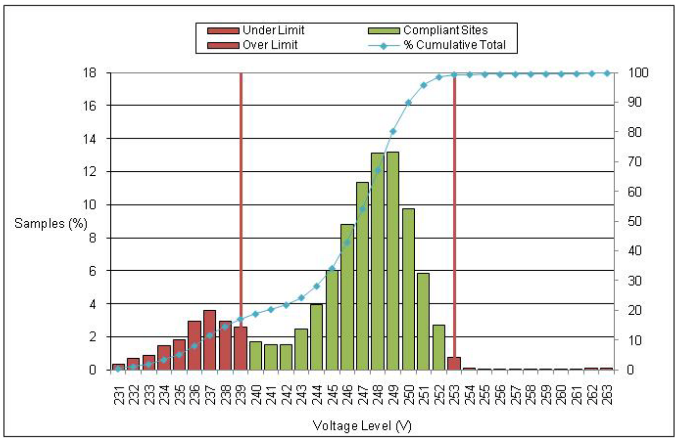

Figure 6. Voltage Distribution of CLVC PQ Meter Sites with ZS AVR and Setpoint

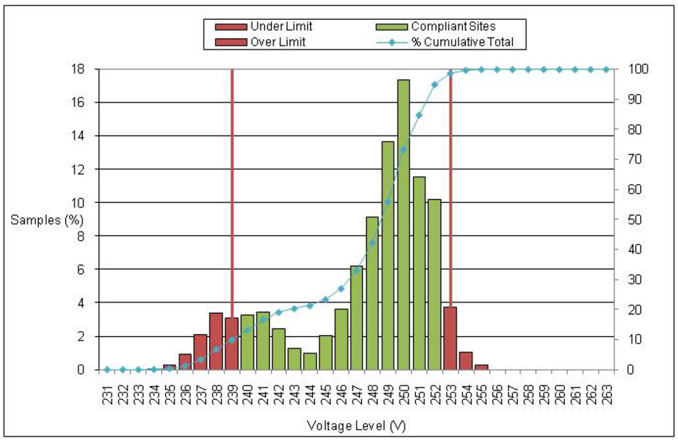

Figure 7. Voltage Distribution of CLVC PQ Meter Sites with Closed Loop Voltage Controller

In the CLVC test, the voltages were, on average, closer to the top end of the band. 1 of the 5 PQ meters had consistent under voltages as it was just downstream of an out of service line voltage regulator. CLVC acted to correct this meter (2.9% to 17.0% within CLVC limits) without significant over voltages at the other strong PQ meter sites.

From the results, CLVC reduced the 'out of limit' voltages at PQ meter sites from 21.01% to 17.88% (3.19% improvement). CLVC also eliminated all voltages outside of statutory limits. It is evident from the histograms that the mean voltage increased from 244.16V to 246.05V. The standard deviation with CLVC was fell from 5.11 to 4.54 which indicates tighter voltage distribution at the PQ meter sites.

A graph of bus voltage variation and current in Figure 8 did not find a conclusive trend for a LDC setting. The CLVC algorithm was restricted by PQ meters with consistent voltages at both ends of the bandwidth. Also there was little bus voltage variation in the test period with light network load in April.

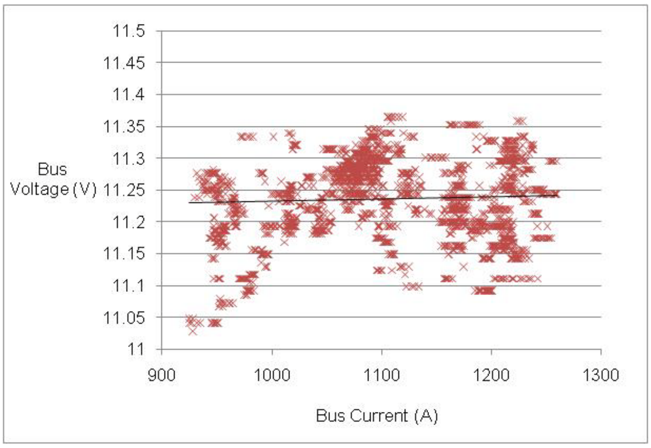

Figure 8. Potential LDC Setting

H. CVR Test

Conservation Voltage Reduction (CVR) was configured to select the lowest tap that still results in the highest number of PQ meter values in limits. The CLVC Greenhouse Gas Savings mode as its final step (3), selects the tap with the lowest average phase voltage. The CLVC CVR mode results are outlined in TABLE III.

TABLE III. YEPPOON ZS (YEPP) DATA FOR VALID CLVC PQ METER SITES (CVR MODE)

	Normal Data	CLVC Test Data
Test Minutes	2140	428
Mean	246.31	246.07
Median	246.44	246.21
Skewness*	-0.36	-0.17
Standard Deviation	2.73	2.10
Out of Limits -Statutory	0.75%	0.00%
Out of Limits - CLVC	2.00%	0.45%
Tap Change Count	38	5

For this CVR trial, the line voltage regulator prior to the undervoltage PQ meter was fixed. Therefore it needed to be excluded from the CLVC algorithm. The CVR results indicate that a reduction of 1.5% in 'out of limits' voltages was still possible with a lower average network CLVC voltage.

In the CVR test, the mean fell and the skewness indicated voltage spread closer to the lower end of the bandwidth. With CVR mode there were also no voltages outside of statutory limits. If CVR is validated for distribution networks, then significant kWh and indirect Greenhouse Gas savings are achievable with CLVC.

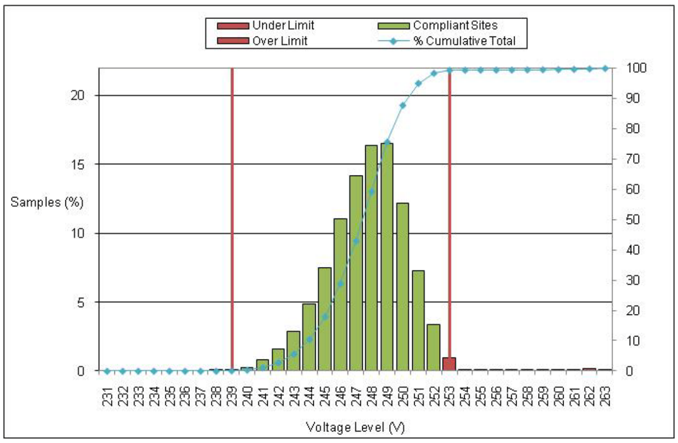

Figure 9. Voltage Distribution of CLVC PQ Meter Sites with ZS AVR and Setpoint

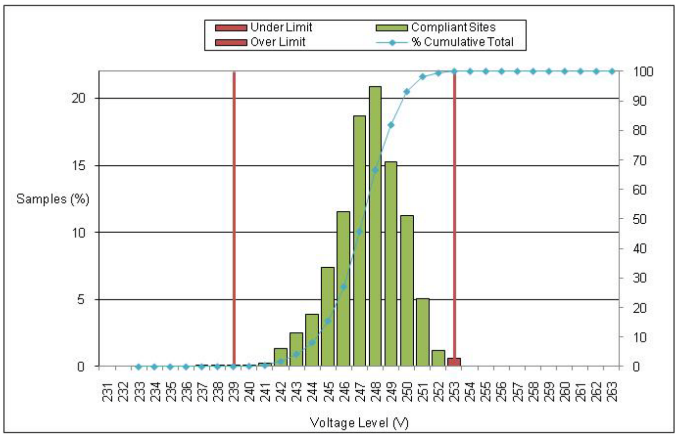

Figure 10. Voltage Distribution of CLVC PQ Meter Sites with Closed Loop Voltage Controller (CVR Mode)

I. Future Work

It should be noted that it is unviable to run CLVC PQ meters as a SCADA polling unit due to data restrictions on a public carrier. The future plan is to use voltage thresholds on PQ meters to trigger a CLVC calculation. The CLVC algorithm would run until a stable 'no tap change' state is output. CLVC could then go into 'sleep mode' until another trigger event.

A single OLTC AVR set point at the zone substation still provides limited control. It is proposed that future CLVC algorithms will incorporate SCADA control of taps on line voltage regulators.

Network switching occurs to transfer load in contingency events. With CLVC, the network hierarchy must be verified to ensure that PQ meters report to the correct substation. The future DMS will store a built in, real time, network model.

Ergon Energy also plans to install AMI at customers' premises as a strategic investment in the electrical 'Smart Grid'. Selected PQ meters could be configured to report direct to CLVC.

The next step is to test CLVC on a worse network in a peak load period with greater voltage fluctuation. Based on the tests, LDC settings limits will be found and verified. An IT solution will be developed to run a network with automatic CLVC override based on PQ meter trigger limits.

III. CONCLUSION

Compared with traditional bus set point and LDC AVR regimes, the CLVC concept has significant merit. Voltage regulation improvements were realised in a practical context. Also for the first time, Network Controllers were able to refer to PQ meter data in real time on a GUI.

CLVC could therefore be a part of the future 'Smart Grid' toolbox. With the expansion of high speed data networks and the DMS, CLVC is a viable option for future zone substation bus voltage regulation.

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