A Comparison of AdaptiVolt™ and Line Drop Compensation Conservation Voltage Regulation Implementation Methodologies

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1. Conservation Voltage Regulation

Conservation Voltage Regulation (CVR) sometimes called Conservation Voltage Reduction is the long term practice of controlling distribution voltage levels in the lower range of American National Standards Institute (ANSI) standard C84.1 – 1995 "Electrical Power Systems and Equipment – Voltage Ratings" or Canadian Standards Association (CSA) standard CAN3-C235-83 "Preferred Voltage Levels for AC Systems, 0 to 50 000V" acceptable levels in order to reduce demand and energy consumption.

1.1 CVR History

In 1980s electric utilities began studying the effect of voltage reduction on energy usage on distribution feeders. In 1981 EPRI commissioned the University of Texas at Arlington to test and study the effects of reduced voltage on the efficiency of important power system loads [1]. That study included such utilization devices as television sets, microwave ovens, motors, heat pumps, air conditioners, distribution transformers, resistance heating devices as well as others. Also in 1982 the Environmental Defense Fund (EDF) published an article discussing the efficacy of CVR as an energy conservation method [2].

In 1985 the Northwest Power Planning Council (now the Northwest Power and Conservation Council) (NWPCC) mentioned CVR and called for assessment of loss reduction through reduced voltage. In 1987 Bonneville Power Administration (BPA) commissioned Pacific Northwest National Laboratory (PNNL) to assess CVR applicable in the BPA service area0. The assessment concluded that CVR was an effective energy conservation measure and that that potential conservation available in the BPA service territory was up to 270 average Mw or 2.37×10^6 MWh/year[3].

In 1988-90 Snohomish PUD conducted a pilot study of CVR on 12 distribution feeders. The results of the study confirmed significant energy conservation on those feeders[4]. (Snohomish PUD has since implemented CVR on all of its distribution feeders.) In 1990 BC Hydro launched a program which included load to voltage dependency studies at a substation on Vancouver Island. The tests showed a significant reduction on both load (kW) and reactive power (kVAR.) [5]

With the California Energy Crisis in 2000-01 interest in CVR as a long term conservation and demand reduction measure gained impetus. In 2002, the author's company fielded its first automated CVR system projects at Inland Power and Light Company. That project showed significant energy conservation and demand reduction along with significant kvar reduction.

In 2004 the Northwest Energy Efficiency Alliance (NEEA) began a major study on the effects of CVR. Known as the NEEA Distribution Efficiency Initiative (DEI) Study, several Pacific Northwest utilities undertook CVR projects utilizing several different methods of accomplishing CVR. That study showed significant energy conservation available by implementing CVR. Additionally it showed very significant kVAR reduction when CVR is implemented. The final report was issued in December, 2007 [6].

In 2005 Hydro Quebec implemented a CVR pilot project to study the effect of controlled voltage reduction [7].

In 2009 the NWPCC identified over 400 average MW of conservation available using CVR or voltage optimization in its "6th Northwest Power Plan" [8].

With the advent of "smart grid" initiatives the term Volt/VAR optimization (VVO) has come into common use. VVO is the operation of a distribution system with automatic coordinated operation of voltage regulation devices and switched capacitor banks with the goal of minimizing lagging kVAR and controlling distribution voltage levels to some "optimum" point to reach a utilities optimal goal. The goal can vary from utility to utility and can be to reduce peak demand, implement CVR, minimize distribution system losses or even in some cases to increase load.

Until the advent of AdaptiVolt™ and other "smart grid" VVO systems, the only way to implement CVR was to use a technique called Line Drop Compensation (LDC).

2. AdaptiVolt™

AdaptiVolt™ is a "smart grid" technology which utilizes measured "real time" feedback from the remote ends of distribution feeders (in a patented configuration). The central or distributed AdaptiVolt™ core uses patented algorithms and design to determine capacitor bank switch positions regulator and/or LTC tap positions which are then set to meet the current operational requirements or goals of the electric utility operators.

3. Line Drop Compensation

Almost all regulator controllers and on-load tap-changer transformer (LTC) controllers in use today have the ability to implement LDC. When implementing LDC the controllers use an internal "model" to represent the physical characteristics of a distribution feeder or several feeders fed by the same substation bus. The "model" consists of two (2) settings that can be entered or adjusted in the controller. Those two (2) settings are the X setting and the R setting. Those settings represent the impedance of the feeder or system of feeders being fed by the regulator or LTC. Then based upon the current or load, the voltage set-point at the regulator or LTC output (or bus) is computed so that at a point distant in the system is held at a constant voltage. The controller then adjusts tap position to hold the output voltage at the set point.

When using LDC to implement CVR the distant voltage point is selected so that customer delivery voltages at the "electrically" distant points of the feeder or system of feeders is in the low end of ANSI or CAN voltages but does not go below minimum acceptable levels.

The regulator and LTC controls also have two other basic adjustments that will be discussed later in this white paper, those being the Time Delay setting and the Bandwidth or Deadband setting.

4. LDC versus AdaptiVolt™ based CVR

There are several major differences between LDC based CVR and AdaptiVolt™ CVR implementation.

4.1 Open-Loop operation versus Closed-Loop Feedback Operation

The most significant difference between the AdaptiVolt™ implementations of CVR and LDC implementation is that LDC is an open-loop system with respect to the distribution feeders and tap changes are made based upon current load and voltage as measured at the transformer or regulator. A "model" of the distribution system is set using the X (reactive component of the distribution system) and R (resistive component of the distribution system) parameters. The X and R settings are used to by the controller to compute the assumed voltages at the end of the line and the voltage set point settings are adjusted based upon the computation. The controller then operates the tap changer based upon the adjusted assumed voltages.

An AdaptiVolt™ system measures the actual end-of-line voltage in "real-time" and feeds that data to the controller which then makes tap changes based on actual measured voltages.

*Note: Although some would argue that AdaptiVolt™ and LDC are both in fact closed loop control schemes; their performance in practical situations differs significantly due to one salient **difference**. In AdaptiVolt™ the controlled variable (end-of-line voltage) is sensed; in LDC, it is modeled. A glaring limitation in the LDC approach to remote voltage modeling is that there is no mechanism for verification of the model estimates, thus motivating the application of generous safety margins on voltage set points and thereby limiting the conservation performance. The AdaptiVolt™ system can readily accommodate additional voltage sensing points if required by structural changes in the feeders originating from the subject control element, such that optimal performance can be maintained. By contrast, the LDC designer must select R and X on the basis of some compromise, for example, between expected loading on "major" branches and worst case impedance of long branches, as discussed in the next section of this white paper.*

4.2 Distribution System "Models"

Because AdaptiVolt™ uses measured "real time" end of line voltages modeling the distribution feeder or feeders is not required to implement CVR with it.

Determining X and R settings that correctly "model" the distribution system is an intensive exercise in distribution engineering that still yields only an approximation of the distribution system characteristics. Very simplistically, LDC is trying to consolidate all of the characteristics of a system as complex as an electrical distribution feeder and all of the characteristics of the loads and usage patterns of customers into two unchanging values – X and R.

Even the most simple distribution feeder will have several branches that have varying types of loads; residential, commercial and/or industrial. These loads are located at varying locations along the feeder and its branches. The individual loads also vary depending upon time of day, day of the week or year, temperature, humidity and other causations. Multiple feeders supplied by a single LTC which have different loads also complicate the issue. Changes in loads on different feeders, branches and at particular customers will change the "model" of the system and require changes in the X and R settings at the regulator or LTC control. New construction by customers, the addition of new facilities and new loads, changing patterns of customer electrical usage and distribution line reconfiguration all require "model" changes.

4.2.1 Computerized Models

There are several computer based distribution feeder modeling programs that can be used to determine the "model" so X and R settings can be computed with less engineering computation effort. Before the X and R settings are computed, data regarding the physical distribution system such as conductor sizing, phasing, underground or overhead, distances of conductor, capacitor locations, etc. is required for entry in the computer program. Assumptions must be made regarding loads, load distribution, and customer utilization patterns. <u>Assumptions must be as accurate as possible for results to be accurate.</u>

Among the most important assumptions are the percentages of load types at different locations on the feeder(s). Typically the loads are assumed to be constant energy, constant impedance (Z%) loads, constant current (I%) loads or constant power (P%) loads. That is when input voltage is varied, those types of loads remain constant. This is commonly referred to as the "ZIP" model.

The last assumption, that of constant power or P% loads, presents a very serious error in the accuracy of the model based systems and the output results of the model, that is the X setting and the R setting. The basis of the assumption of P% loads is that electric motors are basically P% loads. In North America approximately 25% of residential load consists of electric motor load. Commercial and industrial electrical motor load is a much larger percentage.

The fact is that research done by EPRI and PNNL has shown that motor input power is not constant when motor terminal voltage is varied, even if the output is constant. This is because when motors are operating at less than 100% of their rated output HP (the vast majority of motors operate at less than rated HP) motor efficiency improves as motor terminal voltage is lowered within ANSI and CAN standard levels. Data collected on AdaptiVolt™ systems that are 100% electric motor load also show that motors are <u>**not**</u> P% loads. Therefore the values of X and R computed using these computer models have error built in before taking into account load characteristics and usage patterns.

4.3 Voltage Set points and Voltage spreads

Voltage set points in LDC systems are generally set more conservatively to insure ANSI and CAN standard voltage levels are not exceeded either on the high end or on the low end. The low settings would be set higher and the high settings would be set lower than required with AdaptiVolt™ systems. This is because LDC based systems are estimating or computing end-of-line voltages for control rather than measuring the actual voltage.

This results in wider potential voltage spreads with which in turn result in less energy conserved and less demand reduction with an LDC system than could be obtained with an AdaptiVolt™ system.

4.4 Bandwidth or Deadband

The amount of potential energy conservation depends upon the bandwidths around the voltage set points. The smaller the necessary bandwidth, the lower the voltage set point can be. The lower the voltage set point the higher the energy conservation and demand reduction potentials.

Bandwidth is the difference between the upper and lower acceptable voltage around the voltage set point. Empirical experience over many years by utilities and manufacturers has led to the recommended minimum bandwidth setting of no less than the equivalent of one tap position above and one tap position below the set point. (Failure to observe this minimum bandwidth leads to excessive tap change operations and to premature tap changer failure.) This means that usually bandwidth is at least two times the step voltage and is symmetrical above and below the voltage set point. Most distribution engineers set the bandwidth higher than the minimum to minimize tap changer wear. Setting of 2, 2.5 or 3 volts on a 120 volt basis are commonly used. These recommendations do not change regardless whether LDC is being implemented or not.

When applying AdaptiVolt™ systems, a tap inhibit dead band of ±0.35 basis volts beyond the tap changer step size is adequate to prevent excess tap operations under automatic voltage control conditions. Since the applicable tap changer step size at Port Angeles is 0.75 basis volts, a tap inhibit dead band of ±1.10 volts or 2.2 volts around the target or nominal end-of-line voltage would be recommended.

4.5 Tap Changer Operations

The life of tap changer contacts and mechanism depends almost exclusively upon the number of tap change operations (except mechanical defects which can cause premature failure). When tap changes are controlled conventionally, either with or without LDC, the number of tap changes that occur (assuming the same upstream voltage profile) depends upon the Bandwidth and the Time Delay settings (how long the voltage must be "out of band" before the regulator control initiates a tap change.) One Pacific Northwest utility reports that with the existing tap changer control settings the average number of tap change operations is between 800 and 1000 operations per month.

Experience has shown that the number of tap change operations using an AdaptiVolt™ system has ranged between 10 and 25 per day. The lower range of tap-changer operations has been found when the transmission system voltages are more stable (in Ontario, for example, which has a very strong transmission grid). The highest range of tap changer operations was found on a small isolated system (Kauai Island Utility Cooperative) with transmission voltages levels which vary more significantly than levels do on strong transmission grids.

As the number of tap change operations in an LDC system depends upon the bandwidth and the time delay settings, if those settings remain the same as the way they are currently set the number of tap operations should be expected to remain essentially unchanged. If an attempt is made to reduce the bandwidth or time delay to increase conservation, the number of tap changer operations should be expected to increase from the present level.

Using an AdaptiVolt™ system at the utility mentioned earlier in this section would result in only 300 to 750 tap changer operations per month, providing much longer tap changer and tap contact life with longer periods between required maintenance.

4.6 Other Maintenance Considerations

With an AdaptiVolt™ system, maintenance includes, cleaning the fans and filters on the core unit computer; inspecting the End-of-Line unit heaters and fans, annual software maintenance fees and labor and material for out of warranty failures. Lower LTC operations lead to lower annual costs which offset some of the AdaptiVolt™ maintenance costs.

With an LDC system the major maintenance item are the annual (or more frequent if required) engineering and technical costs of reviewing the distribution system for changes that may affect the models for X and R settings, re-determining and re-entering them if needed.

4.7 Reconfiguration

When a feeder or feeders are reconfigured either permanently or temporarily by switching AdaptiVolt™ has the inherent ability to automatically reconfigure itself and continue operating. LDC based CVR implementations do not have this capability and require re-modeling and re-engineering.

If the distribution system is changed, Line Voltage Monitors at the ends of the distribution feeders can be moved or new ones added at new locations by utility technical personnel, communication re-established and the system is operational in the new configuration. With LDC a new model would need to be determined and settings entered.

When line improvements such as reconductoring and rebalancing phase loads are made or there are large changes in load characteristics AdaptiVolt™ automatically controls the voltage to the appropriate set point to maintain maximum energy conservation and demand reduction. LDC based CVR implementations do not have this capability and require remodeling and re-engineering.

4.8 CVR Factors

CVR factor is a dimensionless value that is a per unit measure of how much per-unit energy conservation or demand reduction is obtained per unit voltage reduction.

Experience with AdaptiVolt™ has yielded CVR factors between 0.95 and 1.9 as measured and verified using *CVR Verification Protocol #1* which has been approved by the Regional Technology Forum (RTF) and BPA [9][10][11].

The NEEA Distribution Efficiency Initiative (DEI) final report listed CVR factors between 0.3 and 0.86. These CVR factors were computed using procedures that had not been reviewed by and have not been presented to or been approved by the RTF or BPA. Of the ten CVR projects studied, eight of them used LDC. One of them used AdaptiVolt™. The Avista CVR factor, using an AdaptiVolt™ system (which was provided by PCS UtiliData had a computed CVR factor of .84, the second highest of the ten CVR factors. (Using approved *CVR Verification Protocol #1* to evaluate the test results at Avista yielded much higher CVR factors than did the computation method used in the DEI.) The average CVR factor for the 8 LDC systems was 0.67.

4.9 Integrated Capacitor Control, Reactive Power and CVRQ Factors

Many electric utilities have switched capacitor units on their distribution feeders. Capacitors can have a significant effect on feeder voltages, i.e. switching capacitors on will usually increase distribution line voltage and therefore increase energy consumption on the feeder.

LDC based implementations of CVR do not have a mechanism for coordination with switched capacitor banks. AdaptiVolt™ uses a set of algorithms called SimpleVAR™ to coordinate switched capacitors with the over voltage control and CVR implementation.

As a consequence of reducing distribution system voltages, kVAR requirements on a system are reduced. CVRQ factors are a per unit number which indicate how much per unit reactive power is reduced per unit voltage reduction. In fielded AdaptiVolt™ systems CVRQ factor is on average 3 times larger than the CVR factor.

The same type of comparison between LDC CVRQ factors and AdaptiVolt™ CVRQ factors can be made as in the previous section.

4.10 Measurement and Verification

Measurement and verification (M&V) of energy conservation and demand reduction is a requirement for utilities to receive rebates from BPA and other agencies. It is also a requirement in Washington State to meet I-937 rules.

Measurement and verification is problematic for LDC based implementations of CVR. LDC implementation does not provide for any systematic data acquisition or storage. As a consequence the addition of any measurement and verification capability adds costs to initial implementation of LDC based CVR.

A program has been set up by BPA where if a utility performs upgrades on their distribution system to certain high power factors, low voltage spreads and certain load balances (often at a cost of tens to hundreds of thousands of dollars) they can then be eligible for recovering the cost of LDC implementations of CVR just by proving that they have reduced voltage. The upgrade work is required to assure that customers at the end of a distribution line to not receive unacceptably low voltages. (Of course the voltage reduction needs to be recorded) [11].

AdaptiVolt™, as a “smart grid” implementation of CVR inherently has data acquisition and storage capability. In fact data is collected on a phase by phase basis every 15 to 30 seconds. Data collected includes bus voltages, end of line voltages, currents, kWs, kVARs, temperature and operating status. The data collected and stored by AdaptiVolt™ can be used with *Protocol #1 for Automated CVR.*

Implementation of AdaptiVolt™ does not require significant distribution upgrades in order to provide CVR and accurate M&V. This is not to say that distribution feeder upgrades are never required. There have been instances where the enhanced system visibility provided by AdaptiVolt™ has shown utilities where improvements should be made or could enhance the conservation and demand reduction.

4.11 Conservation and Demand Reduction Levels

LDC based implementations of CVR do not measure or monitor end of line voltages. Because they do not, a margin of safety must be left in the target end of line voltage set points. Because AdaptiVolt™ implementations of CVR actually measure and end of line voltages and control based on actual measured voltages more aggressive voltage control can be implemented.

In a January 2009 telephone conversation between Mr. Robert Fletcher of Snohomish PUD, a well known expert in the area of LDC, and the author, Mr. Fletcher stated that he felt that based upon all the information he has seen, it is likely that the average voltage reduction for an AdaptiVolt™ may often be as much as 2 basis volts lower than with an LDC based CVR implementation.

On a 120 volt basis, 2 volts is 1.67% voltage reduction more than can be had with an LDC based implementation of CVR. With a CVR factor of .8 this leads to an additional energy reduction of 1.3%. Based upon existing AdaptiVolt™ installations where the average energy conservation has been approximately 3.5% an average LDC based implementation could be expected to provide an average energy conservation of only 2.2%. Stated in other words an AdaptiVolt™ based system could be expected to provide, on average, 59% more energy conservation and demand reduction than an LDC based implementation of CVR.

4.12 Transmission System Reliability

Since the Blackout of August 14, 2003, much emphasis has been placed on upgrading the transmission infrastructure in the United States and Canada to improve electric system reliability and stability. Very little has been mentioned about the possibility of using or operating the distribution system as a transmission asset or system stability tool.

AdaptiVolt™ is dispatchable from system control centers. This allows system operators to effectively manage peak load and reactive power being consumed by the distribution system on a "real time" basis. During system emergencies, AdaptiVolt™ can be used to further reduce peak load and reactive power requirements. It can prevent the distribution regulating systems (on-load tap changers or voltage regulators) from trying to increase distribution voltage levels when that action only exacerbates the transmission system emergency. While blocking of transformer tap changing is a common emergency control tactic (particularly in Europe), just blocking the taps doesn't take full advantage of the available control. Further, these schemes are often implemented using simple voltage relays that sense low voltage conditions rather than being coordinated from control centers. AdaptiVolt™ can be a valuable tool preventing voltage collapse by sending control signals from the control centers. This would be more effective than tap blocking and less disruptive than low voltage load shedding.

AdaptiVolt™ could also be used to raise voltage and energy use in wide areas during system emergencies. A potential example of this would be when a Pacific Intertie line trips leaving excess generation in the Northwest. Higher voltage set points could be dispatched to raise voltage thereby sinking excess power while hydro generator gates are being closed to maintain system stability.

LDC based CVR implementations offer none of these benefits.

4.13 System Visibility

LDC implementations of CVR do not provide any additional visibility to the operation and status of a utility distribution system over what already existed.

AdaptiVolt™ inherently provides significant distribution system visibility even if no other SCADA system is available. Voltage levels, load, kW, kVAR and system operational status are all available to the operators.

Because AdaptiVolt™ systems are almost always integrated with a utility SCADA system they provide more visibility of the distribution system than do LDC systems which are often not integrated with the SCADA system. Integrating LDC systems with SCADA system adds initial cost which tends to start equalizing the initial costs of an LDC system compared with an AdaptiVolt™ system.

Integrated AdaptiVolt™ systems provide more system visibility to system operations personnel than do non-integrated LDC systems. End-of-line voltage data as well as other operational parameters are available to assist utility personnel with system operation and system planning. End of line voltage can be used for outage management, distribution system improvement planning, etc.

AdaptiVolt™ systems provide visible measured assurance that customer voltages are maintained within acceptable levels. Monitoring/measuring end-of-line voltages in "real time" and using that information for positively controlling the voltage assures adequate voltage levels while at the same time assuring the lowest possible average voltages and maximizing energy and demand savings. A LDC system does not provide this assurance, especially if the "model" is incorrect or does not match the system or the settings were wrongly entered in the LTC or regulator controller.

AdaptiVolt™ systems can provide more operational flexibility than LDC systems. Voltage set points can be modified remotely and they can be turned on and off remotely. If this is required for an LDC system additional initial costs are incurred.

As new voltage control algorithms are developed by the AdaptiVolt™ system vendor, updates can be installed to help the utility benefit. Some examples would be the potential addition of "brown-out/blackout" control which minimizes demand during system emergencies.

4.14 Economics

Initial costs of LDC implementations are typically significantly less than AdaptiVolt™. However there is a continuing requirement for maintenance of LDC implementation in the form of distribution engineering time required to verify the continuing applicability of, or the development of new "models" because of distribution feeder configuration changes for the X and R controller settings and technician time and associated expense in entering the new settings.

Because the AdaptiVolt™ systems can yield more energy conservation, demand reduction, kVAR reduction and other tangible economic benefits, the long term economics of CVR implemented with an AdaptiVolt™ system are quite often much better than with CVR implemented using LDC methodologies.

As an example of the difference between an AdaptiVolt™ implementation of CVR and an LDC based implementation of CVR we can look at what economics difference would have been for an actual AdaptiVolt™ implementation in Ottawa, Ontario Canada. The measured and verifiable savings on that particular system were 3,699 MWh per year. If CVR had been implemented using LDC the savings would have been only 2,325 MWh per year, a difference of 1,374 MWh per year in favor of AdaptiVolt™. Assuming an average retail power rate of $0.0989 per kWh, the 2009 average retail rate for all sectors according to the DOE [13], the annual $ difference in savings would be $ 135,886. Using a discount rate of 6% per annum and a 15 year life cycle of an AdaptiVolt™ implementation the Net Present Value (NPV) of the additional savings stream for the AdaptiVolt™ implementation is over $1,320,000.

An additional initial savings that needs to be included is the savings for peak demand generation that does not need to be built. The AdaptiVolt™ system would deliver 156.8 kW more of demand reduction than the LDC based implementation. According to the DOE [14] the 2008 costs for peaking power was: $1,681 per kW or approximately $263,580 for conventional distributed peaking costs; $1,966 per kW or approximately $308,268 for wind and $6,171 per kW or approximately $967,612 of PV (solar panel) capacity. The total NPV of the AdaptiVolt™ implementation would be at least $1,583,580 or 5 to 10 times more than the difference in the initial costs of an AdaptiVolt™ implementation and a LDC implementation of CVR.

5. Conclusion

There is no equivalency between an AdaptiVolt™ implementation of CVR and an LDC based implementations of CVR. Not only do they not have the same features and benefits, they do not operate the same way and they do not provide the same end energy conservation and demand reduction results.

LDC based CVR implementation is a “legacy” approach which does not offer the flexibility or benefits that a “smart grid” approach such as AdaptiVolt™ implementation.

Finally, when all the economic factors are taken into account, the AdaptiVolt™ implementation of CVR has much better economic value than an “equivalent” LDC implementation of CVR!

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