TRANSMISSION &DISTRIBUTION WORLD

Trending Toward Distributed Voltage Optimization: A Simple Solution Overlooked

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The retail electric utility is under assault. Regulatory agencies, customers, economic conditions and advances in technology are forcing changes to the business and social paradigms under which utilities have traditionally operated.[1] Today's utilities are expected to accommodate heavy investments in demand-side resources and distributed generation, often under existing – and unfavorable – revenue frameworks, while continuing to provide distribution networks and backup capacity. Thirty states have passed legislation mandating renewable-energy and energy-efficiency targets in an effort to reduce their economies' dependence on fossil fuel generation, and to shift utilities away from a business model based on increasing supply towards a conservation-based structure that invests in efficiency to lower demand.[2] As utilities struggle with this shift from megawatts to negawatts, they also have to figure out how to integrate not only growing quantities of utility scale renewable generation[3], but also rapidly proliferating installations of distributed energy resources (DERs) such as building-scale solar and wind generation, energy storage and electric vehicles.[4]

These mandates fall especially heavily on distribution network infrastructures that are aging and in need of replacement nationwide. Distribution efficiency is increasingly a topic of discussion among utilities and research organizations and funders.[5] The U.S. Department of Energy (DOE) just issued new efficiency standards for distribution transformers.[6] And rapidly increasing installations of distributed generation require distribution networks to cope with reverse power flows from solar PV arrays on individual buildings, something they were never designed to do. Utilities, government agencies and university researchers universally acknowledge the challenge posed by distributed generation and struggle to find solutions.[7]

The Challenge of Voltage Control

Controlling voltage is a fundamental task of distribution networks. A utility must deliver power to a building's service entrance within the American National Standards Institute (ANSI C84.1) range of 114 to 126 volts (within +/-5%), compensating for line losses, daily and seasonal demand fluctuation, and changing load patterns. Historically, utilities have found it safer and more profitable to set substation voltages higher. Voltage decreases as distance from the substation increases and during times of higher loads, a phenomenon known as “line drop.” Thus, setting voltage higher helps to avoid brown-outs at the end of the feeder line, especially during peak periods. Utilities’ economic incentives align with setting voltages higher because it increases energy consumption and, therefore, revenues. Delivering higher voltage also avoids customer complaints. Excessively low voltage can produce readily noticeable issues on the customers’ end, such as lighting flicker and reduced motor output. Conversely, the downsides to the customer of higher voltage are buried out of sight in higher energy bills and more rapid degradation of electrical equipment.

Today, distributed energy resources (DER) such as distributed generation (DG) and local energy storage present the most worrisome challenge to effective voltage control. Thetotal worldwide capacity of distributed generation contained in microgrids will more than quintuple over the next six years, growing from 764 megawatts (MW) in 2012 to nearly 4,000 MW in 2018.[8] Rapidly falling panel prices[9] are helping to push rooftop solar PV growth to more than 20% a year through 2020.[10] The two-way power flows resulting from distributed generation have already begun to cause problems for utilities due to voltage rise on secondary feeder lines.[11] Additionally, utilities that face 15% or even just 10% penetration of DG on a feeder line worry about experiencing generation loss that occurs more quickly than the substation load tap changer (LTC) transformers can respond (so-called “cloud transients”). Consequently, in today’s environment, simply keeping voltage within allowable limits is no longer sufficient: utilities must learn how to optimize voltage to serve multiple objectives.

Conservation Voltage Reduction: the Grandfather of Voltage Optimization

In recent years, an old approach to voltage management has garnered renewed interest: Conservation Voltage Reduction, or CVR. Known also as volt-var optimization, CVR saves energy by lowering voltage on the feeder line. It found its first widespread application in 1977, when the California Public Utilities Commission initiated the Conservation Voltage Reduction Program. The program required California utilities to reduce service voltages to the, lower half of the ANSI range (120-114 volts). By 1985, 75% of the 5,716 residential and commercial circuits for which the CVR program was designed were CVR compliant; the remaining 25% were not deemed cost effective for conversion at the time. By the mid-1980s, the program was saving just shy of 3 billion kWh/year, at an average cost of 2.5 mills per kWh, or roughly 6.8 mills in 2013 dollars. The final program report in 1986 called it “one of the most effective electric energy conservation programs in California.”[12]

The energy savings from CVR comes via two mechanisms:

1) Load reduction – for devices that are either constant impedance or constant current, where a reduction in voltage will result in a reduction in power

2) Efficiency gains – for devices that run more efficiently at lower voltage because of a reduction in losses, e.g., core losses, solid-state switching losses, conversion losses, and operational efficiencies gained through lowering operating temperatures (e.g., motor winding temperatures)

CVR saves energy by increasing distribution system efficiency and end user efficiency. For utilities, lowering feeder-line voltage reduces the iron losses in secondary transformers. On the customer side, most electrical equipment uses less energy at lower voltages, with the amount of savings dependent on the load type. The responsiveness of different load types to voltage regulation has been studied by, among others, the California Energy Commission[13], the Sacramento Municipal Utility District[14], the Electric Power Research Institute[15], Pacific Northwest National Laboratories[16], and the US Department of Energy[17]. The potential savings from CVR are commonly expressed using a CVR factor (*CVFf*), which is the percentage change in power divided by the percentage change in voltage, or %DP/%DV. EPRI's Distribution Green Circuits program found average CVR factors for kW at around 0.8, and for VARS at around 3.0.[18]

According to a 2010 Battelle report that estimated the benefits of feeder line CVR on a national scale, "CVR provides peak load reduction and annual energy reduction of approximately 0.5%-4% depending on the specific feeder." Extrapolating this number to a national level, a complete deployment of CVR on 100% of distribution feeders, would reduce annual energy consumption by 3.04%; deployment on just the highest value distribution feeders, roughly 40% of the total, would still achieve a 2.4% reduction.

Optimizing voltage also substantially lessens equipment maintenance costs. The service life of electrical equipment is roughly halved with each 10°C increase in operating temperature. Each one volt increase in voltage raises the operating temperature of most appliances by approximately 0.5°C. Additionally, each 1% of voltage imbalance increases three-phase motor winding temperature by 10°C.

According to the US Department of Energy, the utility standard 3-phase voltage delivery is no more than 3% imbalance. Consequently, voltage imbalance can dramatically lessen both motor efficiency and life even within the acceptable delivery standard. Voltage imbalances greater than 1% have a detrimental effect, a fact that most consumers are unaware of.[19]

TABLE 1

The effects of unbalanced voltage on temperature rise, losses, efficiency, and life expectancy of a typical 3-phase motor operating at rated load

% voltage unbalance	Winding temp. (°C)	I^2R losses (% of total)	Efficiency reduction	Expected winding life (years)
0	120	30%	—	20 years
1	130	33%	Up to 1/2%	10
2	140	35%	1-2%	5
3	150	38%	2-3%	2.5
4	160	40%	3-4%	1.25
5	180	45%	5% or more	Less than 1

Source: US Department of Energy[20]

CVR Strategies

Utilities can either regulate voltage on an entire distribution circuit – feeder line CVR – or regulate voltage at the service entrance to a building, known as Distributed Voltage Optimization (DVO). These two strategies differ in levels of initial investment, complexity of implementation and maintenance, potential energy savings, controllability, and ability to integrate distributed generation such as rooftop solar PV onto the grid.

Currently, most utilities that undertake feeder-line CVR employ one or both of two basic approaches. Line Drop Compensation (LDC) regulates the substation voltage to keep the most distant portion of the circuit at the minimum acceptable voltage level. A real-time signal is sent from monitoring devices at the end of the distribution feeder back to the substation to ensure that substation voltage is no higher or lower than necessary to deliver minimum voltage at the end of the line. Therefore, LDC does not reduce the amount of line drop because customers closer to the substation still receive higher voltages.

The other approach, voltage spread reduction (VSR), flattens the voltage profile across the feeder line through a combination of voltage regulators and capacitor banks installed at key points to attenuate the degree of line drop. VSR provides more uniform voltages to customers all along a feeder line, potentially -- though not necessarily-- lowering voltage significantly. Some utilities, such as Snohomish County PUD, have implemented a combination of LDC and VSR.

Both LDC and VSR have operational and implementation shortcomings, however. Put simply, feeder line CVR is an operational nightmare for utilities, and for that reason more often than not it does not get implemented.

- Feeder line CVR requires considerable expertise to do the necessary engineering.
- Even if that expertise is available, it takes a significant amount of time to design, plan and implement.
- Individual feeder line characteristics differ substantially so that a cookie cutter approach is not feasible. Most feeder line designs must be done on an individual basis.
- Feeders are constantly changing due to load growth, changing load profiles, switching other circuits in during maintenance, and other factors.
- The costs are borne by the utility alone.
- Feeder-line CVR is not designed to address the over voltage issues associated with DERs.

Distributed Voltage Optimization

Distributed Voltage Optimization, on the other hand, simplifies this complex task by reducing the variables involved. It bypasses almost all of the technical difficulties common to feeder-line CVR and offers important additional benefits. By dynamically regulating voltage to the ANSI minimum at the utility service entrance to a building, DVO can accomplish the several things that feeder line CVR utilizing load tap-changing (LTC) transformers and capacitor banks cannot:

- DVO balances three-phase voltages precisely, increasing the life and efficiency of three-phase motors. (see *Table 1, The effects of unbalanced voltage on motor life*) For commercial and light industrial loads this represents significant additional savings.
- The voltage drop on the secondary circuit is an uncontrollable variable that limits the extent that voltage on the feeder can be lowered. DVO circumvents the need to allow a buffer (typically 2-4 volts) to accommodate this variable. This creates 1.5 to 2 times the potential savings compared to feeder line CVR methods.
- DVO can hold the voltage exactly at the ANSI C84.1 low limit, even when the feeder voltage dips too low, (i.e., after a large load increase or decrease in DER output) until the utility's load tap-changing transformers can compensate. DVO can therefore harvest more potential energy savings without stressing equipment during sags.
- In the presence of DVO the LTC response can then be slowed, thereby increasing its usable life and reducing maintenance expenses.
- With the proper voltage-regulation equipment, DVO can address problems arising from DER installations such as high secondary voltages and voltage fluctuation from cloud transients.

- Bi-directional DVO allows greater penetration of distributed generation without the voltage exceeding ANSI C84.1 at the service entrance.
- DVO can be network controlled, which gives the utility an additional tool to manage demand.

One criticism that has been leveled at DVO by proponents of line drop compensation is that it does not reduce transformer iron losses, nor does it realize as much in savings from line losses as feeder-line CVR does.[21] However, a 2010 study of feeder line CVR by the Pacific Northwest National Laboratory concluded that, "Without exception, the reduction in load accounts for the vast majority of the change in energy consumption. In general, when CVR is in operation 98%-99% of the change in energy consumption occurs in the end use loads, while only 1%-2% of the reduction in energy consumed can be attributed to feeder losses. Reduction in systems losses is not a significant benefit of CVR."[22] The California PUC drew the same conclusion from its CVR program, noting, "...it is better, when seeking to maximize CVR energy savings, to simply minimize the average service voltage (while still maintaining a minimum service voltage of 114 volts).[23]

In other words, *the closer to the load the regulation occurs, the greater the savings*; this approach consistently provides the lowest operating voltage. And because DVO occurs *after* the 2-4 volt line-drop buffer on the secondary circuit, it ensures that building loads consistently see the lowest voltage possible.

Trending Toward DVO: Enter the LVR

A Seattle-based company, MicroPlanet Technologies Inc., has pioneered DVO technology capable of regulating voltage with three key parameters: speed, accuracy, and efficiency. MicroPlanet's regulators use a microprocessor-controlled AC-to-AC converter that controls a series injection transformer that enables high performance.

- It responds to changes in utility voltage in 20 milliseconds, thereby providing both steady-state and transient-response correction.
- It dynamically regulates voltage to within 0.4% accuracy.
- It is 99.7% efficient.

Other benefits of this technology include:

- Elimination of sags, swells, spikes and voltage volatility
- Ability to withstand and protect itself from large-fault currents
- No added harmonics
- Standard Bluetooth enabled, and flexible for conversion to modem and other media
- Four-quadrant regulation that allows bi-directional power flow

- Individual phase regulation balances three-phase voltages

MicroPlanet began collaboration with Ergon Energy in Australia in 2006 to qualify its LVR (low voltage regulator) on their SWER distribution system.[24] The LVR has since proven to be a utility-grade device with over 1,600 installations on the Australian grid. Its bi-directional regulation capability made it especially attractive to maintain voltage compliance on LV networks with high distributed energy resources. Three phase LV MicroPlanet regulators are now in trial by several Australian utilities on urban LV networks for this purpose, motivated by the high rate of adoption by Australians of solar PV. Some parts of Australia, in fact, now have PV on 28% of the homes.[25]

Additionally, integrated 11kV-to-240/415V regulating distribution transformers are soon to be released. These Regformers™ further illustrate the migration of DVO towards the end-use loads. This should not come as a surprise. European standards for PV inverters now include provisions for Var management as a tool to support voltage management. Academic papers are also beginning to emerge which support DVO as a solution to managing distributed generation problems.[26], [27]

Managing Distributed Generation

Utilities in North America and globally are struggling to cope with the rapid adoption by their customers of rooftop solar photovoltaic power generation. To integrate large quantities of solar PV requires utilities to manage the rise in voltage that almost inevitably occurs from distributed generation.

Electricity leaves a utility distribution substation typically between 2,400 and 19,920 volts. Utilities use secondary transformers to reduce that feeder line voltage to a range suitable for delivery to customers in the ANSI standard of nominal +/- 5%. When distributed energy resources such as rooftop solar PV push energy back onto the utility grid, the voltage rises on the secondary of the distribution transformer. During peak production -- when the sky is clear and the sun is strong -- the net combination of low load and high energy produced by distributed generation installations on the secondary circuit of a feeder line can cause voltage to exceed the high limit of the delivery standard.

Why does this happen? As noted earlier, utilities expect a voltage drop from line losses of between 2 and 4 volts from the secondary transformer to customers' buildings, and set the secondary transformer taps accordingly. Voltage drop occurs according to the formula $V_{drop} = I^2R$, where R is the resistance of the wire, V_{drop} is the voltage change and I is the amount of current. Given a wire of a certain resistance, therefore, voltage is proportional to current: as I rises, V falls correspondingly, and vice versa. This relationship has important implications for the connection between the utility grid and distributed energy resources.

Let's use an example of a building with installed PV capacity that substantially exceeds building loads during peak production. The utility voltage at the secondary transformer is 122, and the line drop is 4V at high load. As solar PV output increases during the day, the building's net need for utility power decreases. The drop in current from the utility's secondary transformer reduces line loss, causing voltage at the service entrance to rise. When PV output matches the building load, the line loss goes to zero because there is no current draw from the utility, and building voltage rises to match the 122V of the secondary transformer. When PV output exceeds building demand, voltage from the PV at the building must exceed the feeder voltage to be able to push power onto the grid. Line losses now occur in reverse, and building voltages must rise accordingly for power to flow from the building to the grid. In the case described, the building voltage could conceivable rise to 126 volts or more.

This causes several problems for the PV-owning customer. Higher voltage means that building loads use more energy, leaving the customer less to send out to the grid and diminishing the return of the PV investment. Higher operating voltages also mean more wear and tear on electrical equipment. Finally, if the building voltage exceeds 126 for long enough, the PV inverter will shut down, causing the customer to lose temporarily the benefit of having a solar PV system.

Multiple PV sites on the same transformer secondary circuit, such as neighboring houses with rooftop solar, can exacerbate the problem. Secondary transformers, themselves, present impedance, so that for current to pass through to the primary feeder requires even higher voltage levels on the secondary side. By increasing the total amount of power moving onto the grid, each additional PV producer further raises the voltage threshold.

MicroPlanet's Regformer addresses this problem by presenting 114V (or whatever voltage setpoint the user has chosen) to the inverter and the building, and boosting the voltage leaving the regulator to enable reverse power flow. The building loads run efficiently and the inverter is never in danger of tripping out. For this reason, the US National Renewable Energy Laboratory (NREL) deployed MicroPlanet's equipment to manage the voltage on the microgrid at the 2011 Solar Decathlon. Over a two week period, the event achieved a 74% capacity penetration of the microgrid (defined as maximum PV generation divided by maximum system load).

> "The Solar Decathlon 2011 microgrid operated extremely well over the duration of the event, with no power quality or reliability problems. The use of the electronic voltage regulators was key to maintaining voltage control at the competition houses because of the event's unique constraints...[The event] demonstrated that it is possible to have a high-penetration of PV systems within a microgrid or subdivision with acceptable performance and power quality for both the utility and the customers."[28]

Conclusion

Powerful, disruptive forces are changing how utilities do business. Distribution is an electric utility's most expensive, most complicated, most important function. And distribution is where the stresses of infrastructure maintenance, distributed generation and changing customer loads make themselves felt. Effective voltage control is fundamental to a successful smart grid transformation.

Distributed Voltage Optimization offers utilities the ability to reshape their distribution systems in a way that combines substantial energy efficiency savings, flexibility, low maintenance and, perhaps most urgently, a crucial step toward seamless integration of distributed energy resources. Because DVO benefits both utilities and end users, implementation costs could be shared, just as other end user investments in energy efficiency and renewable generation frequently receive utility incentives. Another advantage of using DVO to integrate building level generation is that it is a hands-off approach, a plug-and-play-and-walk-away strategy for both the utility and the generation owner. Why aren't more of them taking notice?

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[1] Disruptive Challenges: Financial Implications and Strategic Responses to a Changing Retail Electric Business. Peter Kind, Energy Infrastructure Associates, for Edison Electric Institute. January 2013.

[2]For example, California has state mandated goals of 33% renewable energy and 12 GW of distributed generation by 2020. It also has some of the most stringent product efficiency standards and building energy codes in the U.S.

[3]According to the Federal Energy Regulatory Commission (FERC), New Electricity Generation In-Service for January through March of 2013, broke down as follows: 958 MW wind, 490 MW solar, 24 MW biomass, 0 MW fossil fuels. Source: http://www.ferc.gov/legal/staff-reports/2013/mar-energy-infrastructure.pdf

[4] REFERENCE from 1 above

[5] For example, EPRI's Green Circuits program, NEEA Distribution Efficiency Initiative, USDOE's SmartGrid Investment Grant Program, the Regulatory Assistance Project (see RAP Issuesletter May 2010)

[6]http://www1.eere.energy.gov/buildings/appliance_standards/product.aspx/productid/66

[7]https://solarhighpen.energy.gov/2013_doe_cpuc_high_penetration_solar_forum

[8]http://www.businesswire.com/news/home/20121022005194/en/Total-Worldwide-Distributed-Generation-Capacity-Microgrids-Quintuple

[9]According to Bloomberg New Energy Finance, *Solar Module Price Index*, PV panel prices declined from $3.80/watt in 2008 to $0.86/watt in mid-2012.

[10]Disruptive Challenges: Financial Implications and Strategic Responses to a Changing Retail Electric Business. Peter Kind, Energy Infrastructure Associates, for Edison Electric Institute. January 2013.

[11]Three U.S. utilities at the forefront of grappling with high levels of distributed generation are Hawaiian Electric Company (HECO), San Diego Gas & Electric (SDG&E), and Sacramento Municipal Utility District (SMUD).

[12] Conservation Voltage Reduction (CVR) Program, Calendar Year 1985. California Public Utilities Commission Evaluation & Compliance Division – Energy Branch – San Francisco California – February 1987, (p. 5).

[13]"Advanced Switches for Soft Blacks, Critical Infrastructure Protection, Unanticipated Discovery of Emergency Voltage Reduction for Grid Protection, Appendix IV to Final Report", California Energy Commission, Public Interest Energy Research Program, CEC-500-2006-058, June 2006.

[14]Customer Advanced Technologies Program, Technology Evaluation Report: MicroPlanet HVR, Energy Efficiency, Customer Research & Development, Sacramento Municipal Utility District, December 5, 2007.

[15]M.S. Chen, R.R. Shoults and J. Fitzer, "Effects of Reduced Voltage on the Operation and Efficiency of Electric Loads," EPRI, Arlington: University of Texas, EL-2036 Volumes 1 & 2, Research Project 1419-1, 1981.

[16]K.P. Schneider, J.C. Fuller, F.K. Tuffner, R. Singh, "Evaluation of Conservation Voltage Reduction (CVR) on a National Level," Pacific Northwest National Laboratory, PNNL-19596, July 2010.

[17]J.G. DeSteese, S.B. Merrick, R.C. Tepel, J.W. Callaway, Assessment of Conservation Voltage Reduction Applicable in the BPA Service Area, US DoE Contract No. DE-AI79-83BP14031, 1987

[18]Cited online in "Conservation Voltager Reduction: An Easy Way to Improve Energy Efficiency and Lower Demand," by A. Berl Davis, Jr., 2011, p. 15. A presentation delivered to the National Rural

Electric Cooperative Assocation's (NRECA) 2011 CRN
Summit. http://www.nreca.org/programs/CRN/smartgridsummit/Documents/Planning%20a...

[19]EPRI TR-104581. Proceedings, Power Quality Issues and Opportunities, PQA '93', June 1995, page 6-4:7 Figure 8.

[20]http://www1.eere.energy.gov/manufacturing/tech_deployment/winter2005.html

[21] Energy Conservation with Voltage Reduction – Fact or Fantasy. 'Revision 1.1, 4/1/04. (Originally Presented at the IEEE 2002 Rural Electric Power Conference. T.L. Wilson, PCS UtiliData. Spokane, WA 99127 USA.

[22] Evaluation of Conservation Voltage Reduction (CVR) on a National Level. KP Schneider, JC Fuller, FK Tuffner, R Singh. Pacific Northwest National Laboratory, PNNL-19596, July 2010, page 25.

[23] CPUC, 1987, p. 16.

[24]SWER stands for "Single Wire Earth Return", a single wire network used for electricity transmission to remote areas.

[25]According to one expert, one million homes in Australia have rooftop solar PV systems, representing an investment of about $8 billion. See: reneweconomy.com.au/2013/rooftop-solar-owners-vs-utilities-the battle-begins-63919

[26]Thomas Degner, Gunter Arnold, Thorsten Reimann, Philipp Strauß, Michael Breede and Bernd Engel.Increasing the Photovoltaic-System Hosting Capacity of Low Voltage Distribution Networks, 21st International Conference on Electricity Distribution, Frankfurt, 6-9 June 2011

[27] Thomas Degner, Gunter Arnold, Thorsten Reimann, Philipp Strauß, Michael Breede and Bernd Engel. Photovoltaic-System Hosting Capacity of Low Voltage Distribution Networks. Fraunhofer Institut fur Windenergie und Energiesystemtechnik IWES, Kassel, Germany, and SMA Solar Technology AG, Kassel, Germany.

[28]Design and Performance of Solar Decathlon 2011 High-Penetration Microgrid, NREL Conference Paper NREL/CP-7A30-54719, April 2012, p. 8.