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2023 VoltVar Voltage Control Program EM&V Report

Prepared for:

Appalachian Power Company

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1. Introduction

This report addresses the measuring, verifying and evaluating of energy savings and demand reductions that resulted from the implementation by Appalachian Power Company (APCo) in 2023 of its VoltVar Voltage Control Program (VVO) Program. APCo implemented this program in conjunction with Eaton.

1.1 Description of Program

The VoltVar Voltage Control Program achieves energy conservation through automated monitoring and control of voltage levels provided on distribution circuits, otherwise known as conservation voltage reduction (CVR). End use customers realize lower energy and demand consumption when VoltVar is applied to the distribution circuit from which they are served.

A distribution circuit facilitates electric power transfer from an electric substation to utility meters located at electric customer premises. Electric power customers employ end-use electric devices (loads) that consume electrical power. At any point along a single distribution circuit, voltage levels vary based upon several parameters, mainly including, but not exclusive of, the actual electrical conductors that comprise the distribution circuit, the size and location of electric loads along the circuit, the type of end-use loads being served, the distance of loads from the power source, and losses incurred inherent to the distribution circuit itself.

All end-use loads require certain voltage levels to operate and standards exist to regulate the levels of voltage delivered by utilities. The Company is required to maintain a steady state +/- 5% of the respective baseline level (e.g., 120-volt baseline yields an acceptable voltage range of 114 volts to 126 volts).

Because most devices operated by electricity (especially motors) are designed to operate most efficiently at 115 volts, any "excess" voltage is typically wasted, usually in the form of heat. Tighter voltage regulation allows end-use devices to operate more efficiently without any action on the part of consumers. Consumers receive a lower but still acceptable voltage and use less energy to accomplish the same tasks.

1.2 Impact Evaluation Findings

Table 1-1 below presents the total aggregated annual gross and net energy (kWh) savings achieved by the VVO Program during PY2023.

Table 1-1. Summary of Ex Post PY2023 kWh Savings

Ex Ante kWh Savings	*Gross Ex Post kWh Savings*	*Gross Realization Rate*	*Net Ex Post kWh Savings*	*Net-to-Gross Ratio*
1,922,318	1,922,318	100%	1,922,318	100%

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Table 1-2 presents the total gross and net peak demand (kW) impacts achieved by the VVO Program during PY2023.

Table 1-2. Summary of Ex Post PY2023 kW Peak Demand Impacts

Ex Ante kW Savings	*Gross Ex Post kW Savings*	*Gross Realization Rate*	*Net Ex Post kW Savings*	*Net-to-Gross Ratio*
527.23	527.23	100%	527.23	100%

Table 1-3 compares average participant realized net energy savings with the average energy usage of accounts for each applicable eligible rate schedules.

Table 1-3 Summary of Savings by Eligible Rate Schedule

Rate Schedule Class	*Total Net Ex Post kWh Savings*	*Number of Participating Accounts*	*Average Participant Account-Level Net Ex Post kWh Savings*	*Average Rate Schedule Account-Level kWh Usage*	*Average Participant Account-Level Net Ex Post kWh Savings as Percentage of Average Rate Schedule Account-Level kWh Usage*
RS	1,030,311	4,508	229	12,719	1.80%
200	887,324	797	1,113	45,526	2.45%
300	3,696	1	3,696	17,987,762	0.02%
800	987	11	90	190,121	0.05%

1.3 Organization of Report

This report is organized as follows:

- Chapter 2: Data Collection
- Chapter 3: Impact Evaluation Methods
- Chapter 4: Impact Evaluation Findings
- Chapter 5: EM&V Costs

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2. Data Collection

The effects of voltage optimization for 2023 were analyzed using voltage and power data extracted from APCo's VoltVar management software and meter-level interval voltage and power data.

APCo used an "on/off" procedure for voltage reductions during various parts of 2023.[1] This procedure involves disengaging the conservation voltage reduction (CVR) system during specified days to enable the provision of data sets with measurements of voltages and energy use that include both regular voltages (measured on "off" days, during which the CVR system is disengaged) and reduced voltages (measured on "on" days, during which the CVR system is engaged).

During 2023, data were collected for regulated source voltages by phase and power by circuit. After January 2023, voltage and power were measured at 1-minute intervals, giving 60 data-points per hour for each element. During January, such data were provided at 5-minute intervals. Voltages were measured at the circuit level for three phases. The analysis includes two circuits at Brush Tavern substation for which CVR was enabled during 2023.

Hourly temperature readings were available from the quality controlled local climatological data program of the National Climatic Data Center[2] for 2023 for the multiple weather stations selected based on proximity to the substation for which CVR is enabled. This temperature data was used for the analysis.

Table 2-1 shows the time during 2023 during which the CVR system was engaged, as well as associated average CVR factors and energy savings rate.

Table 2-1 PY2023 CVR System Engagement, CVR Engaged State Energy Savings, and CVR Factors by Circuit

Circuit	*Average CVR Factor*	*Hours Engaged*	*Engaged State kWh Consumption*	*Engaged State kWh Savings*	*kWh Savings Rate*
Whitestone	0.55	6,573	30,455,623	783,680	2.57%
Wyndhurst	0.66	6,575	36,024,203	1,138,638	3.16%

2.1 Meter-Level Voltage Review

ADM reviewed meter-level voltage data including approximately 183 million 15-minute meter-level observations collected throughout 2023 from the two circuits for which VVO was engaged to determine the percentage of observations within the ANSI C84.1 Range A and Range B service voltage standards for nominal voltages of 120V and 240V.

[1] For discussion of "on / off" testing, see, for example, Pacific Northwest Regional Technical Forum, *Standard Protocol #1 for Automated CVR*, November 2011.

[2] For information on the QCLCD data, see http://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/quality-controlled-local-climatological-data-qclcd

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Findings, detailed in Table 2-2, include the following:

- Compliance with Range A Standards: 99.88% of the meter-level voltage observations across both circuits fell within the Range A standards.
- Compliance with Range B Standards: 99.97% of observations complied with Range B standards, with out-of-range observations limited to 20 meters.

For reference, ANSI C84.1 service entrance voltage standards are as follows:

- 120V nominal voltage: Range A service voltage 126V - 114V
- 240V nominal voltage: Range A service voltage 252V - 228V
- 120V nominal voltage: Range B service voltage 127V - 110V
- 240V nominal voltage: Range B service voltage 254V - 220V

Table 2-2 PY2023 Voltage Metrics for Meters on Circuits with CVR System Engagement

Sector	*Metric*	*Criterion*	*Whitestone*	*Wyndhurst*	*Total*
Residential	Number of Meters	n/a	2,499	2,002	4,501
	Percent of Observations within Range	Range A	99.9879%	99.9827%	99.9856%
		Range B	100.0000%	100.0000%	100.0000%
	Number of Meters with One or More Out of Range Observations	< Range A	54	99	153
		> Range A	512	107	619
		< Range B	-	9	9
		> Range B	-	1	1
	Percent of Observations Out of Range	< Range A	0.0039%	0.0124%	0.0077%
		> Range A	0.0083%	0.0049%	0.0068%
		< Range B	0.0000%	0.0000%	0.0000%
		> Range B	0.0000%	0.0000%	0.0000%
	Number of Observations Out of Range	< Range A	3,317	8,566	11,883
		> Range A	7,140	3,369	10,509
		< Range B	-	14	14
		> Range B	-	5	5
Non-Residential	Number of Meters	n/a	209	581	790
	Percent of Observations within Range	Range A	99.0884%	99.2923%	99.2388%
		Range B	99.9093%	99.8743%	99.8835%
	Number of Meters with One or More Out of Range Observations	< Range A	17	31	48
		> Range A	80	77	157
		< Range B	7	3	10
		> Range B	-	-	-
	Percent of Observations Out of Range	< Range A	0.8604%	0.7052%	0.7460%
		> Range A	0.0512%	0.0025%	0.0153%

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Sector	*Metric*	*Criterion*	*Whitestone*	*Wyndhurst*	*Total*
		< Range B	0.0907%	0.1257%	0.1165%
		> Range B	0.0000%	0.0000%	0.0000%
	Number of Observations Out of Range	< Range A	60,635	139,471	200,106
		> Range A	3,607	491	4,098
		< Range B	6,391	24,859	31,250
		> Range B	-	-	-
Total	Number of Meters	n/a	2,708	2,583	5,291
	Percent of Observations within Range	Range A	99.9199%	99.8289%	99.8755%
		Range B	99.9931%	99.9720%	99.9656%
	Number of Meters with One or More Out of Range Observations	< Range A	71	130	201
		> Range A	592	184	776
		< Range B	7	12	19
		> Range B	-	1	1
	Percent of Observations Out of Range	< Range A	0.0686%	0.1668%	0.1165%
		> Range A	0.0115%	0.0043%	0.0080%
		< Range B	0.0069%	0.0280%	0.0172%
		> Range B	0.0000%	0.0000%	0.0172%
	Number of Observations Out of Range	< Range A	63,952	148,037	211,989
		> Range A	10,747	3,860	14,607
		< Range B	6,391	24,873	31,264
		> Range B	-	5	5

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3. Impact Evaluation Methods

This chapter discusses the method used for analysis of data to determine energy savings attributable to the VVO Program.

3.1 Determination of CVR Factors

CVR system data analysis was performed using Stata, a statistical software program used for data analysis, data management, and graphics. Stata code was used to analyze CVR data to assess the performance of the system based on the energy usage and voltage data across different time intervals and conditions.

The panel data is organized in a structured manner that represents multiple circuits of stations for which CVR is enabled. Circuit-level data is further broken down into its respective phases. This means for every single circuit in the dataset, there are three corresponding entries or groups – one for each phase of that circuit. Each circuit-phase combination (e.g., Circuit 1 - Phase A, Circuit 1 - Phase B, Circuit 1 - Phase C, and so forth) serves as an individual group within the panel, allowing for detailed analysis and comparison of CVR's performance across different circuits and their respective phases. While circuit-level power data was referenced to perform the analysis, meter-level interval data was referenced to ensure that aggregate kWh referenced in the analysis matches the amount actually consumed by end users.

The raw data files contain circuit-phase-level time series data, including energy usage, voltage, and CVR operating status information. Three files are conveyed for each hour, with data for the various stations and circuits divided between the three files.

The data analysis is aimed at creation of two products facilitating calculation of energy savings:

- **Circuit-Phase Operational Report**: This comprehensive report provides circuit-phase-level insights, including voltage levels, power consumption, and the operating status of the CVR system for each circuit and its respective phase. It serves as a detailed snapshot of the system's operational history, with information presented for each month of system operation.
- **Regression Analysis Report**: This report presents the results of regression analyses performed on data samples. It provides detailed information on CVR factors and related data.

Regression analysis is used to relate circuit power data day type (business day/non-business day), CVR operating state and weather. The regression model used is given in Equation 3-1 below.

Equation 3-1

$$kWh_i = \beta_0 + \beta_1 Engaged_j + \beta_2 CDH_i + \beta_3 HDH_i + \beta_4 Hour_i + \beta_5 Day\_Type_i + e_i$$

Regression analysis model variables are described in Table 3-1.

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Table 3-1. Regression Analysis Model Variables

Variable Name	*Variable Description*
kWh	Dependent variable; hourly power (kW).
Engaged	1 if CVR is engaged; otherwise 0.
CDH	MAX (Outdoor Temperature - 65°F, 0)
HDH	MAX (65°F - Outdoor Temperature, 0)
Hour * Day_Type	Group of dummy variables for hour of the day, by day type (business day, non-business day).

For each circuit and phase, regression models using the specification in Equation 3-1 are estimated. Regression models are performed using a sample of data generated through pairing hourly observations occurring during CVR system engagement with hourly observations occurring during CVR system disengagement. Paired observations occurred during consecutive days of the same day type (business/non-business) and during the same hour of day. The approach to selection of paired observations is intended to minimize the impact of non-CVR-related variables impacting energy usage that are not otherwise controlled for by model independent variables.

The value for β_1 estimated through the regression analysis captures the impact of CVR system engagement on circuit-level energy usage, controlling for weather, day type, and hour of day.

The results of the regression analyses and associated voltage reduction reflected in the regression data set are used to determine applicable conservation voltage reduction factor (*CVRf*) for each circuit and phase. A *CVRf* measures the relationship between changes in energy in response to changes in voltage effected under the operation of the CVR system. Mathematically, *CVRf* is calculated as the ratio between the percentage change in energy usage and the percentage change in voltage, as shown below in Equation 3-2.

Equation 3-2

$$CVRf = -(\beta_1 / (kWh_{engaged\_sample} + \beta_1)) / ((V_{idle\_sample} - V_{engaged\_sample}) / V_{idle\_sample})$$

Inputs to the calculation of *CVRf* are described in Table 3-2.

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Table 3-2. CVRf Calculation Input Variables

Variable Name	*Variable Description*
β_1	Coefficient of *Engaged* variable of applicable circuit-phase regression analysis, which is the estimate of the change in energy usage associated with CVR system engagement.
$kWh_{engaged\_sample}$	Average hourly kWh electric energy usage for the applicable circuit-phase when the CVR system is engaged, based on the selected sample of data used in the regression analysis.
$V_{engaged\_sample}$	Average voltage for the applicable circuit-phase when the CVR system status is engaged, taken from the same data subset utilized for regression analysis.
V_{idle_sample}	Average voltage for the applicable circuit-phase when the CVR system status is idle, also derived from the data subset used for the regression analysis.

The Regression Analysis Report presents the results of the regression analyses performed for each circuit and phase. The CVR factors presented in the report are then referenced along with the system data presented in the Circuit-Phase Operational Report to estimate ex post energy savings. This is facilitated by estimating the applicable baseline energy usage ($kWh_{baseline\_pop}$) using Equation 3-3 shown below.

Equation 3-3

$$kWh_{baseline\_pop} = (kWh_{engaged\_pop} * V_{idle\_pop}) / (-CVRf * V_{idle\_pop} + CVRf * V_{engaged\_pop} + V_{idle\_pop})$$

Inputs to the calculation of CVRf are described in Table 3-2.

Table 3-3. Baseline Energy Usage Calculation Input Variables

Variable Name	*Variable Description*
CVRf	Applicable CVR factor calculated by using Equation 3-2.
$kWh_{engaged\_pop}$	kWh electric energy usage for the applicable circuit-phase when the CVR system is engaged, based on the population of observations for the applicable circuit and phase.
$V_{engaged\_pop}$	Average voltage for the applicable circuit-phase when the CVR system status is engaged, taken from the same population of observations.
V_{idle_pop}	Average voltage for the applicable circuit-phase when the CVR system status is idle, also derived from the population of observations.

The calculation of $kWh_{baseline\_pop}$ enables calculation of energy savings ($kWh_{savings}$) using Equation 3-4 shown below.

Equation 3-4

$$kWh_{savings} = kWh_{baseline\_pop} - kWh_{engaged\_pop}$$

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3.2 Ex Post Savings Calculations

The CVR factors the system data presented in the Circuit-Phase Operational Report (described in section 3.1) were referenced to estimate ex post energy savings. This is facilitated by estimating the applicable average baseline energy usage ($kWh_{avg\_baseline}$) using Equation 3-5 shown below.

Equation 3-5

$$kWh_{avg\_baseline} = (kWh_{avg\_engaged} * V_{baseline}) / (-CVRf * V_{idle\_pop} + CVRf * V_{engaged} + V_{baseline})$$

Inputs to the calculation of CVRf are described in Table 3-4.

Table 3-4. Baseline Energy Usage Calculation Input Variables

Variable Name	*Variable Description*
CVRf	Use CVR factor calculated by using Equation 3-2.
$kWh_{avg\_engaged}$	Average hourly kWh electric energy usage for the applicable circuit-phase when the CVR system status is engaged during the applicable year.
$V_{engaged}$	Average voltage for the applicable circuit-phase when the CVR system status is engaged during the applicable year.
$V_{baseline}$	Use average voltage when the CVR system status was idle, derived from the population of observations of the 365-day regression analyses associated with CVRf.

The calculation of $kWh_{avg\_baseline}$ enables calculation of the energy savings rate ($kWh_{savings\_rate}$) using Equation 3-6 shown below.

Equation 3-6

$$kWh_{savings\_rate} = (kWh_{avg\_baseline} - kWh_{avg\_engaged}) / kWh_{avg\_baseline}$$

To calculate ex post energy savings, the energy savings rate is factored by energy consumption during system engagement. Ex post energy savings ($kWh_{savings}$) are calculated using Equation 3-7, where $kWh_{engaged}$ is the total electric energy consumption during the engaged operating periods.

Equation 3-7

$$kWh_{savings} = (kWh_{engaged} * (1 + kWh_{savings\_rate})) - kWh_{engaged}$$

Ex post peak demand savings ($kW_{savings}$) are calculated using Equation 3-8, where $kWh_{engaged\_peak}$ is the electric energy consumption during the engaged operating periods during the applicable peak period, and $hours_{peak}$ is the number of hours comprising the applicable peak period.

Equation 3-8

$$kW_{savings} = ((kWh_{engaged\_peak} * (1 + kWh_{savings\_rate})) - kWh_{engaged\_peak}) / hours_{peak}$$

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4. Impact Evaluation Findings

This chapter presents the results from the analysis of data for the VVO program in 2023 to determine kWh savings and CVR factors associated with voltage reduction for the various circuits and phases.

4.1 Circuit/Phase-Level Energy Savings and CVR Factors

For each circuit and phase, kWh savings and CVR factors were calculated. The percentage savings from reducing voltage was calculated and divided by the percentage reduction in voltage to determine the CVR factor. The resulting estimates of engaged state kWh savings and CVR factors for the various phases of the circuits and phases are reported by substation in Table 4-1.

Table 4-1 PY2023 Energy Savings and CVR Factors by Phase: Brush Tavern Circuits

Circuit ID	*Phase*	*Baseline Off Voltage*	*On State Voltage*	*On State kWh Savings*	*On State kWh Consumption*	*Percent Savings*	*CVR Factor*
Whitestone	A	20.82	19.91	231,083	12,104,989	1.87%	0.44
	B	20.76	19.78	317,264	10,192,777	3.02%	0.66
	C	20.76	19.76	235,333	8,157,857	2.80%	0.60
	Total /Average	20.79	19.83	783,680	30,455,623	2.51%	0.55
Wyndhurst	A	20.82	19.91	347,293	13,507,580	2.51%	0.59
	B	20.77	19.78	394,047	11,258,247	3.38%	0.74
	C	20.76	19.77	397,298	11,258,376	3.41%	0.74
	Total /Average	20.78	19.82	1,138,638	36,024,203	3.06%	0.66
Total		20.78	19.83	1,922,318	66,479,826	2.81%	0.61

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4.2 Peak Reduction

This chapter presents the results of the analysis of demand reduction occurring during 2023 PJM 5CP hours. Demand reductions, accounting for those circuits for which the CVR system was enabled during the 5CP hours, are presented in Table 4-2.

Table 4-2. kW Reduction during PY2023 PJM 5CP

Circuit ID	*7/5/2023*	*7/27/2023*	*7/28/2023*	*9/5/2023*	*9/6/2023*
	5:00 PM - 6:00 PM	*5:00 PM - 6:00 PM*	*5:00 PM - 6:00 PM*	*4:00 PM - 5:00 PM*	*4:00 PM - 5:00 PM*
Whitestone	186.25	224.63	222.69	202.24	206.38
Wyndhurst	279.32	332.59	333.48	319.57	329.01
Total	465.56	557.22	556.17	521.81	535.39

The summarized results for each PJM 5CP hour are presented in Table 4-2 below.

Table 4-3. Summary of kW Reductions during PJM 5CP Hours

Date	*Hour Start*	*Hour End*	*Ex Post Net kW Savings*
7/5/2023	5:00 PM	6:00 PM	465.56
7/27/2023	5:00 PM	6:00 PM	557.22
7/28/2023	5:00 PM	6:00 PM	556.17
9/5/2023	4:00 PM	5:00 PM	521.81
9/6/2023	4:00 PM	5:00 PM	535.39
Maximum Peak kW Reduction			557.22
Average Peak kW Reduction			527.23

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5. Confidential: EM&V Costs

Information relating to PY2023 EM&V costs is presented in Table 5-1.

Table 5-1 PY2023 EM&V Costs

Program	*EM&V Cost*
VoltVar Voltage Control Program	$[redacted]