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Memorandum

To: Andrew Parker, AIC and Jennifer Morris, ICC Staff
From: Opinion Dynamics Evaluation Team
Date: June 16, 2020
Re: Ameren Illinois Company Voltage Optimization CVRf Analysis Results

Introduction

This memo presents the results of the conservation voltage reduction factor (CVRf) analysis for Ameren Illinois Company (AIC). The present study was conducted in accordance with ICC Docket No. 18-0211 (Ameren Illinois Voltage Optimization Settlement Stipulation), which required AIC to complete a study of CVRf values on a sample of Voltage Optimization (VO) circuits by May 1, 2020 to inform the Illinois Statewide Technical Reference Manual (IL-TRM) update process. The analysis was conducted on VO data for 70 circuits where on/off testing was deployed from June 1, 2019 through February 29, 2020, representing Summer, Fall and Winter seasons. This memo presents estimates of circuit specific and average CVRf as well as study limitations and methodology.

Findings

The evaluation team used regression models to estimate a CVRf for each eligible circuit (n=70[1]) and calculated a weighted average of the individual models to estimate an overall CVRf. The average CVRf of all circuits was 0.74. Statistically significant circuit-specific CVRfs ranged from 0.17 to 1.74. Table 1 summarizes the circuit-specific estimated percent reduction in energy, percent reduction in voltage, and CVRf for each circuit. Note that positive values in the percent reduction columns indicate a decrease in MW or kV.

Table 1. AIC Circuit-Specific and Pooled CVRf Model Results

Circuit	% Reduction MWh	SE % Reduction in MWh	MWh P Value	% Reduction kV	SE % Reduction in kV	kV P Value	CVRf	Stat. Sig. at 90%[a]
A17025	3.31%	0.16%	0.00	4.48%	0.56%	0.00	0.739	Yes
A17026	3.70%	0.20%	0.00	4.35%	0.54%	0.00	0.850	Yes
A91003	3.97%	0.22%	0.00	4.97%	0.62%	0.00	0.798	Yes
A91004	4.02%	0.20%	0.00	5.82%	0.73%	0.00	0.691	Yes
B00002	2.45%	0.18%	0.00	3.37%	0.43%	0.00	0.727	Yes
B00003	2.67%	0.18%	0.00	3.37%	0.43%	0.00	0.790	Yes
B44001	3.47%	0.20%	0.00	4.25%	0.54%	0.00	0.816	Yes
B44002	3.22%	0.19%	0.00	4.40%	0.55%	0.00	0.732	Yes

[1] The methodology section provides details regarding the sample size of 70.

Circuit	% Reduction MWh	SE % Reduction in MWh	MWh P Value	% Reduction kV	SE % Reduction in kV	kV P Value	CVRf	Stat. Sig. at 90%[a]
B44003	3.06%	0.20%	0.00	5.26%	0.66%	0.00	0.582	Yes
C52001	2.47%	0.18%	0.00	3.20%	0.43%	0.00	0.771	Yes
C52002	2.30%	0.20%	0.00	2.83%	0.38%	0.00	0.813	Yes
D31015	3.47%	0.21%	0.00	3.97%	0.53%	0.00	0.874	Yes
H00163	3.49%	0.22%	0.00	3.85%	0.51%	0.00	0.907	Yes
H06135	2.74%	0.21%	0.00	3.76%	0.50%	0.00	0.729	Yes
J34357	2.08%	0.23%	0.00	3.54%	0.48%	0.00	0.588	Yes
J34377	2.41%	0.20%	0.00	3.34%	0.45%	0.00	0.720	Yes
J83140	2.39%	0.23%	0.00	3.44%	0.46%	0.00	0.694	Yes
J87111	3.24%	0.31%	0.00	3.34%	0.45%	0.00	0.970	Yes
J87120	3.45%	0.33%	0.00	4.34%	0.58%	0.00	0.795	Yes
J87150	2.76%	0.38%	0.00	3.97%	0.53%	0.00	0.695	Yes
J99121	3.48%	0.35%	0.00	3.77%	0.50%	0.00	0.924	Yes
J99127	4.03%	0.41%	0.00	4.66%	0.62%	0.00	0.864	Yes
J99128	3.07%	0.31%	0.00	3.88%	0.52%	0.00	0.792	Yes
J99141	4.37%	0.47%	0.00	4.39%	0.58%	0.00	0.997	Yes
J99151	8.49%	0.32%	0.00	4.89%	0.65%	0.00	1.737	Yes
K01236	3.52%	0.41%	0.00	5.19%	0.69%	0.00	0.678	Yes
K01238	3.29%	0.45%	0.00	4.60%	0.61%	0.00	0.715	Yes
K01239	2.72%	0.39%	0.00	4.04%	0.54%	0.00	0.674	Yes
K01240	3.41%	0.42%	0.00	4.38%	0.58%	0.00	0.780	Yes
K01241	3.61%	0.44%	0.00	4.24%	0.57%	0.00	0.853	Yes
K11376	2.33%	0.21%	0.00	2.83%	0.38%	0.00	0.825	Yes
K27150	3.30%	0.37%	0.00	3.55%	0.47%	0.00	0.930	Yes
K39153	2.48%	0.18%	0.00	3.61%	0.48%	0.00	0.689	Yes
K39154	2.67%	0.16%	0.00	3.88%	0.52%	0.00	0.689	Yes
K52400	1.93%	0.15%	0.00	3.16%	0.42%	0.00	0.610	Yes
K52401	2.19%	0.21%	0.00	3.93%	0.53%	0.00	0.557	Yes
K52421	2.24%	0.13%	0.00	4.16%	0.56%	0.00	0.538	Yes
K76541	2.53%	0.18%	0.00	3.51%	0.47%	0.00	0.722	Yes
K76542	3.34%	0.20%	0.00	4.52%	0.60%	0.00	0.739	Yes
K76543	2.32%	0.32%	0.00	4.22%	0.56%	0.00	0.551	Yes
K76545	2.04%	0.36%	0.00	3.73%	0.50%	0.00	0.545	Yes
K76546	3.31%	0.27%	0.00	4.32%	0.58%	0.00	0.767	Yes
K76547	2.50%	0.26%	0.00	3.67%	0.49%	0.00	0.680	Yes
K89141	2.65%	0.12%	0.00	4.12%	0.55%	0.00	0.642	Yes
K89142	0.72%	0.37%	0.05	4.18%	0.56%	0.00	0.173	Yes
L12126	3.47%	0.22%	0.00	5.04%	0.67%	0.00	0.688	Yes

Circuit	% Reduction MWh	SE % Reduction in MWh	MWh P Value	% Reduction kV	SE % Reduction in kV	kV P Value	CVRf	Stat. Sig. at 90%[a]
L93132	5.80%	0.41%	0.00	3.56%	0.47%	0.00	1.630	Yes
M36184	2.83%	0.13%	0.00	4.14%	0.55%	0.00	0.683	Yes
M36185	3.21%	0.22%	0.00	4.01%	0.54%	0.00	0.801	Yes
P17108	3.41%	0.24%	0.00	4.14%	0.55%	0.00	0.825	Yes
P58155	3.00%	0.37%	0.00	4.06%	0.54%	0.00	0.739	Yes
P69173	3.77%	0.29%	0.00	3.15%	0.42%	0.00	1.198	Yes
Q34360	2.85%	0.19%	0.00	3.08%	0.41%	0.00	0.926	Yes
Q83168	3.48%	0.27%	0.00	4.90%	0.65%	0.00	0.710	Yes
Q83172	2.22%	0.26%	0.00	4.01%	0.53%	0.00	0.553	Yes
R73840	4.34%	0.21%	0.00	3.58%	0.48%	0.00	1.213	Yes
U31565	2.46%	0.20%	0.00	3.78%	0.51%	0.00	0.649	Yes
U31598	2.03%	0.17%	0.00	4.76%	0.64%	0.00	0.426	Yes
U32579	1.85%	0.17%	0.00	4.29%	0.57%	0.00	0.431	Yes
V40556	1.95%	0.18%	0.00	3.60%	0.48%	0.00	0.542	Yes
V41533	2.16%	0.18%	0.00	3.33%	0.44%	0.00	0.649	Yes
V42572	3.18%	0.16%	0.00	3.81%	0.51%	0.00	0.836	Yes
V45574	2.31%	0.12%	0.00	3.48%	0.46%	0.00	0.663	Yes
X12525	1.19%	0.67%	0.08	4.24%	0.57%	0.00	0.280	Yes
X12526	2.36%	0.35%	0.00	3.21%	0.43%	0.00	0.736	Yes
X35501	2.45%	0.16%	0.00	4.22%	0.56%	0.00	0.581	Yes
Y36559	3.57%	0.23%	0.00	3.85%	0.51%	0.00	0.929	Yes
Y37593	2.93%	0.19%	0.00	4.69%	0.63%	0.00	0.626	Yes
Y79500	2.17%	0.16%	0.00	3.28%	0.44%	0.00	0.662	Yes
Y98532	0.50%	0.50%	0.32	4.34%	0.58%	0.00	0.115	No

[a] The "Stat Sig at 90%" column indicates circuits for which the estimated percentage reduction in both MWh and kV were statistically significant at 90% confidence.

Study Limitations

When interpreting these results, it is important to consider the following:

- **Results represent a limited number of sample circuits.** The results of the CVRf analysis are based on on/off testing data from 70 circuits out of the eventual 1,047 circuits that AIC will deploy by 2024. The number of available circuits for on/off testing represents the number that was feasible for AIC to deploy by June 1, 2019 to meet the Stipulation deadline. Based on a power analysis conducted by the evaluation team, the ideal sample size would have been nearly double this amount (n=131).
- **Results do not reflect a full year of data.** This study does not include data from March, April, or May, which represent the Spring season, and as a result, the circuit specific and average CVRf do not represent annual results. Existing literature suggests that there may be seasonal variations of CVRf

due to different weather and human behaviors, likely related to load composition.[2] For this reason, the omission of spring data could bias the CVRf results.

Given these limitations (i.e., the inherent uncertainty surrounding the generalizability of the sample of circuits, and the seasons incorporated within the analysis), the evaluation team does not feel that these results on their own provide sufficient evidence to support a change to the Stipulated CVRf value. For that reason, it is important to note this analysis was developed to inform the IL-TRM update process, specifically for inclusion in a statewide predictive model to develop a CVRf look-up table based on circuit characteristics. As such, we do not feel that these results should be used independently.

Methodology

Below we summarize the various components of the methodology used to estimate CVRf.

Data Sources

The data sets for this analysis include supervisory control and data acquisition (SCADA) data and VO system on/off logs received from AIC, and weather data from the National Oceanic and Atmospheric Administration (NOAA):

- Data start date: 2019-06-01
- Data end date: 2020-02-29

Core inputs for the analysis include:

- Hourly power readings (measured in MW) and hourly voltage readings (measured in kV) from SCADA data
- VO system on/off logs
- Hourly weather data from NOAA

Importantly, though most circuits for the on/off testing went live on June 1, 2019, some circuits came online later in the month. As a result, we implemented a go-live cut-off date of July 1, 2019. This criterion resulted in the eligibility of 70 out of the intended 77 circuits.[3] Additionally, the seven circuits that were removed from the analysis also did not meet the criteria of having circuit-level voltage data, as voltage data was only available at the sub-station level. Data for the resulting 70 circuits were cleaned prior to modeling.

Data Ingestion and Processing

Prior to conducting the analysis to generate CVRf estimates, the evaluation team ingested core inputs and joined them for each feeder. System status, hourly voltage, and hourly power readings for each circuit with go-live dates before July 1, 2019 were joined first for all 70 eligible circuits. Next, weather data were imported from NOAA's National Climatic Data Center (NCDC) server of Quality Controlled Local Climatological Data

[2] Wang, Z. and Wang, J. 2014. Review on Implementation and Assessment of Conservation Voltage Reduction. IEEE Transactions on Power Systems, Vol. 29, NO. 3

[3] The circuits removed from the analysis included substation B80 circuits B80001 through B80004 (n=4) and substation D89 circuits D89001 through D89003 (n=3).

(QCLCD) for each circuit's location. All 70 circuits had applicable weather data available. Where temperatures were above 100 degrees for fewer than 4 consecutive hours or where data were missing for fewer than 4 consecutive hours, data were filled with linear interpolation. Where temperatures were above 100 degrees for more than 4 consecutive hours or where data were missing for more than 4 consecutive hours, temperatures were pulled from the next-closest weather station.

Data Cleaning

The following data cleaning steps were conducted prior to modeling:

- **Missing values**: Missing and non-numeric values in kV and MW were removed from the analysis.
- **Interpolated or repeated values**: Prior evaluations of VO have revealed that SCADA systems commonly interpolate or repeat data inputs across gaps in time series caused by equipment failures, comms failures, or inappropriately broad bandwidths. Interpolation was flagged in cases where a constant slope in MW or kV was detected across two or more time points. Repeated values were flagged in cases were repeated between two or more time points. Interpolated and repeated values in kV and MW data were removed from the analysis.
- **Negative and zero values**: Negative and zero values in kV data were flagged and removed from the analysis. In cases where a three-phase device recorded zeros for one of the phases, the zeros were removed, and the average voltage was taken based on the other two reported values.
- **Outliers**: Outliers were screened on a circuit-by-circuit basis. Outliers are currently defined as hourly values that are greater than 3 times the standard deviation from the mean kV or MW for that specific circuit. Outliers on kV and MW were flagged and removed from the analysis.
- **Excludable times**: AIC, ICC Staff, and stakeholders have reached agreement that a subset of VO events ("excludable events") should be excluded in this analysis. Types of VO events that were approved for exclusion were those that (1) had a circuit outage for any reason, (2) had repair or maintenance, causing VO to be disabled, (3) had switching occurring (where VO was disabled due to any necessary switching event), and (4) had experienced a failure in information or communication technology. All excludable events and associated kV and MW were removed from the analysis.

Table 2 summarizes the data removed from the analysis.

Table 2. Data Cleaning Results for the CVRf Analysis

Step	Circuits	Rows	Change	% Change
Flag and remove excludable hours	70	859,702	40,170	4.464%
Flag and remove interpolated values	70	917,017	3,823	0.415%
Flag and remove kV and MW values greater than 3 standard deviations from the mean	70	899,872	2,459	0.273%
Flag and remove negative and zero values	70	902,331	10,004	1.097%
Flag and remove repeated values	70	912,335	4,682	0.511%
Join kV and MW data	70	920,840	N/A	N/A
Join weather data	70	920,840	0	0.000%

Regression Methodology

To provide estimates of CVRf for circuits with data available, we calculated circuit specific regressions. Circuit specific estimation of changes in MW and kV associated with VO were estimated via the following two equations, respectively:

$$MW_{it} = \alpha VO_{it} + \sum_{h=1}^{24} \beta_h * {}^{\tau_{h,WD}} + \sum_{h=1}^{24} \lambda_h * {}^{\tau_{h,WE}} + \gamma CDH_{it} + \omega CDH_{it}^2 + \phi HDH_{it} + \mu HDH_{it}^2 + e_{it}$$

$$kV_{it} = \alpha VO_{it} + \sum_{h=1}^{24} \beta_h * {}^{\tau_{h,WD}} + \sum_{h=1}^{24} \lambda_h * {}^{\tau_{h,WE}} + \gamma CDH_{it} + \omega CDH_{it}^2 + \phi HDH_{it} + \mu HDH_{it}^2 + e_{it}$$

where:

- η_i: A circuit fixed effect, controlling for fixed circuit characteristics that may affect VO savings
- VO_{it}: An indicator equal to 1 when the VO system is engaged ("on") and 0 otherwise, generating savings estimate α
- ${}^{\tau_{h,WD}}$; ${}^{\tau_{h,WE}}$: Hourly MW or kV fixed effects for circuit i during hour-of-day h during a weekday or weekend, respectively
- CDH_{it} and CDH_{it}^2: Cooling degree hours, base 65, and its square to capture nonlinear impacts of temperature on cooling load
- HDH_{it} and HDH_{it}^2: Heating degree hours, base 65, and its square to capture nonlinear impacts of temperature on heating load
- e_{it}: In the pooled model, this is the cluster-robust error term for circuit i at time t; cluster-robust errors account for heteroskedasticity and autocorrelation at the circuit-level. Note: Only pooled modeling uses cluster-robust errors, as clustering at the circuit-level is not required for circuit-level modeling

Each term in the equations was interacted with $Season_t$, a 4-level variable indicating whether time t falls in the spring, summer, winter, or fall season. Interaction of $Season_t$ with other covariates allows for seasonal differences in load shapes, temperature effects, and other seasonal characteristics that drive demand or voltage but may not be fully captured in the available data.

CVRf Calculation

The core estimated change in MW and kV attributed to the VO system being powered on is given by α, hereby referred to as α_{MW} and α_{kV} . Percentage changes in energy (MWh) and voltage (kV) were estimated as follows:

$$\%\Delta MWh = \frac{\alpha_{MW}}{\mu_{MW}^{off}}$$

$$\%\Delta kV = \frac{\alpha_{kV}}{\mu_{kV}^{off}}$$

where μ_{MW}^{off} indicates the mean MW observed during the system off period of the on/off testing, and μ_{kV}^{off} indicates the mean kV observed during the system off period of the on/off testing.

Resulting estimates are then used to generate a circuit specific CVRf, calculated as:

$$CVRf = \frac{\%\Delta MWh}{\%\Delta kV}$$

After circuit specific CVRf estimates were generated, a load-weighted average was calculated. Here, a load-weighted average was calculated as the product of circuit-level $CVRf_i$ and $\mu_{MWh,i}^{Off}$, the circuit's average energy usage during the VO off period, divided by the summation of all 70 circuits' average energy usage during the VO off period:

$$CVRf_{AIC} = \frac{\sum_{i=1}^{70} CVRf_i * \mu_{MWh,i}^{Off}}{\sum_{i=1}^{70} \mu_{MWh,i}^{Off}}$$