Understanding Voltage Sag Impact on Large Industrial Consumers

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Abstract -- Voltage sags on the transmission system frequently result in down time, waste, and lost productivity for large industrial consumers. This paper discusses how the Tennessee Valley Authority measures transmission-level voltage sag performance through the Large Sensitive Consumer Voltage Sag metric, and how the metric informs targeted transmission investment and maintenance. We will discuss factors impacting consumer voltage sag exposure, the tools used to collect voltage sag impact data, and how the metric enables strategic partnership with sensitive consumers to improve voltage sag ride through performance.

I. INTRODUCTION

The Tennessee Valley Authority (TVA) is a generator and transmission owner/operator serving 153 local power companies and 65 transmission-connected large industries and federal facilities in the watershed of the Tennessee River Valley. This service area encompasses more than 10 million people, providing power through a network of 16,000 miles of high voltage transmission lines and 2,300 substation buses across a seven-state footprint [1], shown in Figure 1.

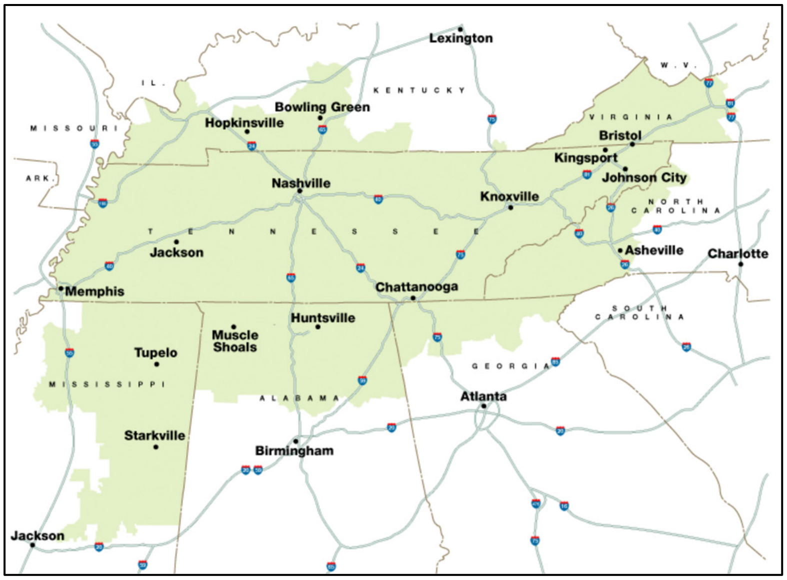


Figure 1 - TVA Service Territory

Site Selection Magazine has named TVA one of the top 10 utilities in economic development for the 17th straight year [2], engaging existing businesses and industries to help them grow in a sustainable way. TVA is committed to serving our communities and corporate citizens to help them achieve lasting success in our dynamic, prosperous region. The population of the TVA region has grown over 8% in the last 10 years [3] and TVA is committed to grow jobs to match this population growth. One focus for expansion is the industrial sector.

Industrial consumers run highly efficient processes and do not want power problems impacting production. Modern industries in TVA's service territory have expressed the need for highly reliable power as well as power delivery without momentary deviations. TVA management recognizes this need and has instructed the transmission organization to minimize transmission-related disturbances to allow for the most industrial efficiency possible.

TVA actively monitors transmission power quality performance for a subset of consumers known as Large Sensitive Consumers (LSCs). LSCs have a contract demand of 10 MW or more and operate industrial manufacturing or large-scale data processing facilities. United States federal government installations of any size are also included in the LSC population. LSCs include TVA directly served and local power company served facilities that are closely connected to the transmission system due to their size. In 2023, there are 169 LSCs in TVA's service territory with cumulative contract demand of approximately 7,450 megawatts and over 85,000 employees. The industries represented include food production, textiles, paper, printing, chemicals, rubber, plastics, primary metals, electronics, and automobile manufacturing. LSCs commonly rely on continuous, automated processes and electronic components that are sensitive to disruption due to voltage sags.

One important way to assist industries is to allow them to be minimally impacted due to weather related events such as voltage sags that may occur during thunderstorms. When a fault occurs on the line (typically due to lightning) high currents flow towards the faulted location temporarily sagging the voltage in the area. These voltage sags are of short duration – usually less than one tenth of one second – associated with the time needed to clear the faulted line from the transmission grid. Sensitive electronic equipment may detect the event and shut down, resulting in downtime, waste, and lost productivity [4].

This paper discusses how TVA measures transmission-level voltage sag performance through the Large Sensitive Consumer Voltage Sag (LSCVS) metric. We will discuss factors impacting consumer voltage sag exposure, the tools used to collect voltage sag impact data, and how the LSCVS metric enables strategic transmission investment and partnership with sensitive consumers to improve voltage sag ride through performance.

II. VOLTAGE SAG BACKGROUND

A. *Definition*

One of the foundational commitments of TVA is the delivery of reliable electric service to the people of the Tennessee Valley. For many consumers – particularly sensitive industrial consumers with high load factors – the distinction between *reliability* and *power quality* has become increasingly obscured to the extent that the terms are inseparable in importance and consequence. Power quality can be defined as the "electromagnetic phenomena that characterize the voltage and current at a given time and at a given location on the power system" [5]. This manifests in a variety of forms including transients, imbalance, and distortion, but the most common power quality event on the TVA system is a voltage sag. Measured in terms of both magnitude and duration, a voltage sag "is a decrease in rms voltage to between 0.1 per unit (pu) and 0.9 pu for durations from 0.5 cycles to 1 minute" [6]. The events are categorized by the lowest voltage relative to nominal measured across the entirety of the duration for which voltage stayed at or below 90% of nominal as shown in Figure 2.

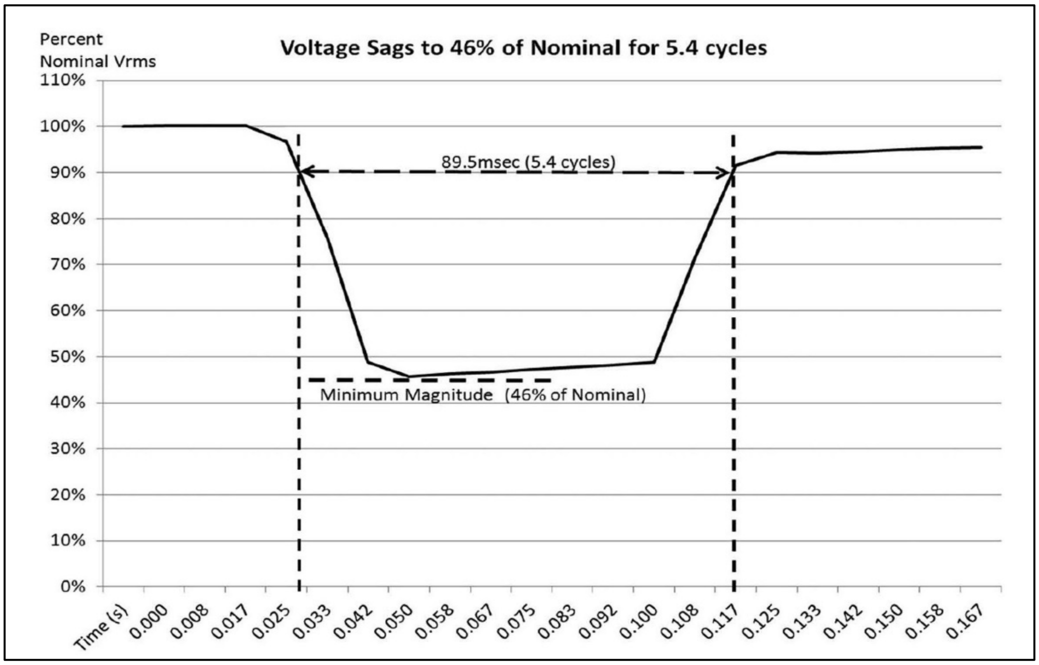


Figure 2: Single-phase voltage sag (instantaneous voltage rms plot) [6, Figure 1]

Voltage sags can be initiated by system-connected load activity, such as the starting of large motors, but the vast majority of measured voltage sags are initiated by faults on the electric system. Like a stone cast into a body of water, a single system fault can propagate a voltage sag that ripples across the interconnected utility grid.

B. *Impact Factors*

The voltage sag phenomenon is certainly not new, and in many cases, the occurrence of voltage sags is imperceptible and without effect. However, changes to the electric grid and modern trends in consumer equipment have elevated both the frequency and impact of these events. TVA utilizes the concept of *Area of Vulnerability* (AOV) to evaluate consumer risk for voltage sags in terms of transmission system exposure. This AOV measurement quantifies the transmission line segments for which a system fault will produce a voltage sag between 0.1 pu and 0.9 pu at a given bus. Figure 3 provides a visual representation of an example consumer bus with an AOV of 152 miles.

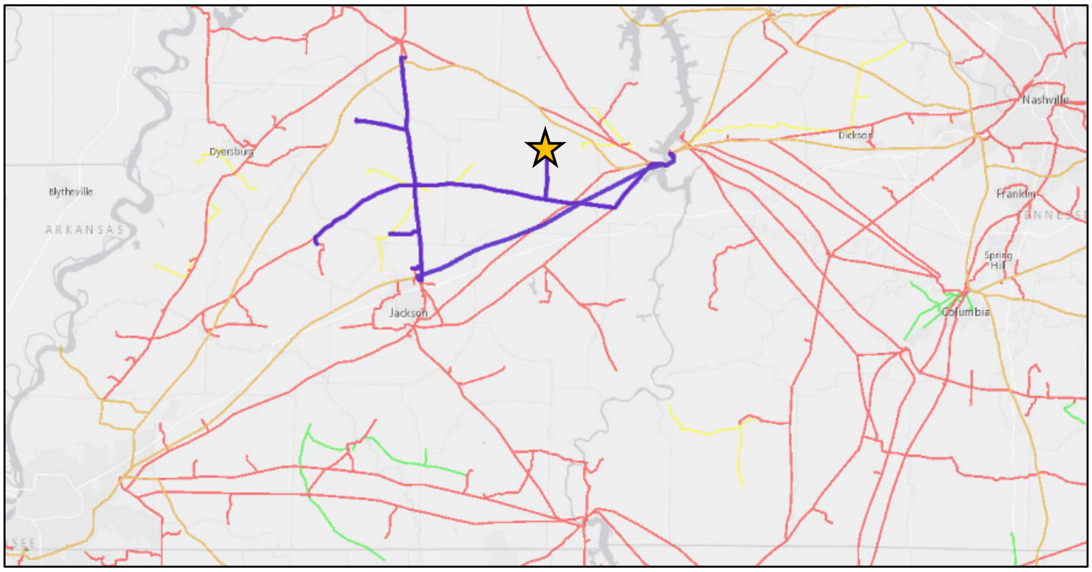


Figure 3: Original Consumer Area of Vulnerability

Like many large-scale electric utilities in the United States, the TVA grid is in a state of transformation. The fossil fuels that once powered rotating generators will be retired in favor of renewable, inverter-based resources (IBR), and the transmission system will be adapted accordingly. An emerging consideration in planning these changes is the impact to AOV. One characteristic of the fossil plant that is not replicated in its modern IBR-equivalent is the inertia of a rotating machine that serves to dampen the reach of voltage sags following a system fault, among other benefits. Without this dampening effect, AOV for local consumers would increase. Compounding the effect is the resultant transmission system adjustment that often accompanies these generation changes. As the generation portfolio becomes more reliant on renewables, it becomes less localized to load and more regionalized to geographical resources. As a result, TVA is more heavily relying on its extra high voltage (EHV) network to move energy to the demand, and this has necessitated intertie transformer banks that more tightly couple the high voltage (HV) and EHV networks. The closer relationship between these systems also results in an increase to local consumer AOV. To illustrate this, consider the consumer bus previously shown in Figure 3. Figure 4 illustrates how after a local coal plant was retired and a new EHV:HV intertie bank was installed, the AOV more than tripled. Not surprisingly, an industrial consumer served from that bus saw a significant increase in the frequency of voltage sags.

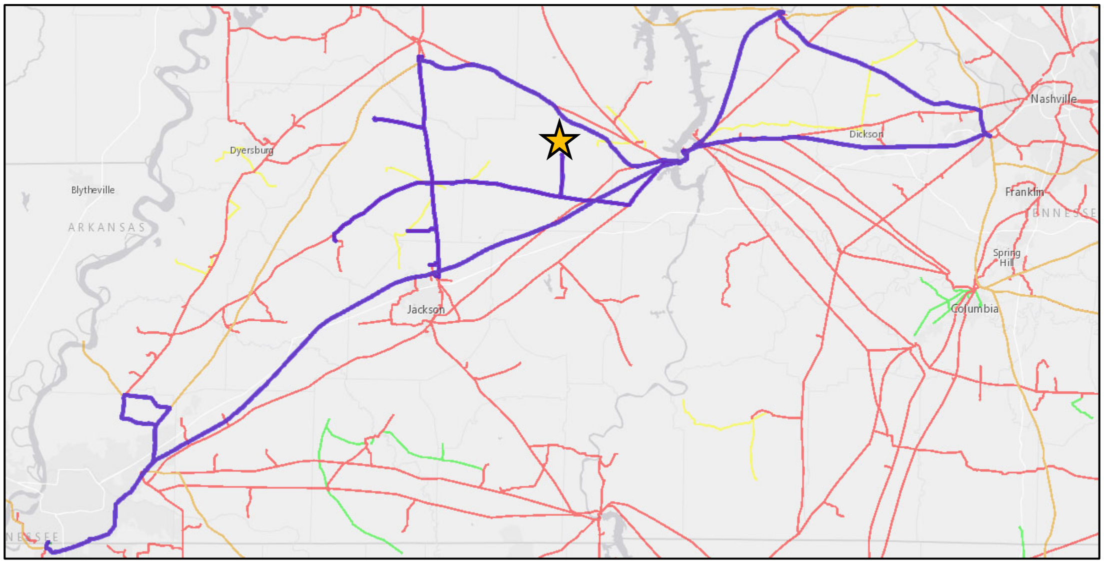


Figure 4: Increased Consumer Area of Vulnerability After Grid Changes

At the same time that the electric utility grid is undertaking material transformative changes, industrial consumers are also modernizing the equipment they rely on for their business processes. Digital controls, variable speed drives, and robotic technologies are just a few examples of process equipment with an increased sensitivity profile relative to the technologies that preceded them. Electric Power Research Institute (EPRI) has tested thousands of these devices to ascertain the performance parameters that are adversely affected even under mild (low magnitude, low duration, or both) voltage sag conditions. The cumulative effect of these changes both for the grid and the industrial consumer is that the demand for adequate planning and an effective strategy to manage voltage sag performance is as critical to power quality as it has ever been.

C. Example

A recent example on the TVA system helps bring real-world context to the principles described herein. In August 2022, a 127-kA lightning strike faulted a 500-kV transmission line. The strike flashed across faulting all three phases and damaged insulators in the process. The protective relaying acted as designed with all primary elements clearing the fault and isolating the interruption to the faulted transmission line alone. Because this was a multi-phase fault on an EHV system line, the resultant voltage sag was seen broadly throughout the service area. Figure 5 provides a contour map of the instantaneous voltage depression in terms of the nominal voltage (pu).

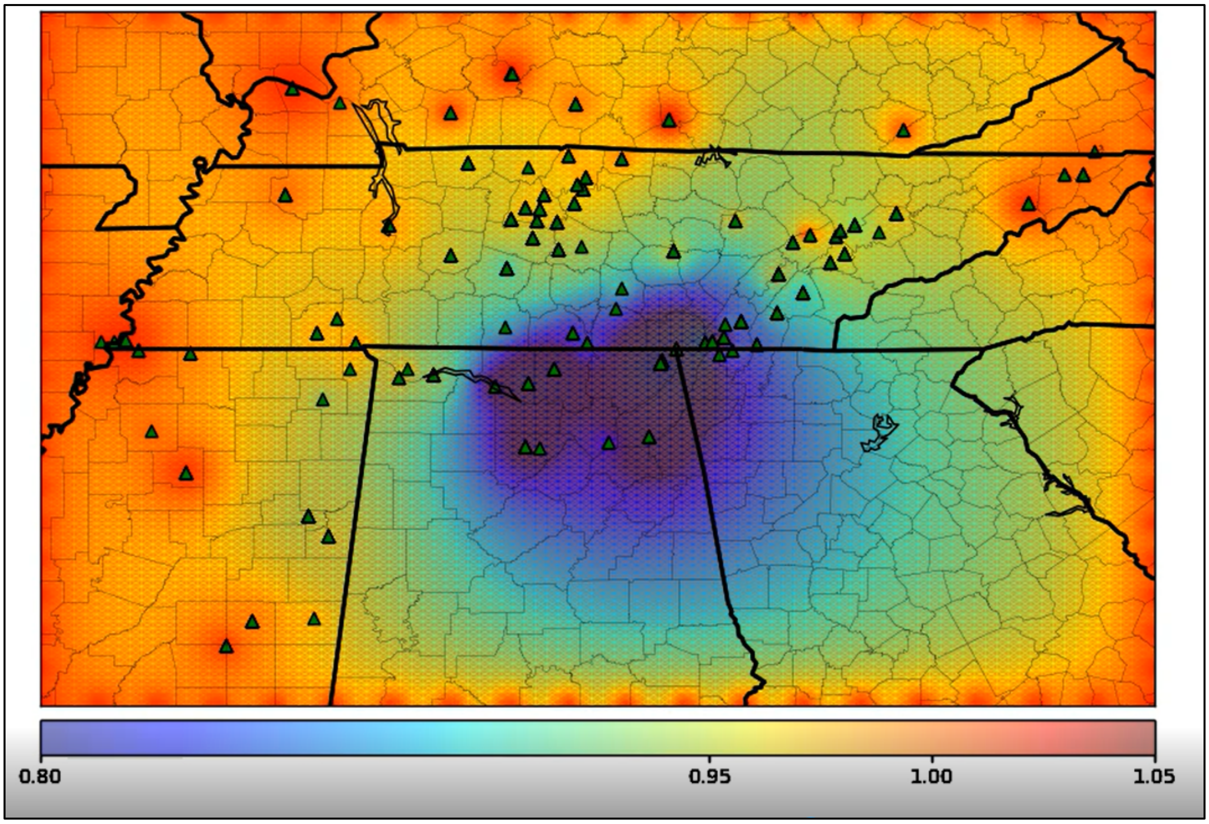


Figure 5: Instantaneous Voltage Contour Map (pu) Corresponding with a 500-kV Line Fault

Visualizing the reach of the impact is striking, but the true measure of its impact is seen by examining the profile of the TVA net system load coincident to this event. Figure 6 captures an instantaneous load loss of over 300 MW. Recall that this fault occurred on an EHV system transmission line, meaning it directly serves no customers, and cleared normally requiring no backup elements. This means that no customers experienced a power interruption as a result of this fault. The lost load, then, can fully be attributed to the widespread voltage sag and the sensitivity of consumer equipment that was unable to ride through such an event. Traditional reliability metrics would be unaffected by a system fault that produced no interruptions, but the experience for many consumers in this instance would not discriminate between reliability and power quality. This underscores the need to mature our approach to power quality with performance metrics that yield meaningful results with impactful actionable goals.

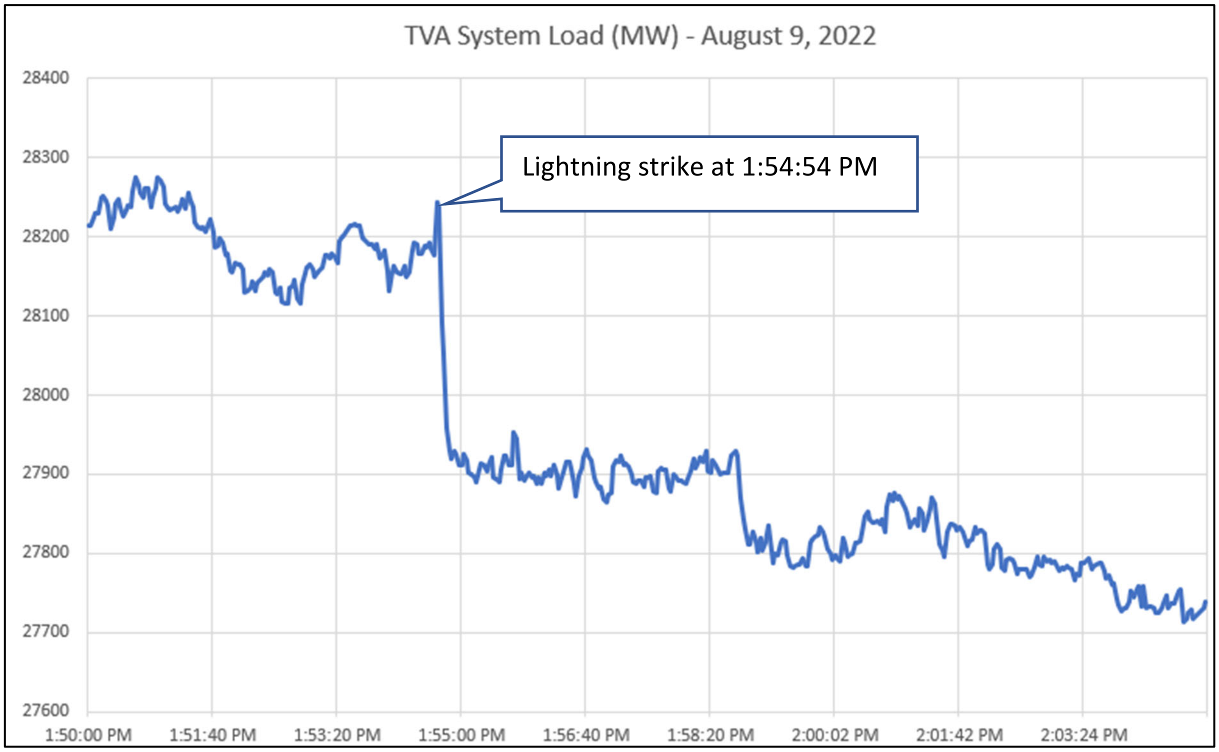


Figure 6: TVA System Load Reduction Corresponding with 500-kV Line Fault

III. IEEE 1668 DISCUSSION

The Institute of Electrical and Electronics Engineers (IEEE) Standard 1668 [6] (IEEE 1668) provides a non-industry specific recommended practice for voltage sag ride-though performance of end-use equipment. The recommended practice defines minimum voltage sag immunity requirements, providing consumers with a performance benchmark that can be used to specify new equipment and identify underperforming existing equipment. TVA staff actively participated in development of the recommended practice which is built upon previous standards such as ANSI C84.1 [7], IEC 61000-4-34 [8], and SEMI F47-0706 [9].

Voltage sags are commonly characterized by magnitude and duration. When analyzing multiple events, it is best to display them using a scatter plot. Figure 7 illustrates how a 0.536 pu voltage sag lasting 57.4 milliseconds (3.6 cycles) can be displayed as one data point. Normally, long-term (say 5-years) power quality studies will have multiple events each displayed with a magnitude and duration dot. It is important to look for recurring issues that tend to show up over time with the distribution of the dots.

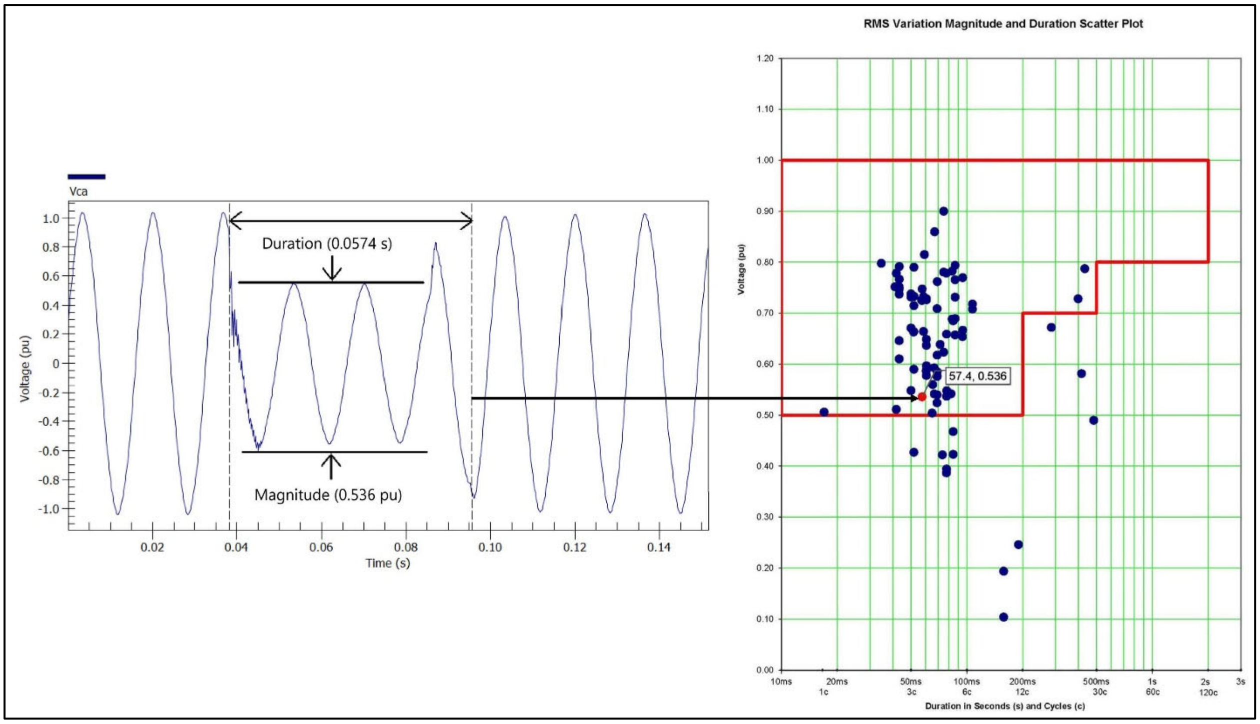
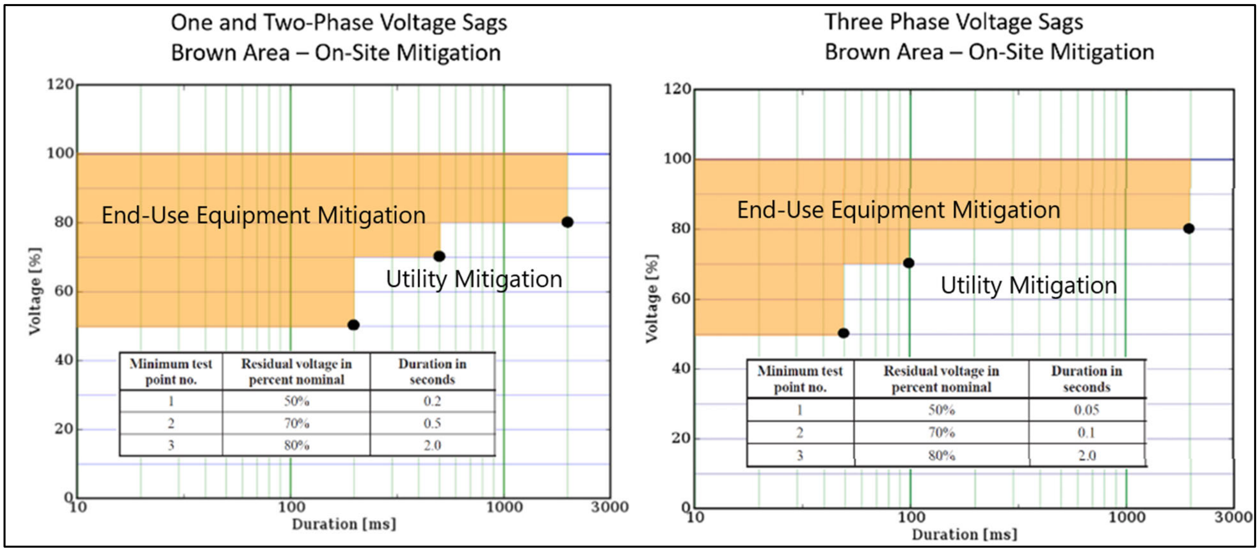


Figure 7: Voltage Sag Magnitude and Duration

Because a voltage sag at the terminals of sensitive equipment may involve one, two, or three phases, there are two IEEE 1668 curves defining recommended device voltage sag immunity levels. These curves are shown in Figure 8.



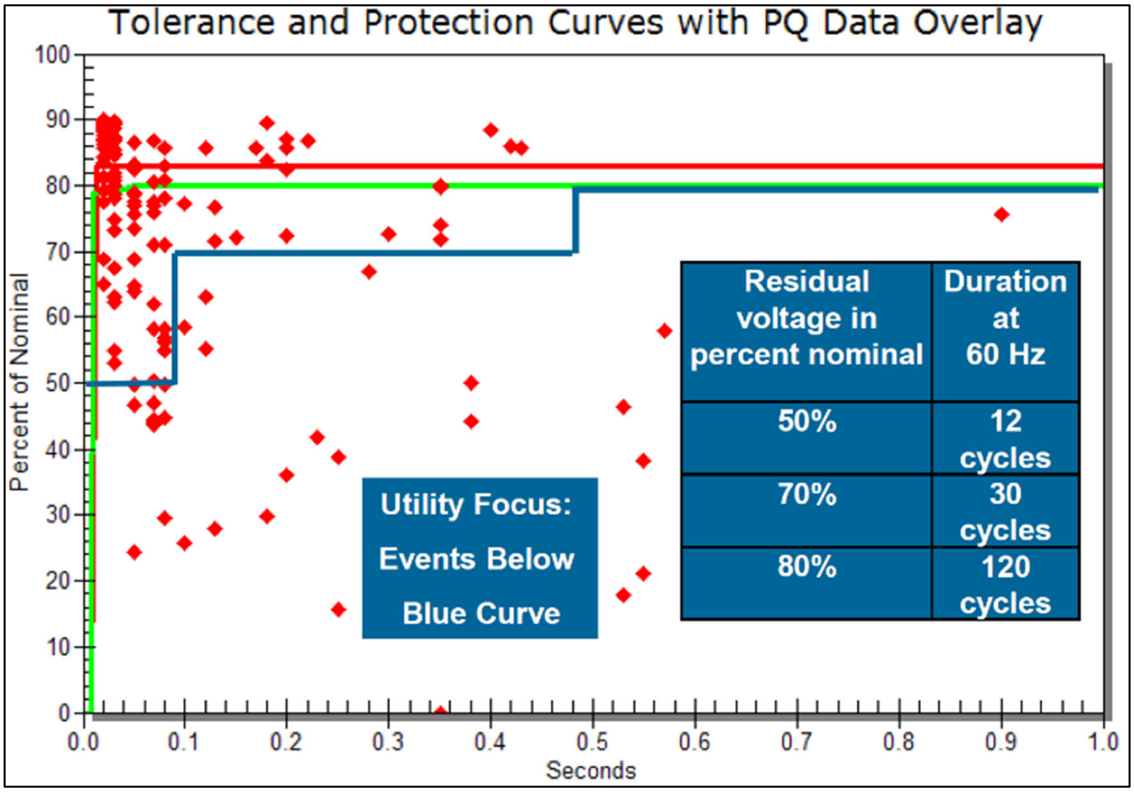
Minimum test point no.	Residual voltage in percent nominal	Duration in seconds
1	50%	0.2
2	70%	0.5
3	80%	2.0

Minimum test point no.	Residual voltage in percent nominal	Duration in seconds
1	50%	0.05
2	70%	0.1
3	80%	2.0

Figure 8: IEEE 1668 Voltage Sag Immunity Curves [6, Figures 22,23]

The IEEE 1668 characterization of the magnitude and duration of each sag as “inside” or “outside” of recommended end-use equipment voltage sag immunity curves dictates where impact mitigation is most cost effective. For voltage sags that fall inside the IEEE 1668 curves, the mitigation focuses on hardening end-use equipment to improve voltage sag ride through performance. For sags that fall outside the curves, TVA’s mitigation focus is on transmission improvement projects to reduce the occurrence and severity of voltage sags impacting the consumer. From 2017 to 2021, approximately 75% of TVA transmission-caused voltage sags having magnitude of 0.8 pu or less recorded at TVA LSCs were characterized as inside the IEEE 1668 recommended immunity curves shown in Figure 8.

Figure 9 illustrates the impact of specifying IEEE 1668 compliant control components. The red and green lines correspond to the voltage sag immunity curves of typical 120 Volt ac control relays. The standard relays would trip for the 72 voltage sags falling below the red line. The enhanced voltage sag immunity offered by an IEEE 1668 compatible relay is indicated by the blue line. Only 31 events fall below the blue line, which indicates a 57% reduction in unwanted relay tripping. All electrical equipment can be hardened to meet the IEEE 1668 tolerance limits. This includes motor systems, process rectifiers, induction furnaces, HVAC systems, boiler systems just to name a few. For new industrial facilities, specifying IEEE 1668 compliant equipment will reduce the likelihood of equipment mis-operation due to voltage sags.



Residual voltage in percent nominal	Duration at 60 Hz
50%	12 cycles
70%	30 cycles
80%	120 cycles

Figure 9: Control Relay Voltage Sag Immunity Curves (Example courtesy of EPRI)

IV. TOOLS

A. Power Quality Monitoring Infrastructure

TVA first deployed stand-alone power quality monitors (PQM) on the transmission system in 2000 as an EPRI research and development project. The initial deployment included a fleet of 70 PQMs which grew to a few hundred over the following decade. Most commonly, the PQM would be installed in a panel or cabinet adjacent to a revenue meter with the PQM recording the same voltage and current signals as the revenue meter. In 2010, the decision was made to begin deploying a multi-function PQM / revenue meter as the standard. This decision accelerated the growth of the PQM fleet with over 2,500 devices in service by 2022. All PQMs deployed today comply with IEC 61000-4-30 Class A [10] requirements and are configured per IEEE and IEC standard specifications. This provides optimal PQ monitoring visibility at each interconnection and consumer delivery point. This visibility is particularly critical at LSC locations.

The growing PQM fleet and the large data requirements represent a challenge to data transport, processing, and storage. Many of the stations on the Bulk Electric System (BES) are equipped with secure high-speed networks; however, customer stations tapped on transmission lines, especially in remote areas, may not have a secure high-speed network available. In such cases virtual private networks (VPNs) over cellular routers or secure radio spectrum communication are utilized. For security purposes, all communication must originate from the more secure zone; therefore, polling software installed on servers in the System Operations Center (SOC) initiate data downloads from the PQMs at the field stations to a file-share at the SOC. Companion software then automatically processes the data files into a database while also performing near real-time analysis, notification, and reporting.

B. Large Sensitive Consumer Voltage Sag Application

To facilitate timely analysis and interpretation of actual consumer impact of recent transmission disturbances, TVA has commissioned development of a web-based software tool known as the Large Sensitive Consumer Voltage Sag (LSCVS) application. This tool aggregates PQM event data, transmission disturbance and cause data, and consumer load profile data on one platform.

The LSCVS application automatically populates a list of voltage sags recorded at LSC PQMs for a user-input date and time range, including magnitude and duration data. The user may select the desired maximum voltage sag magnitude for inclusion in the list (e.g., 0.7, 0.8, or 0.9 pu), permitting custom voltage sag lists to be created for a variety of business needs. The tool automatically associates voltage sags with LSC facilities and characterizes the voltage sags as inside or outside the IEEE 1668 voltage sag immunity curves (see Figure 8, above). Each voltage sag line item includes a visual representation of the root mean square (rms) voltage and current during the event, allowing the user to quickly identify and flag events where the voltage sag was caused by consumer equipment, not a transmission asset. Additionally, voltage sags erroneously triggered by a PQM can be quickly identified and deleted.

The application pulls data from TVA's transmission disturbance database, and displays a disturbance list including the date, time, description of faulted asset, and disturbance cause on a dedicated page within the application. On the voltage sag list page, the application automatically populates a drop-down list of transmission disturbances occurring within twelve hours of the voltage sag under study. The user selects the correct event from the list, establishing a parent-child relationship between the transmission disturbance and resulting voltage sag seen by an LSC.

On the voltage sag list page, each LSC voltage sag line item includes a field for the consumer megawatt hour impact associated with the sag. By clicking this field, the user opens a calculation tool which automatically displays the pre- and post-event load profile for the consumer. The tool automatically calculates the pre-voltage sag average load and allows the user to specify when the load recovers to pre-event levels. The megawatt hours not consumed due to the voltage sag are automatically calculated and stored.

The output of the LSCVS software tool is a database-stored flat list of voltage sag events and associated cause and consumer impact data. In the future, this database will enable users to generate custom reporting to quickly determine the actual consumer impact due to voltage sags caused by specific transmission disturbances.

V. LARGE SENSITIVE CONSUMER VOLTAGE SAG METRIC

Traditional reliability metrics measure the frequency and duration of service interruption. That definition of reliability is inadequate for large industrial facilities as it fails to capture the downtime, waste, and lost productivity frequently caused by voltage sags. TVA leverages power quality and other data streams to quantify transmission voltage sag performance as seen by the largest consumers in the service territory. This section discusses the LSCVS metric, and how the metric is evolving from a focus on voltage sag quantity to a focus on driving investment to improve performance based on actual voltage sag impact.

A. LSCVS Metric Definition

The LSCVS metric tracks the average number of qualifying voltage sags seen by the LSC population each month, reported as a unit rate – number of sags divided by the number of LSCs – normalized to a 30-day month. The results are aggregated to provide fiscal year to date performance trending and are reported monthly at the TVA Chief Operating Officer Level.

For inclusion in the metric, a fault at a TVA asset or a neighboring utility asset must cause the PQM associated with an LSC to record a voltage sag to less than 0.8 pu of nominal line-to-line voltage. This threshold was chosen to align with the IEEE 1668 recommended voltage sag immunity levels illustrated in Figure 8, above. End-use equipment is expected to ride through voltage sags to 0.8 pu of nominal for up to two seconds, which is much longer than the typical transmission fault clearing time.

Voltage sags caused by assets owned by the LSC, or assets owned by the local power company that supplies the LSC are excluded from the metric as self-caused. During restoration of a typical transmission line fault, a line may be tested resulting in more than one voltage sag to an LSC. In these cases, the most severe voltage sag seen by the LSC in a one-hour period is counted against the metric. Momentary or sustained interruptions experienced by LSCs are captured by traditional reliability metrics and are not included in LSCVS. Voltage sags caused by severe weather events such as tornadoes and storms meeting pre-defined thresholds for transmission impact are also excluded from LSCVS.

For each qualifying voltage sag, the following basic data is reported:

- Large Sensitive Consumer name
- Event date and time
- Voltage sag magnitude and duration
- Faulted station or line name (asset)
- Fault cause

B. Shifting Focus from Voltage Sag Quantity to Impact

The existing voltage sag quantity focused LSCVS metric has yielded important insights into transmission voltage sag performance. First, it allows identification of the LSCs that experience the highest number of voltage sags and the transmission assets and fault causes that most frequently cause those sags. Considering LSCVS data from 2017 to 2021, over 60% of LSCVS voltage sags were experienced by just 25% of the LSC population. This subset of LSCs were more likely to report process disruptions due to voltage sags and dissatisfaction with transmission power quality. Another important insight is that the magnitude and duration of over 75% of metric voltage sags during this period was inside the IEEE 1668 curves. This means that with proper equipment specification and industrial power and control design practices, it is feasible for end-use consumer equipment to ride through these voltage sags without impacting production. Applying the IEEE 1668 recommended voltage sag immunity curves, less than one quarter of the voltage sags experienced by LSCs were of magnitude and duration requiring action by the utility to prevent or lessen the severity of the sags.

The voltage sag quantity-focused metric yields no information about which LSCs have sensitive process equipment that is prone to be disrupted by mild voltage sags, and which LSCs have robust process equipment that can ride through most voltage sags without impact. Additional data is required to identify sensitive consumers and target investments where they will have the largest impact on improving voltage sag ride through performance.

Beginning in 2023, the LSCVS metric is evolving to align the performance indicator with the IEEE 1668 standard and the actual consumer impact of transmission-caused voltage sags. In addition to the basic data indicated above, the following data is also recorded for each qualifying voltage sag:

- IEEE 1668 voltage sag type (one, two, or three phase)
- Voltage sag magnitude and duration characterized as inside or outside of IEEE 1668 voltage sag immunity curves.
- LSC megawatt hour impact

Capturing this information enables strategic investment to reduce the actual impact of transmission-caused voltage sags to LSCs. The LSC megawatt hour impact calculation is critical to determine which voltage sags require mitigation and which voltage sags are compatible with end-use equipment voltage sag immunity levels.

Figure 10 illustrates an example of an LSCVS-qualifying sag resulting in significant process impact for a chemical products manufacturer. In this case, a fault on a 500-kV transmission line resulted in a V_{bc} and V_{ca} voltage sag to a minimum of 0.64 pu for 3.6 cycles. Demand at this site dropped 54 MW immediately following the voltage sag, and the facility required over 13 hours to resume production at pre-event load levels. This consumer has a high load factor and but for the voltage sag would have continued operation near the pre-event demand of 137 MW. This event caused over 300 megawatt hours of impact for the consumer, illustrated by the gray shaded area.

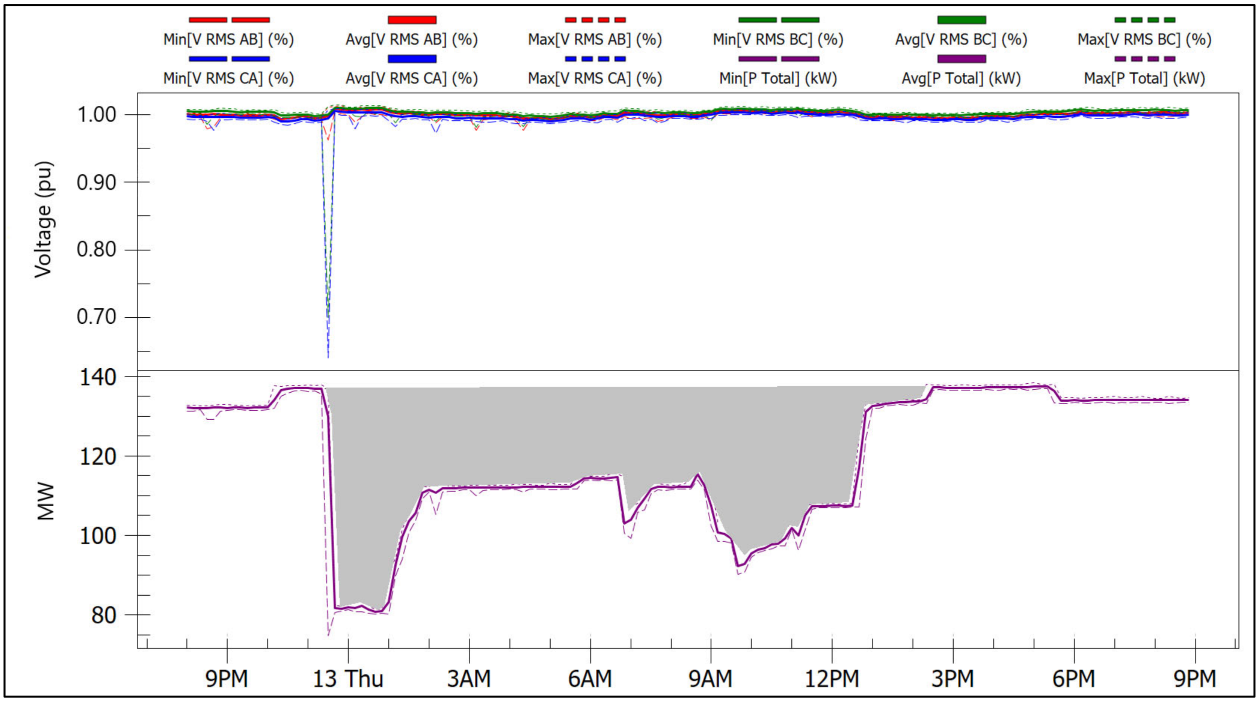


Figure 10: Process Impact Caused by a Mild Voltage Sag at a Chemical Products Manufacturer

The voltage sag that caused this disruption falls inside the IEEE 1668 voltage sag immunity curves, indicating that this impact is best mitigated inside the consumer facility, not on the transmission system.

C. *Data-Driven Voltage Sag Impact Mitigation*

Providing reliable electric service of acceptable power quality is at the core of TVA's mission. As such, TVA leverages the IEEE 1668 recommended voltage sag immunity curves and LSCVS data to inform investment to reduce the frequency and severity of voltage sags experienced by the LSC population and improve LSC voltage sag ride through performance.

1. *Focus Industrial Customer Program*

When LSCs experience process disruption due to transmission-caused voltage sags falling inside the IEEE 1668 immunity curves, mitigation focus turns to hardening end-use consumer equipment to improve voltage sag ride-through performance. As previously illustrated in Figure 9, sensitive control-level electronic components such as relays, power supplies, contactors, and programmable logic controllers (PLCs) are often the root cause of plant-level process disruption. Over the past two decades, EPRI has developed expertise in identifying specific industrial components responsible for process sensitivity and recommending proven, low-cost solutions to harden sensitive process controls to be compliant with the IEEE 1668 voltage sag immunity curves. EPRI has created an extensive library of voltage sag ride through compatibility curves for common industrial process components in an online database [11].

In fiscal year 2022, TVA launched the Focus Industrial Customer (FIC) program to programmatically support the LSCs who are most impacted by transmission-caused voltage sags characterized as inside the IEEE 1668 voltage sag immunity curves. The purpose of the program is to partner with LSCs to invest in hardening end-use equipment to improve voltage sag ride through performance. From 2022 to 2027, TVA plans to target 40 LSCs for program participation. LSCVS data, including the total megawatt hour impact of voltage sags inside 1668 curves will be used alongside other factors such as recent grid changes resulting in increased consumer AOV, and consumer reports of voltage sag impact to select the most-impacted LSCs for program participation.

For program participants, TVA will fully fund a detailed EPRI power quality assessment, performed on-site at the LSC facility by EPRI's Power Quality Services team. EPRI will provide the LSC with a detailed report identifying sensitive equipment and specific control-level mitigation recommendations, along with cost data. If the LSC chooses to implement some or all of the recommendations from the EPRI report, TVA will fund EPRI support during installation, commissioning, and verification of the selected mitigation measures. Finally, TVA will reimburse the LSC 50% of the installed cost of mitigation.

2. Transmission Investment

LSCVS data identifies the transmission assets and fault causes that most frequently result in process impact to LSCs due to voltage sags that fall outside the IEEE 1668 immunity curves. This information is used to target transmission investment to reduce the frequency and/or severity of voltage sags experienced by LSCs. Installation of lightning arresters or bird shields, insulator replacements, and pilot protection upgrades are examples of transmission investments that may be informed by LSCVS data.

In 2022, LSCVS data was used to select four TVA 161-kV lines for lightning mitigation investments based on the actual megawatt hour impact of lightning-caused voltage sags to LSCs located within the AOV of the lines. Planned investments to these four lines include lightning arrester installation and insulator replacements. LSCVS data has similarly been used as an input to bird shield installation projects to prevent faults caused by insulator flashover due to bird nesting and pollution.

Pilot relaying leverages communication between local and remote relay terminals to enable fast clearing of faults at any location on a protected transmission line. TVA evaluates PQ considerations for pilot relaying on active transmission projects. Traditionally, the PQ pilot evaluation included an AOV study and IEEE 1668 analysis to determine the magnitude and duration of LSC voltage sags caused by faults on the line under study. If reducing the duration of an LSC voltage sag by adding pilot relaying to the line would move the sag from outside the IEEE 1668 curves to inside the curves, single channel pilot relaying would be recommended. These efforts demonstrated that in almost all cases, at least one LSC would benefit from the addition of pilot protection. As such, TVA's standard approach was updated to include single channel pilot relaying on all lines 100-kV and above moving forward.

VI. CASE STUDIES

A. Paper Facility –TVA's First LSCVS Support

The lights dimmed for a 10th of a second due to a voltage sag created when the electrical system line was struck by lightning. Although the lights never went out, the 400-foot-long paper plant production line stopped because the equipment is extremely sensitive to subtle voltage sags. During months with storms, thunderstorms repeatedly pummeled the plant, frustrating its 235-person workforce as well as its management. Per the facility general manager, each event created 5 hours of production downtime costing the company over $500,000 in lost sales and equipment damage per year.

TVA gathered a team of experts from within TVA and EPRI to diagnose the events. EPRI used a portable voltage sag generator to determine the process system sensitivity to voltage sags. Armed with that knowledge from testing, the engineers fashioned fixes. Remedies were suggested that would be easy to put in place to de-sensitize the equipment to voltage events associated with storms. TVA provided the information and the paper plant spent $30,000 implementing the modifications. Since the process modifications were installed in 1997 it is estimated the paper plant has saved over $12,000,000 by installing the equipment to allow them to ride through moderate voltage sags.

B. Transmission Level Solution - Lightning Mitigation Project

TVA serves twelve large sensitive industries located in East Tennessee which had experienced 72 voltage sag events cumulatively over a seven-year period from 2005 to 2011 because of 20 lightning caused faults among 8 transmission lines in the area. This resulted in an estimated total customer cost impact of $9 million dollars from production downtime and scrapped product. It was determined that 12 of the 20 lightning caused faults were from lightning strikes with magnitudes which could be mitigated with lightning protection solutions. A lightning mitigation project was undertaken by installing counterpoise or arresters at specific structures in lightning "hot zones" on these eight transmission lines. The cost of the lightning mitigation project was $600,000 with an estimated savings in cumulative customer cost impacts of $900,000 per year. In the seven-year period from 2015 to 2022 since the lightning mitigation improvements were implemented, these eight lines have not experienced faults from lightning strikes within the lightning protection design criteria.

C. West TN Aluminum Plant

In 1968 an industrial manufacturer of rolled aluminum products located its newest facility within a 50-mile radius of one of the largest coal-fired power plants in the heart of the TVA service territory. The proximity to such a large, base load generating source provided the facility with both excellent reliability and power quality. However, by 2016 the age of those coal units, their associated environmental challenges, and TVA's newly announced path toward decarbonization culminated in the permanent retirement of the units. A new 500:161-kV transformer bank was installed as part of a transmission area reconfiguration to preserve the integrity of the bulk electric system and to sustain the continued commitment to reliability that is integral to the TVA mission. The unintended consequence of these actions, however, adversely affected power quality for regional consumers – particularly, those with sensitive processes.

These changes translated to significant increase in AOV for the aluminum facility and by extension, they began experiencing a higher frequency of voltage sags at the point of delivery. Compounding the problem was the growth that the facility had experienced over the decades since first locating to the area. Their load was now exceeding the base rating of their primary service equipment, reducing the steady-state voltage profile, and effectively erasing any margin for sensitive equipment to absorb and ride through voltage sags.

The combination of an increase in voltage sags from the TVA system changes and the customer's reduced position to withstand them was resulting in frequent process interruptions. In just over a two-year period of time from February 2017 to April 2019, the customer experienced 31 voltage sags originating from the TVA system. The frequency of events and their impact was reducing productivity, wasting product, and limiting the facility's ability to compete for expansion opportunities.

Over the next two years, TVA, the local power company, and the customer collaborated on a number of strategies for improvement that would address both the performance of the utility network and the customer's point of use. TVA replaced over 200 insulators in the double-circuit loop line with an innovative design intended to improve performance against bird pollution. This 8-mile section of line was tied to the same transmission bus providing service to the customer and had been prone to operation from bird activity. Additionally, TVA consulted with EPRI to perform a thorough assessment of the sensitive process lines that were common to experience interruption from voltage sags inside of the IEEE 1668 expected immunity curves. The assessment yielded 63 recommendations ranging from adjustable speed drive settings changes to control power hardening techniques that would better position the process line to ride through shallower and shorter duration events. The customer chose to implement 9 of these recommendations in one process area, and the initial returns were encouraging. When the facility would experience a voltage sag event, the hardened process area would see improved ride-through performance by comparison to the areas that had not yet been addressed. However, the timetable and resource availability for the customer to implement all of the recommendations would lead the team to a different overall solution to address voltage sag performance more wholistically.

The team chose to address the low steady-state voltage of the facility as the best measure for improving performance against voltage sags. The stakeholders all agreed on a 13-kV filter bank solution that would boost the operating voltage of the plant back to nominal, add margin for voltage sag ride-through, and have the added benefit of improved power factor. In March 2021, the project was commissioned and since that time the collective results of all efforts to improve the frequency and impact of voltage sags have resulted in drastically improved power quality. So great was the improvement that the customer was selected for a site expansion resulting in more jobs and increased economic development for the surrounding community.

D. North Georgia Appliance Manufacturer

A residential appliance manufacturer supplied at 25 kilovolts from a local power company substation experienced repeated process disruption attributed to TVA transmission-caused voltage sags. This resulted in scrapped parts and production downtime. The metal stamping and paint/oven process areas were particularly susceptible to disruption. Located at the edge of TVA's service territory, this facility experienced 9 voltage sags caused by TVA assets in the 365-day period ending November 1, 2020. Figure 11 shows these voltage sags plotted together with the IEEE 1668 Type I and II voltage sag immunity curves, in red. The plot indicates that end-use equipment could feasibly be modified to ride through 75% of the voltage sags experienced by the facility in the one-year period. TVA engaged EPRI to conduct a PQ assessment at the facility to make recommendations to improve voltage sag ride through performance.

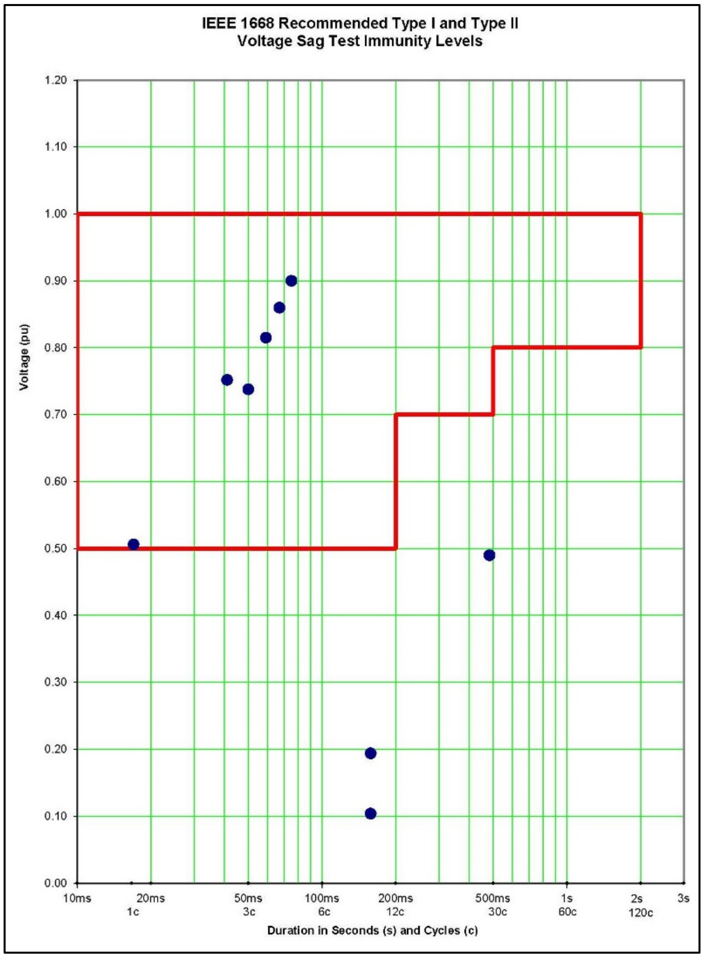


Figure 11: Appliance Manufacturer Power Quality Data and IEEE 1668 Type I and II Immunity Curves

EPRI conducted an on-site assessment and found that control components installed at the facility were sensitive to disruption due to voltage sags of approximately 0.75 pu for less than 50 milliseconds. These sensitive devices included "ice-cube" type ac relays and various contactors. EPRI made specific recommendations for each control panel surveyed including control relay modifications, application of constant voltage transformers (CVTs) and other ac control voltage hardening measures, and enhanced voltage sag ride though parameter settings for adjustable speed drives.

The appliance manufacturer worked with a local contractor to implement the recommendations in stages. The first round of mitigation was targeted at the critical process areas identified by EPRI as most sensitive. Control-level recommendations were implemented in 20 process cabinets, at an installed cost of approximately $950 per cabinet.

Figure 12 includes the site PQ data alongside the EPRI-tested voltage sag ride-through curves associated with four voltage sag hardening devices installed by the manufacturer. The ride through curves are indicated by the gray, orange, violet, and blue lines. The hardened control cabinets were expected to ride through over 75% of voltage sags recorded at the site.

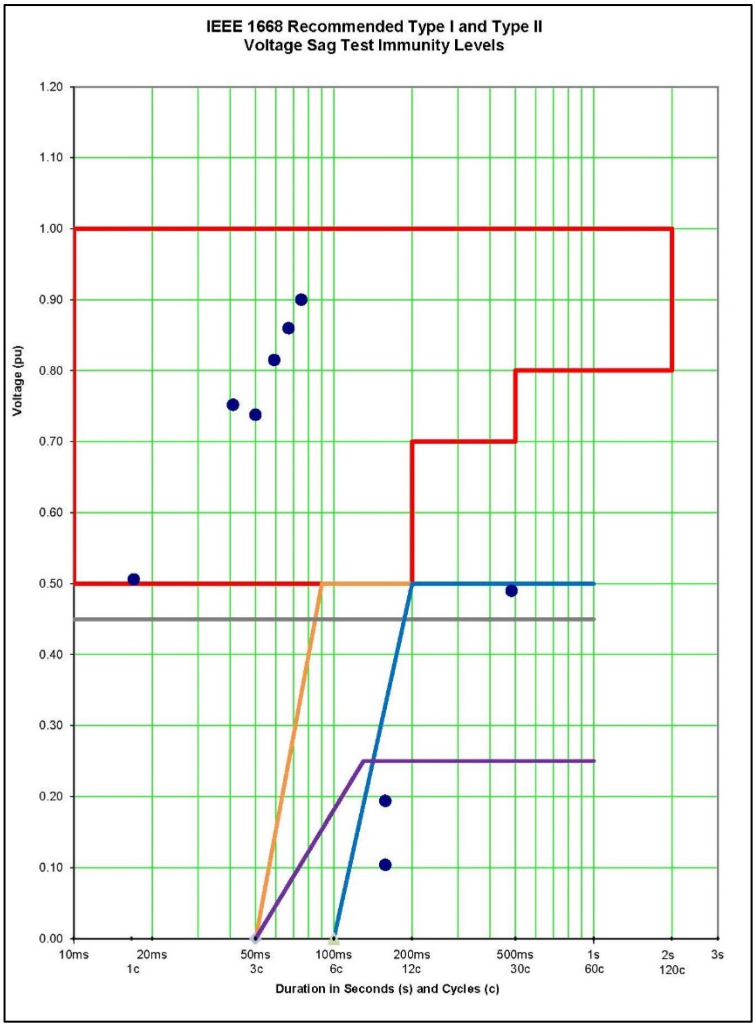


Figure 12: Appliance Manufacturer Power Quality Data and Installed Mitigation Voltage Sag Ride Through Curves

VII. CONCLUSION

Voltage sags caused by faults on the transmission system frequently result in industrial process disruption. As the grid decarbonizes and integrates IBR, the AOV of industrial consumers may increase, resulting in more frequent and severe voltage sags. Traditional reliability metrics do not capture the impact of voltage sags on industrial consumers.

The LSCVS metric leverages power quality, transmission operations, and power billing data to quantify transmission voltage sag performance seen by TVA's largest industrial consumers. LSCVS data identifies consumers most impacted by transmission-caused voltage sags and drives targeted impact mitigation investment, aligned with the IEEE 1668 recommended voltage sag immunity curves.

Consumer impact caused by voltage sags falling outside the IEEE 1668 curves informs transmission investments such as lightning arrester installation, bird shield installation, pilot relaying upgrades and insulator replacements. When LSCs experience process disruption due to voltage sags falling inside the IEEE 1668 curves, mitigation is focused on improving the voltage sag ride through performance of end-use equipment inside consumer facilities. The TVA Focus Industrial Customer program supports consumers to harden sensitive end-use process equipment to meet IEEE 1668 voltage sag immunity recommendations.

TVA's mission is to make life better for the people of the Tennessee Valley through delivery of low-cost, reliable, clean energy and support of economic development throughout our region. As the power grid and industrial processes modernize, the LSCVS metric and Focus Industrial Customer program support the continued success of the large industries that are vital to the people and communities TVA serves.

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