Voltage Unbalance in a Changing Grid

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Abstract -- Voltage unbalance is commonly thought of as an issue impacting end-use loads like three-phase motors and drives, but with the changing grid, voltage unbalance at the EHV and HV levels has gained renewed attention. This paper discusses recent voltage unbalance issues seen at the Tennessee Valley Authority and its impact upon generation, transmission, distribution, and loads. In this paper we will discuss factors believed to be contributing to increases in voltage unbalance, efforts that were taken to mitigate voltage unbalance, modeling efforts to help predict voltage unbalance, and the use of monitoring to alert to voltage unbalance.

I. INTRODUCTION

The Tennessee Valley Authority (TVA) is a generator and transmission owner/operator primarily serving local power companies and transmission-connected industries 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].

Voltage unbalance, the divergence of phase magnitudes and/or phase angles, has slowly become an issue that TVA and its customers have experienced. Most of TVA's transmission system remains under recognized planning limits for high voltage electric systems; however, some regions experience levels near that limit. Figure 1 shows a five year trend of increased voltage unbalance on a subregion of the extra-high voltage (EHV) transmission system. While the vast majority of the EHV system remains well below planning limits, understanding the causes of elevated voltage unbalance and how to mitigate for it is important for TVA.

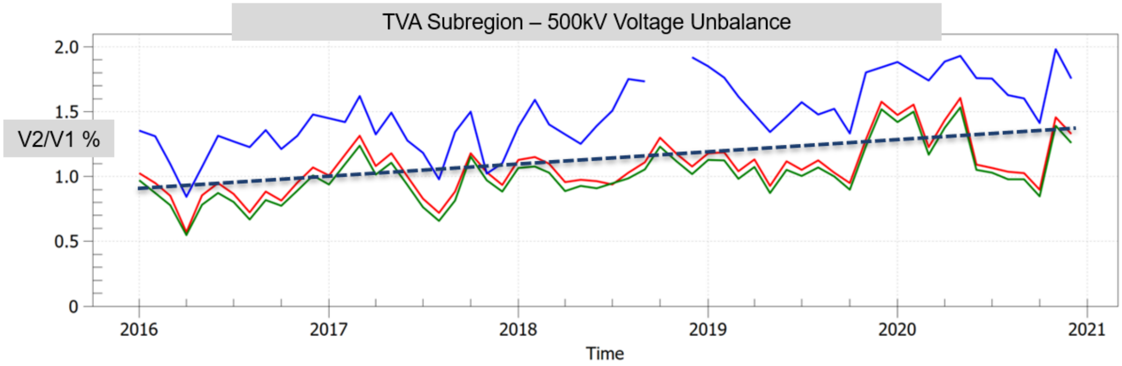


Figure 1. TVA Subregion, 500-kV Voltage Unbalance, 5-year Trend

Experience has shown that elevated voltage unbalance is a regional issue and has three main drivers:

1) Generation Dispatch Profile
2) Transmission Configuration (Outages)
3) Overall system load profile

This paper seeks to discuss issues experienced due to these drivers as well as other issues surrounding voltage unbalance such as real-time mitigation and planning considerations.

II. STANDARDS

The American National Standards Institute (ANSI) has published two standards among others which are commonly referenced regarding the subject of voltage unbalance. The first is ANSI C84.1 [2], which recommends in Annex C.2 that "electric supply systems should be designed and operated to limit the maximum voltage unbalance to 3 percent when measured at the electric-utility revenue meter under no-load conditions." The second is ANSI MG1 [3], which in Part 12.45, specifies that "alternating-current polyphase motors shall operate successfully under running conditions at rated load when the voltage unbalance at the motor terminals does not exceed 1 percent." In Part 14.36, it further specifies that a derating factor should be applied to the rated horsepower of the motor should the voltages be unbalanced and that operating the motor with a 5 percent or greater voltage unbalance condition is not recommended.

In both ANSI C84.1 [2] and ANSI MG1 [3], the voltage unbalance, expressed as a percentage, is defined as the maximum voltage deviation from the average voltage divided by the average voltage where the voltages are measured phase-to-phase.

ANSI C84.1 [2] and ANSI MG1 [3] do not provide recommended voltage unbalance limits for the transmission system at the high voltage and extra high voltage levels under loaded conditions. As such, TVA has referred to International Electrotechnical Commission Technical Report (IEC/TR) 61000-3-13 [4] which in Part 4.2.1 provides indicative values of planning levels for voltage unbalance in medium voltage, high voltage, and extra high voltage systems. Planning levels for voltage unbalance are equal to or lower than compatibility levels and they should allow coordination of voltage unbalances between different voltage levels. For high voltage systems the planning level for voltage unbalance is given as 1.4%.

In IEC/TR 61000-3-13 [4], the voltage unbalance, expressed as a percentage, is defined as the ratio of the modulus of the negative-sequence to the positive-sequence components of the voltage fundamental frequency.

As of this writing, a working group sponsored by the Power Quality Subcommittee within the Power and Energy Society (PES) of the Institute of Electrical and Electronics Engineers (IEEE) has an open Project Authorization Request (PAR) for IEEE P2844 [5] which is intended to become an IEEE recommended practice for voltage unbalance and will include recommended limits for voltage unbalance at different voltage levels, how to calculate voltage unbalance, and help users to understand impacts of voltage unbalance on the power system and utilization equipment.

III. ISSUES

A. Local Power Company 3-Phase Voltage Regulation (Issue 1)

Broadly speaking, the greatest concern from TVA's Local Power Companies (LPC) for elevated voltage unbalance is the difficulty in maintaining ANSI C84.1 [2] voltage regulation levels at end-of-line. Many LPCs employ substation transformers with three-phase load tap changes for voltage regulation which limits their ability to regulate voltage independently on each phase.

B. Conservation Voltage Reduction Programs (Issue 2)

A related case is the difficulty in the use of Conservation Voltage Reduction (CVR) technologies during periods of elevated voltage unbalance. CVR is a distribution-system technology used to increase energy efficiency of some consumer equipment by intentionally lowering voltage to the low end of the ANSI C84.1 [2] voltage range. In some cases, voltage unbalance presented difficulty in maintaining the ANSI C84.1 [2] voltage limits while the CVR system was operational. In these cases, CVR use was discontinued, which represented a limit to the savings potential of the technology investment.

C. Customer Motor Trips (Issue 3)

Another issue experienced by TVA customers was a singular event that led to the inability to start critical process motors. Figure 2 displays the voltage unbalance during this time period with the dashed lines representing step-change increases in voltage unbalance due to various transmission outages. These transmission outages were part of the normal autumn outage season. As a normal part of the outage planning process, load flow contingencies are studied and outages are approved or cancelled depending on the results of the studies. No voltage or loading issues were identified during the study. As can be seen (Fig. 2), each consecutive area-outage resulted in additional voltage unbalance in this region. It should also be noted that, local generation was offline for similar pre-winter outage work. The final peak in voltage unbalance was due to unseasonably cold weather in the area which resulted in higher than expected system loading.

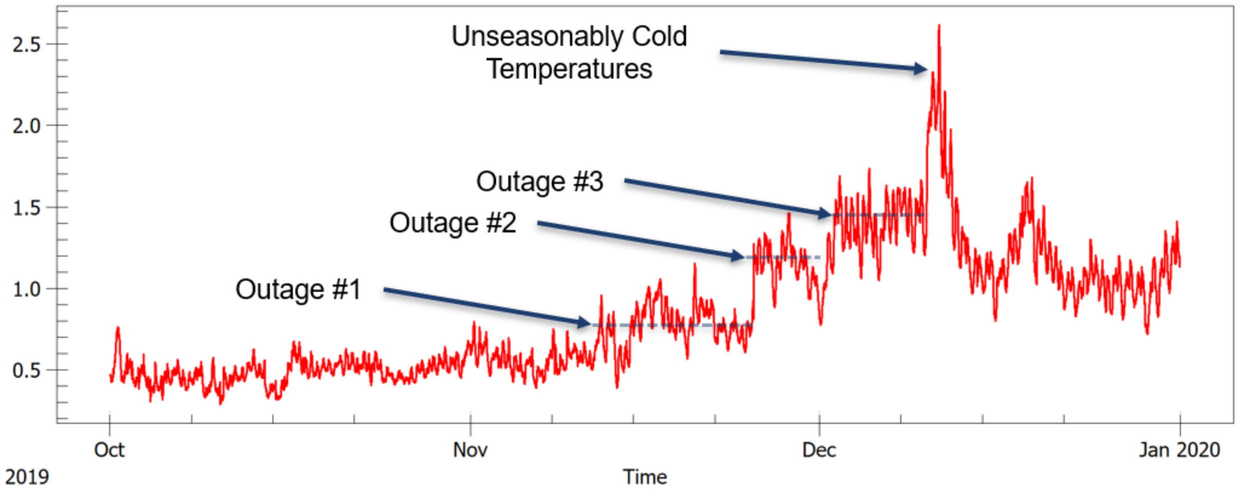


Figure 2. Voltage Unbalance (V2/V1) During Cold Weather and Fall Outage Season

Voltage unbalance had risen to over 2.5% in certain portions of the region due to a combination of the aforementioned voltage unbalance drivers.

D. Isolated Generation Impacts (Issue 4)

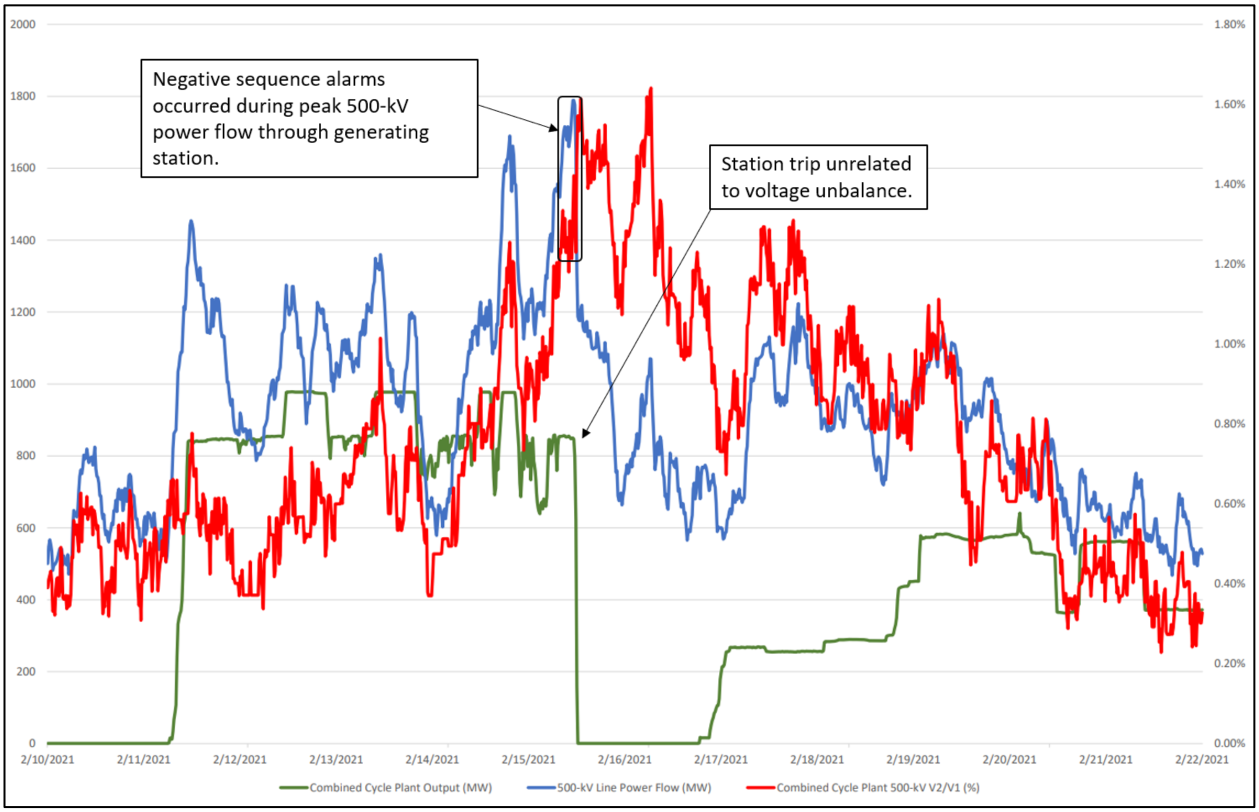
In a 12-month period, TVA documented two cases of adverse generation impacts attributed to transmission system voltage unbalance. Impacts have included negative sequence current protection alarms, and one negative sequence current protection unit trip.

Unbalanced system conditions produce negative sequence currents in generators which may result in severe heating and damage in a relatively short time [6]. Continuous and short-time generator negative sequence current limits are generally defined by machine design standards [7] [8], and are provided by the generator manufacturer for a specific machine. Design standards allow for continuous negative sequence current of 5% to 10% of rated machine current, depending on machine design characteristics. While negative sequence protection of generators is typically considered backup protection for inadequately cleared unbalanced system faults [9], it also provides machine protection against damage that may be caused by steady-state unbalanced system conditions.

1. Combined Cycle Plant Negative Sequence Protection Alarms

During the February 13 - 17, 2021 North American winter storm event [10], 500-kV power flows increased in the western part of TVA's service territory, resulting in increased 500-kV voltage unbalance in the area. One combined cycle gas plant, connected in the center of an 80-mile, untransposed, 500-kV line asserted negative sequence protection alarms as 500-kV power flow through the station increased and voltage unbalance exceeded approximately 1.2%. During the event, the generating units at this plant tripped offline for reasons unrelated to voltage unbalance, which resulted in a step increase in 500-kV voltage unbalance at the station. The units restarted after the period of peak system loading when regional voltage unbalance was reduced.

Figure 3 illustrates the 500-kV power flow on the transmission line, 500-kV voltage unbalance at the generating station tap point, and combined cycle generation station MW output.



Negative sequence alarms occurred during peak 500-kV power flow through generating station.

Station trip unrelated to voltage unbalance.

Figure 3. Combined Cycle Plant Generation Output, 500-kV Voltage Unbalance, and 500-kV Station Power Flow, February 10 - 22, 2021

2. Hydro Unit Negative Sequence Protection Trip

A separate transmission voltage unbalance event resulted in a 15MW hydro generating unit trip on negative sequence protection. A planned 161-kV line outage created an 81-mile long radial line supplying the station via a customer-owned sub-transmission system at the end of the line. Figure 4 illustrates the measured voltage unbalance at a nearby 161-kV station supplied by the radial line and voltage unbalance at the generator bus during the radial line configuration.

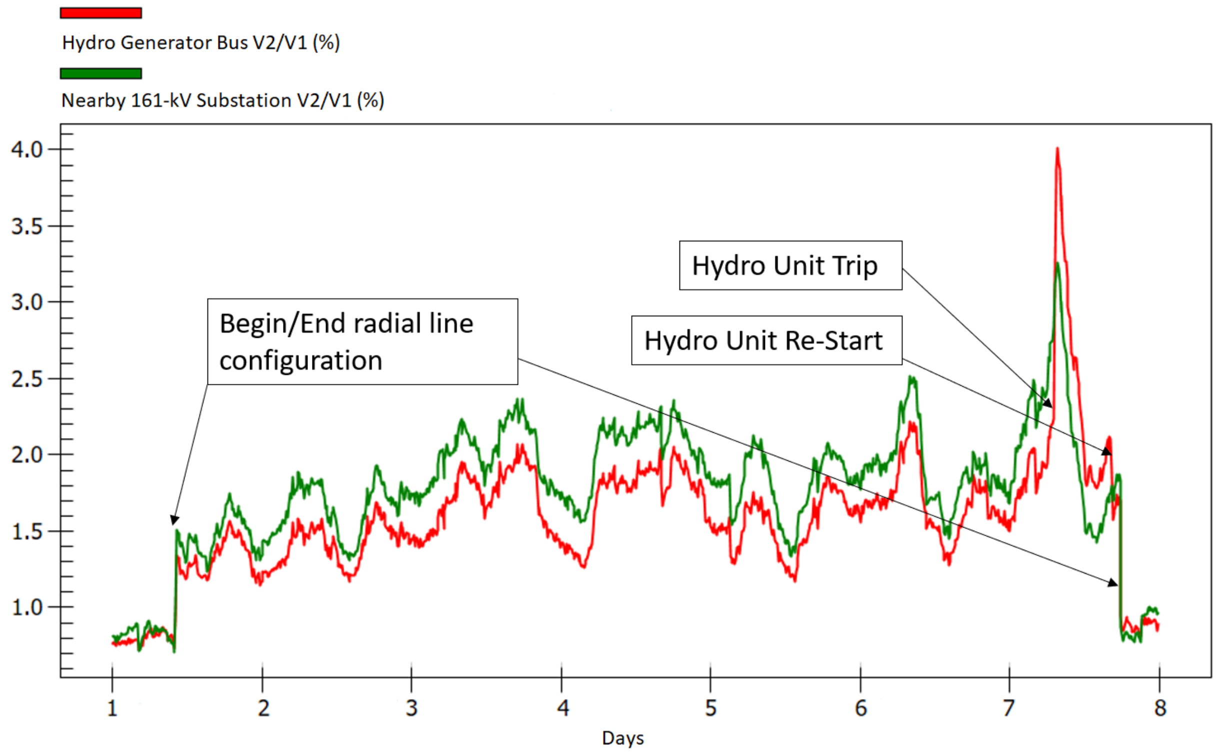


Figure 4. Hydro Generator Bus and Nearby 161-kV Station Voltage Unbalance

When cold temperatures caused line loading to increase on day 7, voltage unbalance at the end of the radial line also increased. The impacted hydro unit tripped on negative sequence protection when voltage unbalance reached 2.23% at the generator bus. Voltage unbalance for this event peaked immediately following the unit trip. No negative sequence alarms are configured at this machine.

The hydro unit re-started approximately 9 hours after the trip when voltage unbalance at the generator bus was near 2.0%. The 161-kV system was returned to its normal configuration, and voltage unbalance on the 161-kV system and at the generator bus reduced to less than 1.0%. This event is discussed in further detail in Subsection F.2 of Section III below.

E. Transmission Capacitor Bank Trips with Non-compensated Unbalance Protection Schemes (Issue 5)

TVA has used various transmission capacitor bank designs and protection schemes over time. The present design standard is a fuseless grounded single wye capacitor bank with a compensated unbalance protection scheme. An older design that had been used prior to 2000 was a fuseless grounded single wye capacitor bank with a non-compensated unbalance protection scheme. A compensated unbalance protection scheme is able to differentiate between unbalance due to changes in the capacitor bank impedance such as from a shorted capacitor element and due to changes external to the capacitor bank such as unbalance in the system voltage. A non-compensated unbalance protection scheme is unable to make this distinguishment. While both unbalance protection schemes receive a set of three voltage signals (one per phase) from the capacitor bank high voltage bus, only the compensated unbalance protection scheme receives a set of three signals (one per phase) for unbalance protection. The non-compensated unbalance protection scheme receives only a single unbalance protection signal from the common neutral of the capacitor bank. TVA has experienced cases where the system voltage unbalance has contributed to unbalance alarms and trips of transmission capacitor banks when using non-compensated unbalance protection schemes.

One such example case involved an 84MVAR, 161-kV capacitor bank which consisted of seven parallel strings of ten capacitor units in series per phase as shown in Figure 5. Any unbalance in impedance between the three phases results in current flow in the capacitor bank neutral. Any unbalance in system voltage will also result in current flow in the capacitor bank neutral even if all impedances are ideally balanced. The protection scheme is blind as to the cause of the neutral current. The unbalance relay trip threshold was set to prevent overvoltage of any capacitor elements of greater than 110% of rating. This means that if 10% of the capacitor elements in any series string become shorted that the remaining healthy elements in the series string would then be subjected to overvoltage of greater than 110% of rating. An inspection of the capacitor bank after the trip found 4% of the elements in one string on one phase had become shorted. The remainder of the neutral current which had reached the relay trip threshold was due to the system voltage unbalance. It is possible that for such large transmission capacitor banks that the unbalance trip threshold could be reached while at the IEC-61000-3-13 [4] planning limit for high voltage systems of 1.4% even if all elements of the capacitor bank are in good health. TVA is upgrading the unbalance protection schemes in such cases.

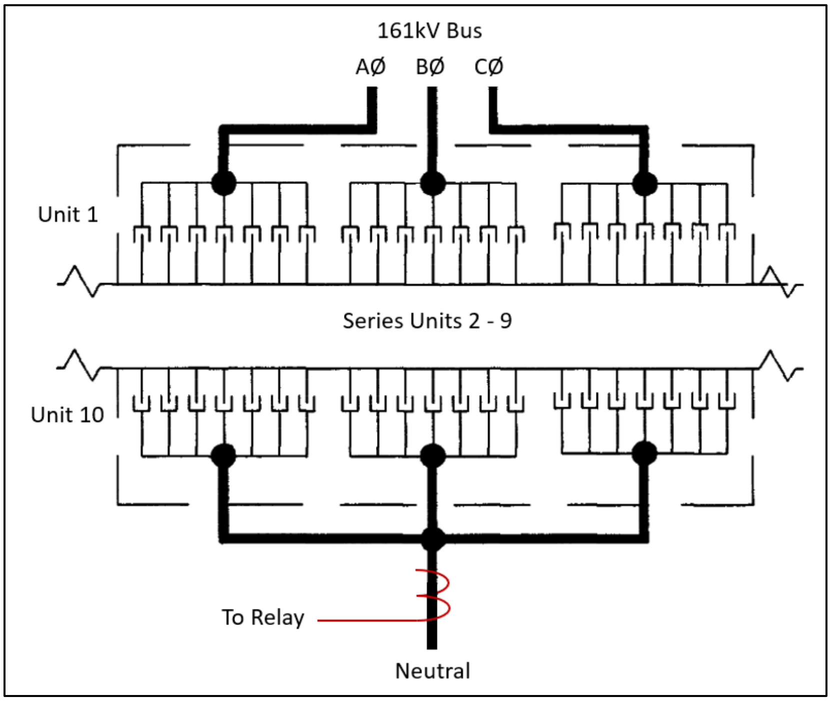


Figure 5. Transmission Capacitor Bank with a Non-Compensated Unbalance Protection Scheme

F. Long, Untransposed Radial Lines (Issue 6)

Over a 12-month period, TVA has documented two cases where planned transmission outages created long, untransposed, radial 161-kV lines during times of heavier system loading. During the radial configurations, total load on the lines increased, resulting in increased voltage unbalance. In both cases, 161-kV voltage unbalance exceeded the 1.4% planning limit at customer tap stations served by the lines during peak load times. TVA used an electromagnetic transient (EMT) software program to simulate each case to analyze the impact of the 161-kV line construction and phasing on voltage unbalance.

1. Long Radial 161-kV Line (Case 1)

In the first case, a 161-kV line segment was taken out of service for planned maintenance, creating a 67-mile radial 161-kV line supplying five customer tap stations. Figure 6 shows the configuration of the radial line.

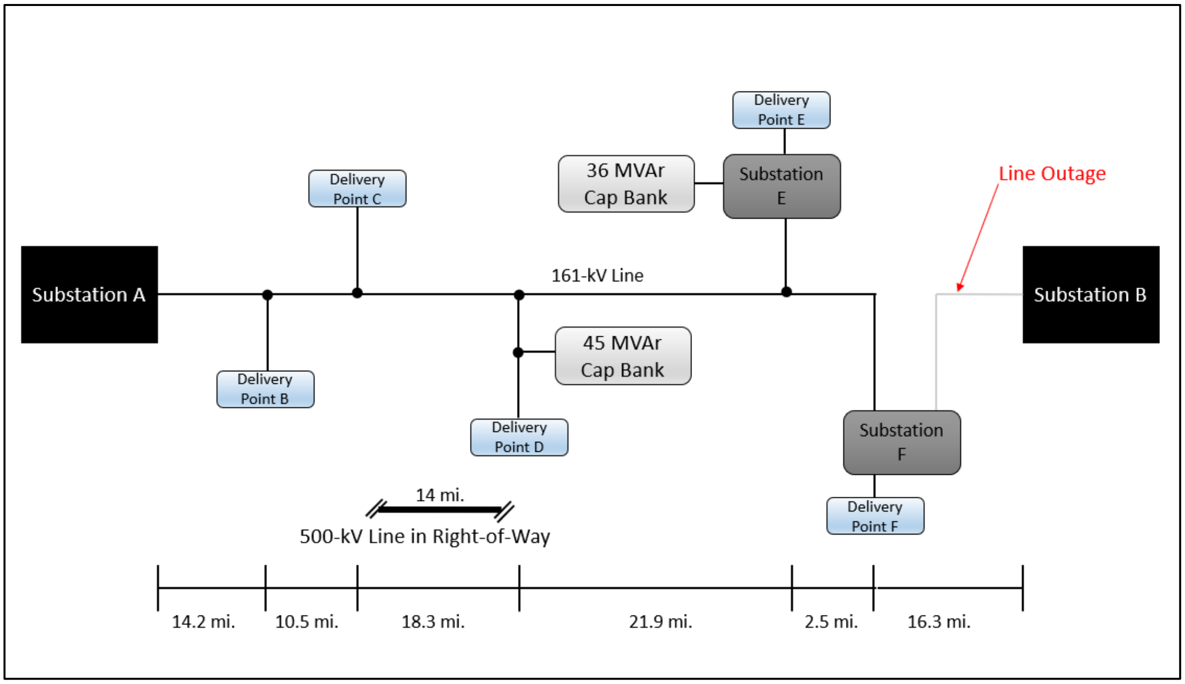


Figure 6. 161-kV Radial Line Overview (Case 1)

During the radial configuration, increased voltage unbalance was recorded at peak load times at the distribution side of delivery points supplied by the line. Figures 7 and 8 illustrate the load profile of the radial line and the recorded delivery point voltage unbalance levels. 161-kV data was unavailable for this event. The step change in distribution system voltage unbalance at the beginning and end of the radial configuration is apparent.

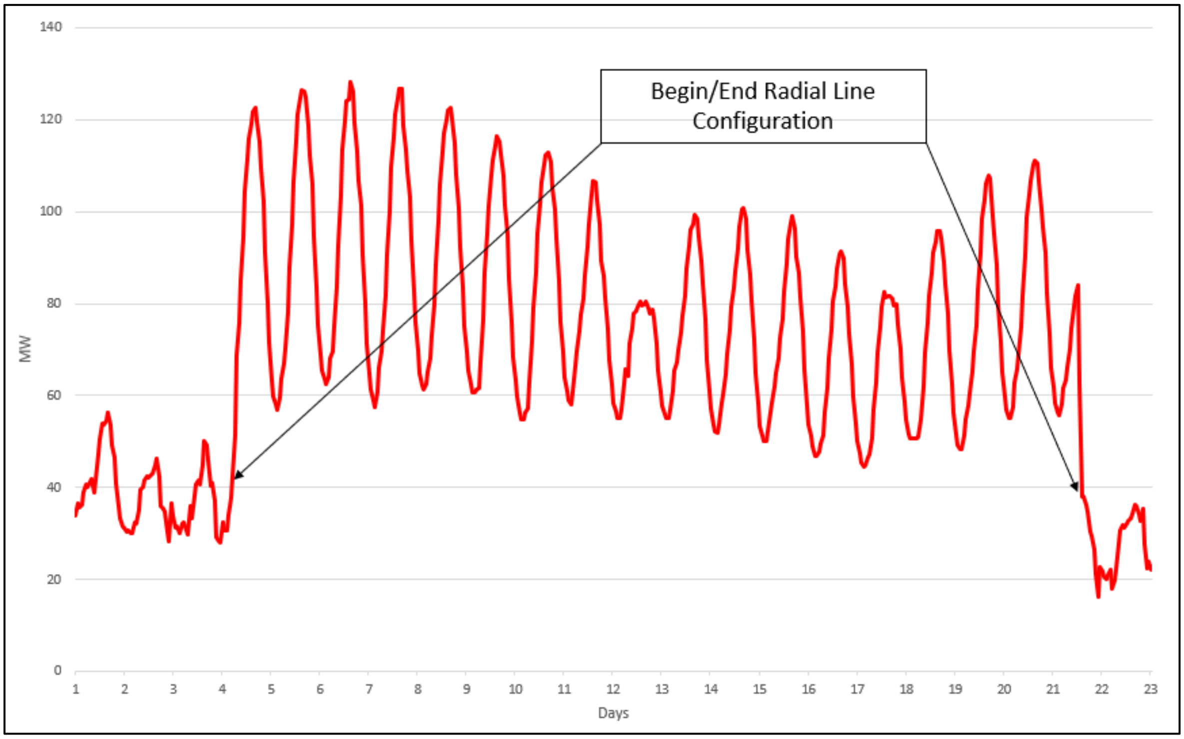


Figure 7. Radial Line Load Profile (Case 1)

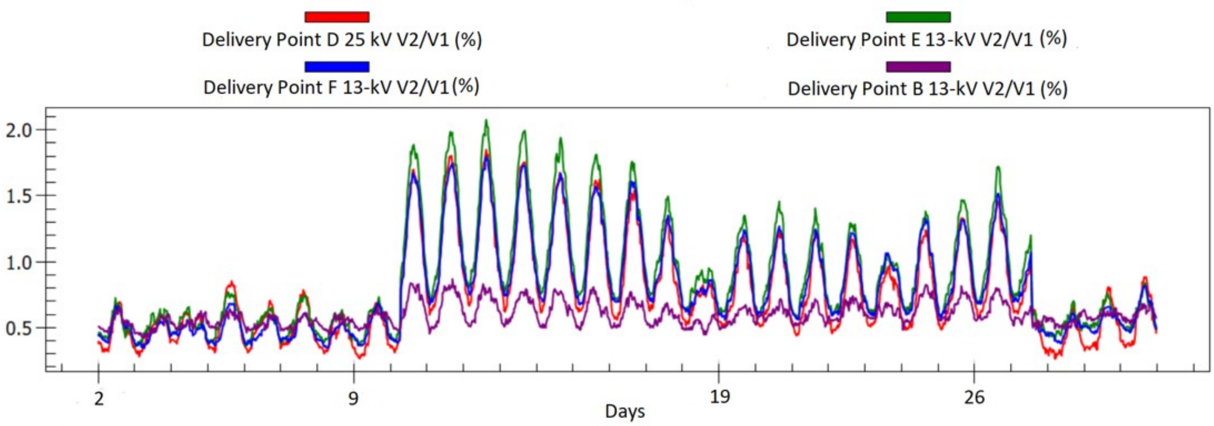


Figure 8. Radial Line Delivery Point Voltage Unbalance (Case 1)

While delivery points at the end of the radial line experienced peak voltage unbalance greater than 2% during the outage, the maximum voltage unbalance attributed to the 161-kV system was approximately 1.8%. The load on the radial line during peak voltage unbalance times was approximately 127 MW. No customer complaints were received during this event.

Some transmission line construction characteristics were considered significant from a voltage unbalance perspective:

- The line is untransposed and uses horizontal conductor configuration for the length of the line.
- The line shares right-of-way with a 500-kV line for 14 miles.
- Approximately 62 miles of the line were constructed in 1936 with 160% larger horizontal conductor spacing between phases than is typical of newer TVA 161-kV lines.
- Approximately 50% of the load on the line is located at delivery points D and E, which are near the end of the radial line.

TVA created an EMT model of the radial line configuration using near-peak line load levels to simulate the elevated voltage unbalance seen during the event. The model accurately represented the construction and phasing of the 161-kV line and the 500-kV line in the shared right-of-way, as well as accurate reactive compensation for the simulation time. The model assumed balanced line loads.

The simulated results from the EMT model closely approximated the measured voltage unbalance levels for the event, confirming that the largest drivers of voltage unbalance during the radial configuration were the line load, and the untransposed, horizontal conductor configuration of the line. The simulation indicated that the presence of the 500-kV line in the right-of-way and the 161-kV line’s larger-than-typical conductor spacing were not major factors in the resulting voltage unbalance levels.

2. Long Radial 161-kV Line (Case 2)

In the second case, a planned transmission outage resulted in an 81-mile radial 161-kV line supplying approximately 225 MW at eight 161-kV customer delivery points. Figure 9 shows the configuration of the radial line.

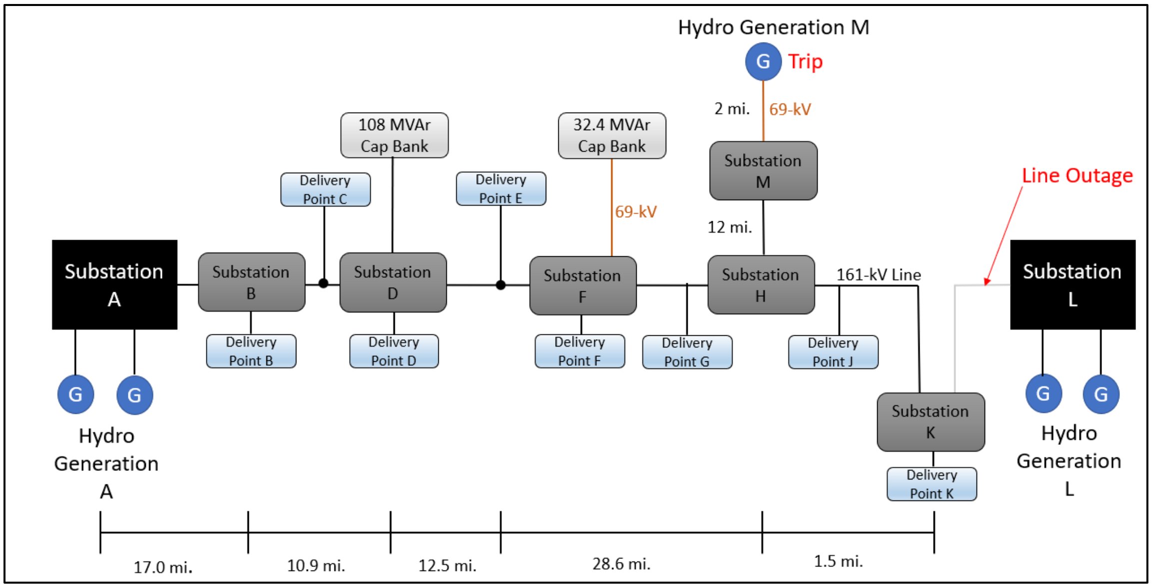


Figure 9. 161-kV Radial Line Overview (Case 2)

As load on the radial line increased, voltage unbalance at stations supplied by the line also increased. Figure 10 shows the load on the radial line and Figure 11 shows the voltage unbalance profile for this event. Recorded 161-kV voltage unbalance at Substation F peaked at 3.26%.

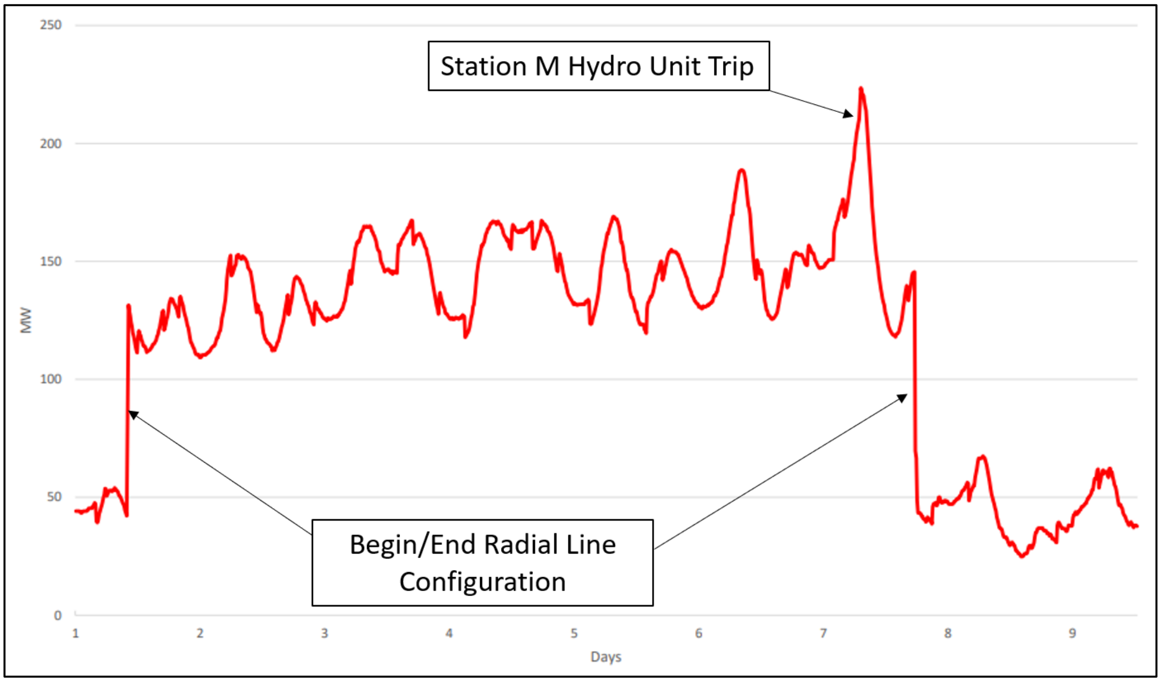


Figure 10. Radial Line MW Load Profile (Case 2)

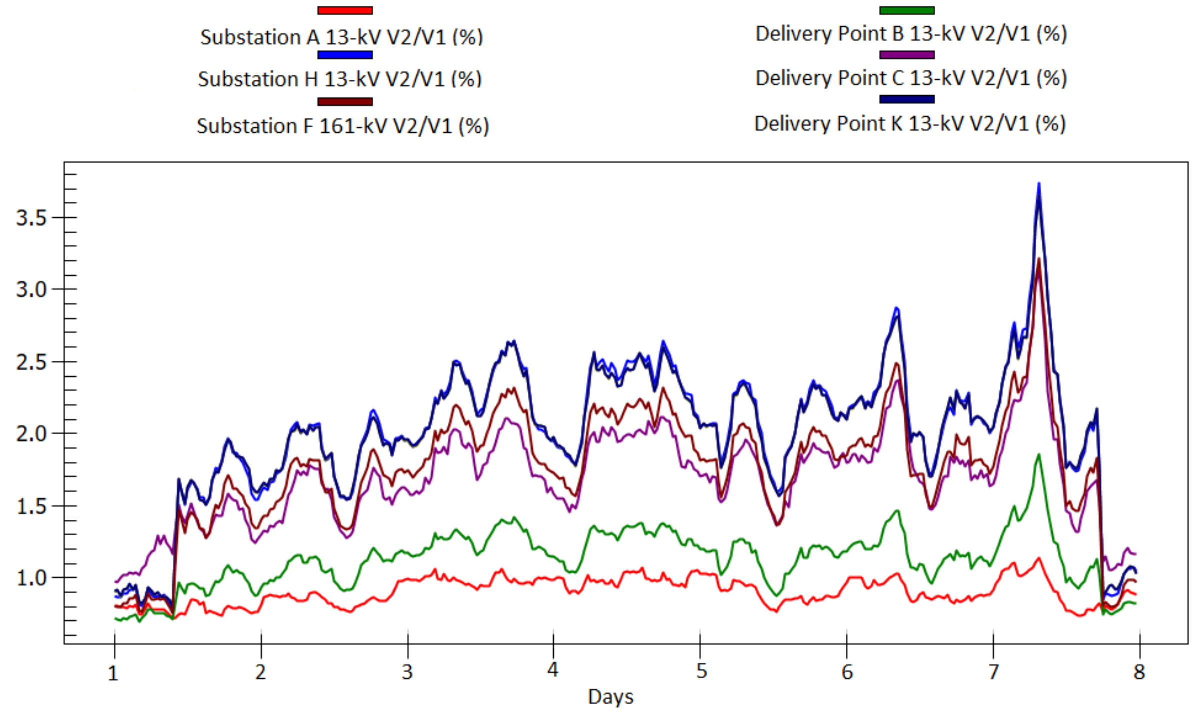


Figure 11. Voltage Unbalance Measurements (Case 2)

As previously discussed in Subsection D.2 of Section III above, one TVA hydro generation unit, supplied from Substation M at the end of the radial line, tripped offline on negative sequence protection just prior to the line load and voltage unbalance peak seen in Figures 10 and 11.

This 161-kV line is untransposed, and approximately 50 miles of the line have horizontal or vertical conductor configurations with typical 161-kV conductor spacing and with B-phase as the middle phase. The remaining sections of the line use triangular conductor configuration with phases A and B on the top and C on the bottom.

As with long radial Case 1, TVA created an EMT model of this case, accurately representing the line construction, phasing, and reactive compensation and assuming balanced line loads. The simulation of this case again confirmed that the line loading and untransposed construction of the line were the main drivers for the increase in voltage unbalance in the radial configuration.

As load is expected to increase in this area, TVA Planning and Power Quality staff have utilized the EMT model of the line to analyze various system improvement options to serve the projected load and maintain 161-kV voltage unbalance below the 1.4% planning limit. Proposed solutions include strategic phasing of a proposed new transmission line in the area and transposing the existing line from Substation A to Delivery Point E.

IV. MITIGATION

Given that transmission configuration (outages), generation dispatch profile, and net system load are primary contributors to increased voltage unbalance, TVA undertook a continuous improvement effort to provide better situational awareness and mitigation for voltage unbalance. Two major focus areas were the outage planning process as well as establishing criteria for dispatching generation to support voltage unbalance needs.

A. Outage Planning

Generally speaking, voltage unbalance presents itself as a regional issue for TVA (small parts of the system are susceptible to increased voltage unbalance near the IEC 61000-3-13 [4] planning limit). Members of the power quality team have become more engaged in the system-wide outage planning process to gain awareness of upcoming outages (10 to 90 day planning horizon) so that correlations could be established between system load and predicted voltage unbalance. While the outage planning process has been focused on meeting voltage and n-1 requirements during the outage, the engagement of the power quality team provided the opportunity to raise concerns for regional voltage unbalance issues. The result has been successful with several events mitigated which may have impacted customers.

B. Generation Dispatch

Dispatching generation for voltage unbalance has also shown to be an effective tool in the event that transmission assets could not be returned to service or outages could not be cancelled before they start. While not the preferred method due to the increased costs associated with dispatching generation, mitigating for voltage unbalance with this approach has occurred multiple times at TVA for specific regional events. In one instance shown in Figure 12, voltage unbalance increased regionally following the trip of a generation unit and a breaker failure which disconnected the generation site from another major substation. Voltage unbalance continued to rise as temperatures dropped in the early January timeframe. Realtime Transmission Operations, Power Quality, and Balancing Authority staff collaborated during this time frame to dispatch fast starting gas combustion turbines to mitigate the voltage unbalance for the area. This yielded successful results, achieving no customer complaints during this period.

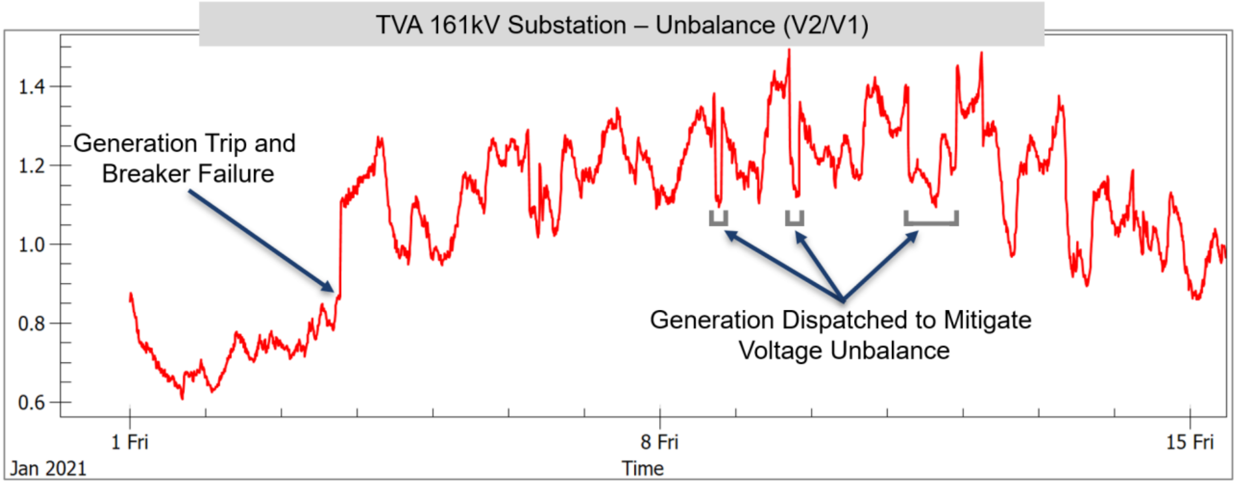


Figure 12. Voltage Unbalance Mitigated by Generation Dispatch

C. Line Transposition Projects

Most of TVA's 500-kV transmission lines were originally constructed without line transpositions during a time of lower transmission system loading. Increasing levels of observed voltage unbalance in a particular region of the TVA transmission system led TVA to form a Voltage Unbalance Team (VUT) in 2011 to study the issue and recommend a solution. The VUT concluded that the key contributor to voltage unbalance was a lack of 500-kV line transpositions. Data showing a positive correlation of voltage unbalance with transmission line loadings substantiated the team's findings. As a result, line transposition projects were completed in 2017 for three 500-kV transmission lines in the affected region.

The layout of the TVA 500-kV system in this region is shown in Figure 13. The highest load flows are typically seen from Station G to Station H followed by load flows from Stations C and D to Station G. The VUT concluded that the most economical solution to the observed voltage unbalance issues was to fully transpose the 500-kV line between Station G and Station H by adding two transposition structures along its length (Figure 14) and to partially transpose the 500-kV lines between Station C and station G and between Station D and Station G by performing a phase swap on each.

Comparisons of voltage unbalance levels were made at multiple locations in the affected region for before and after implementation of line transpositions. For all these locations, voltage unbalance was significantly improved. An example is shown in Figure 15. However, as the geographically limited EMT model used by the VUT suggested, TVA has seen an increase in voltage unbalance on the 500-kV system to the west of the transposition area since the transpositions were performed. This has led TVA to begin an effort to create a complete EMT model of its entire 500-kV system to better target voltage unbalance mitigations.

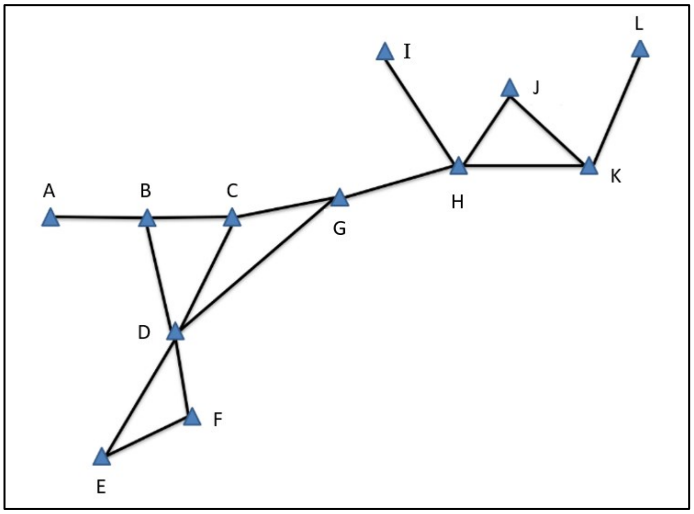


Figure 13. TVA 500kV Regional System

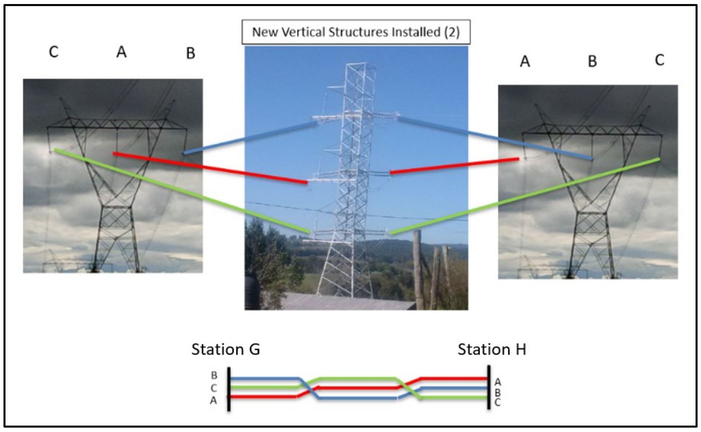


Figure 14. Line Transposition Example

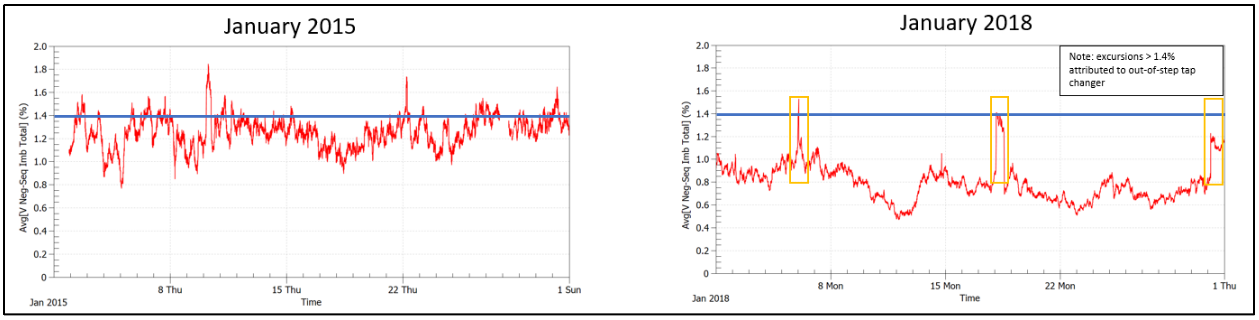


Figure 15. Voltage Unbalance Comparison Before and After Line Transposition Project

D. Other Mitigations

It is widely known that synchronous machines, including synchronous condensers work very well in dampening voltage unbalance as their windings serve as natural sources to dampen negative sequence currents. Likewise, Flexible AC Transmission Systems (FACTS) devices such as Static Var Compensators (SVC) and Static Synchronous Compensators (STATCOM) can be programmed to mitigate voltage unbalance. However, machines and FACTS devices are generally not cost competitive with traditional solutions, such as line transpositions, unless there are other benefit streams.

As inverter-based resources such as solar, wind, and battery energy storage continue to replace rotating machines, it would be highly beneficial if they could be used to address voltage unbalance issues in the future. Injection of negative sequence current by inverters could be programmed into the firmware by OEMs to address voltage unbalance, much like some inverters can be programmed to inject negative sequence fault current for protection coordination.

V. PLANNING

A. Three Phase EMT Model

Previous voltage unbalance studies of the TVA system have been local or regional in nature due to the level of effort required to adequately model the transmission system using EMT simulation tools. However, a regional study conducted for Northeast Tennessee indicated a westward shift of voltage unbalance issues once lines were transposed to the east. Additionally, voltage unbalance issues moved westward following the transposition of three 500-kV lines in the east, which appears to confirm the previous study.

TVA kicked off an effort this year to develop an EMT model of its entire 500-kV system to study voltage unbalance. This model will be utilized to develop optimized system-wide solutions to voltage unbalance and will also be used annually to evaluate the changing generation landscape.

B. Decarbonization

Like many utilities across the country, TVA has sustainability goals which include reducing carbon in the coming years. TVA's carbon reduction plans aim to achieve a 70% reduction from 2005 baseline levels by 2030, an 80% reduction by 2035 and net-zero carbon by 2050. Achievement of those plans require increased use of carbon-free generation and the retirement of large portions of the coal fleet. Consequently, voltage unbalance has the potential to appear at new locations as power flows change across the system due to the new generation mix.

Over the last ten years, several increases in carbon-free generation have occurred. The completion and commencement of commercial operation of a new unit at a nuclear plant in Tennessee added 1,100MW of generation to the EHV transmission system. Nuclear extended power uprate projects have provided additional power to the EHV transmission as well. An example of this is a 465MW uprate at the units at a nuclear plant in

Alabama. From a voltage unbalance perspective, nuclear generation is baseload generation with little variation in daily plant output. As such, this generation, which is connected to the EHV transmission system, is required to travel long distances along untransposed transmission lines to support load requirements. This is a contributor in the upward trend in voltage unbalance in some areas.

Utility-scale, transmission-connected, solar plants are increasing in the TVA area. Several hundred MW have been installed, with thousands of MW in the interconnection queue that are being studied. While this serves to meet carbon reduction goals, we must study the impacts from a voltage unbalance perspective to ensure that we do not have an unintended power quality issue that would be difficult to mitigate. The retirement of synchronous generation which has served as a natural mitigation for voltage unbalance also presents concern.

Environmental impact statements are currently being created to study the potential retirement of thousands of MW of coal generation. Many options exist for replacement of this coal generation:

- Do not replace generation
- Replace coal generation with equivalent rated gas generation
- Replace coal generation with equivalent rated generation at a different location (gas or small modular reactor)
- Replace coal generation with Inverter Based Resources (solar and/or battery)

Voltage unbalance studies must be completed for each of these scenarios (or a combination of these scenarios) to determine the transmission system improvements that need to be made to support voltage unbalance goals.

VI. RESEARCH & DEVELOPMENT

Since voltage unbalance is a phenomenon that can have major effects upon the efficiency, health, and emission of electrical devices, framing limits that can be scientifically justified is important to an efficient system operation, and more importantly, "future proofs" the limits. TVA and other utilities are partnering with the Electric Power Research Institute (EPRI) to assess existing tools and techniques which can inform the development of voltage unbalance limits. This research work will be especially important to the IEEE 2844 [5] working group. This includes assessing existing voltage unbalance limits in North America, analyzing whether these limits are appropriate, evaluating the methods by which the limits are derived, comparing against similar methods from around the world, and recommending alternative methods if the existing ones are not feasible. Developing a documented scientific unbalance allocation process will help maintain system compatibility for all associated stakeholders.

An additional research effort is underway with a university partner to use artificial intelligence to help predict voltage unbalance levels. Using Supervisory Control and Data Acquisition (SCADA) data and Phasor Measurement Unit (PMU) data, a neural network model can be developed and trained. The intent is to then integrate this with the State Estimator software to analyze planned outages, generation dispatch, and forecasted system load flows that may result in problematic voltage unbalance levels at buses on the transmission system.

VII. CONCLUSIONS

Managing transmission system voltage unbalance has emerged as an important issue for TVA, with documented impacts to generation, transmission, distribution, and end-use customer equipment in the TVA service area. For TVA, voltage unbalance has manifest as a regional issue, with voltage unbalance levels generally increasing over a period of several years. This upward trend has been driven by changes to the generation dispatch profile but has other contributing factors, such as transmission system configuration and system load.

TVA has undertaken continuous improvement efforts to improve situational awareness of voltage unbalance and implement effective mitigation solutions. The results of these efforts have included 500-kV line transposition projects, consideration of voltage unbalance during outage planning, and real-time mitigation of emerging voltage unbalance problems by dispatching regional generation. TVA has employed EMT analysis to confirm the key drivers for regional voltage unbalance and recommend targeted mitigation, such as line transpositions or informing acceptable load levels for outage planning purposes. The completion of TVA's EMT model of the complete 500-kV system will be an important planning and mitigation tool, allowing for system-wide voltage unbalance analysis as the generation mix and power flow on the system continue to evolve.

Looking forward, developing strategies to employ utility-scale inverter-based resources such as solar, wind, and battery storage systems to control transmission level voltage unbalance will be useful. Additionally, establishing scientifically justified voltage unbalance limits for transmission systems that are coordinated with generation, transmission, and distribution protection and control systems will be important to effectively managing the issue.

As the grid continues to decarbonize and integrate increasing quantities of inverter-based resources, TVA's experience has shown that awareness and effective control of transmission-level voltage unbalance will remain an important issue for utilities to manage.

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