

EHV Transformer Tap Adjustment to Correct Wide Area Voltage Unbalance

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Abstract— As load increases across the Tennessee Valley Authority’s service area, so does voltage unbalance. Recently, Local Power Companies in Middle Tennessee have expressed concerns about high C-phase voltage at the distribution level, on end-use equipment, and related limitations on using distribution capacitor banks and voltage regulators because of the voltage unbalance at TVA wholesale delivery points. To address these problems, TVA has implemented an unconventional load tap changer configuration on several 500/161-kV transformers to mitigate voltage unbalance at on local power company distribution systems. In this paper we will discuss the details of the Middle Tennessee voltage unbalance issue, TVA’s past attempts at mitigation, and the recently proposed load tap changer adjustment solution. Agency concerns with implementing the load tap changer solution, unexpected problems found during testing, and the results of the configuration change are also discussed.

Keywords: *voltage unbalance, load tap changer, power quality.*

I. INTRODUCTION

The Tennessee Valley Authority (TVA) [1] is a generator and transmission owner/operator serving 153 local power companies (LPCs) and 60 transmission-connected large industries and federal facilities in Tennessee and parts of six surrounding states. TVA provides power through one of the largest transmission systems in the nation; a network that includes over 16,000 miles of transmission lines, over 500 transmission substations, and more than 50 power transformer banks with primary windings rated at 500-kV. The TVA service territory is shown in Figure 1.

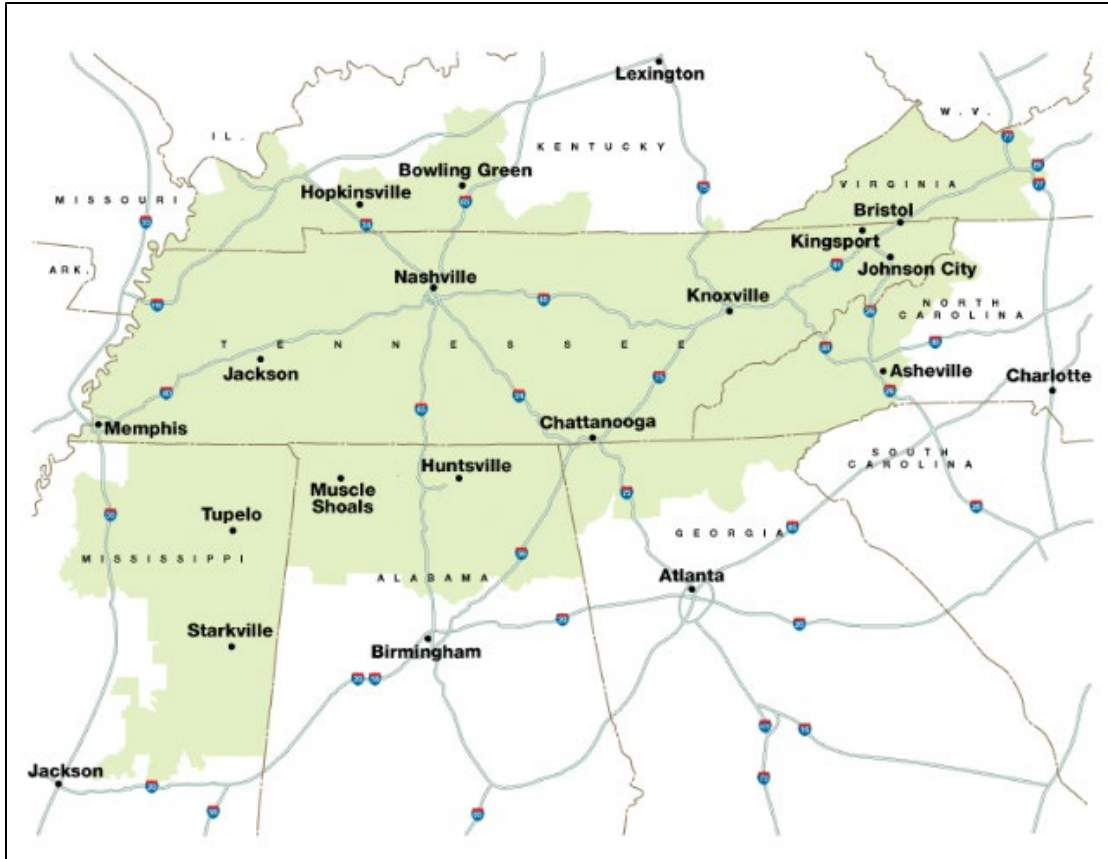


FIGURE 1 – TVA SERVICE TERRITORY

Voltage unbalance is the difference in phase voltage magnitudes and/or phase angular separation in a three-phase electrical system. In the past fifteen years, voltage unbalance on the TVA transmission system has emerged as a power quality issue impacting TVA, local power companies, and end-use customers [2]. While most transmission busses operate well below voltage unbalance planning limits, some regions have experienced voltage unbalance at or above limits, particularly during periods of high system load.

In TVA’s experience, periods of higher regional voltage unbalance are usually driven by three factors:

1. TVA System Load
2. Local generation dispatch
3. Transmission configuration (outages)

TVA Grid System Operations routinely considers these factors to prevent objectionable voltage unbalance on the system. Planned generation and transmission outages are coordinated to avoid unnecessary overlap. Sensitive outages are scheduled during periods of lower system load, reducing the expected voltage unbalance at affected customer busses.

TVA 500-kV and 161-kV transmission lines were originally installed without transposition during times of lower system load. In recent years, the TVA service territory has experienced increasing demand for electricity driven by population and industrial growth, weather trends, and

increasing electric vehicle use [3]. Increasing power flow from generation across the untransposed 500-kV and 161-kV transmission networks into Middle Tennessee, including the Nashville Metropolitan area, has contributed to wide area voltage unbalance in the region, resulting in complaints from LPCs and industries.

This paper will review the voltage unbalance issues experienced by Middle Tennessee LPCs and end-use consumers and a novel approach implemented by TVA Grid System Operations to significantly improve voltage unbalance in Middle Tennessee.

II. VOLTAGE UNBALANCE STANDARDS

LPCs and end-use consumers rely on ANSI C84.1 [4] to establish the nominal voltage ratings and operating voltage ranges of distribution systems and end-use equipment. LPCs operate distribution systems so that service voltage at customer delivery points is within the ranges established by the standard. Likewise, end-use consumers and equipment manufacturers design their systems to operate satisfactorily across the full range of standard utilization voltages. This paper will discuss how transmission voltage unbalance may reduce LPC flexibility to regulate voltage on the LPC-owned distribution system and the resulting difficulty in maintaining service and utilization voltages at customer facilities within the ANSI C84.1 limits.

ANSI C84.1 is also frequently referenced by LPCs and end-use customers with respect to voltage unbalance. Annex C.2 states that “electric supply systems should be designed and operated to limit the maximum unbalance to 3 percent when measured at the electric-utility revenue meter under no-load conditions.” The standard expresses voltage unbalance as a percentage, defined as the maximum voltage deviation from the average voltage, divided by the average voltage where the voltages are measured phase-to-phase.

TVA has adopted the International Electrotechnical Commission Technical Report (IEC/TR) 61000-3-13 [5] definition and planning limits for voltage unbalance on the high voltage (HV) transmission system. IEC/TR 61000-3-13 expresses voltage unbalance as a percentage, defined as the ratio of the modulus of the negative-sequence to the positive-sequence components of the voltage fundamental frequency. The planning level for 161-kV systems is a weekly, 95th percentile, 10-minute average voltage unbalance level of 1.4%.

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 [6] which is intended to become an IEEE recommended practice for voltage unbalance and will include recommended limits for voltage unbalance, voltage unbalance calculation methodology, and information on voltage unbalance impact on the power system and utilization equipment.

III. MIDDLE TENNESSEE VOLTAGE UNBALANCE BACKGROUND

In the past decade, the average weekly 95th percentile voltage unbalance reported by power quality monitors in Middle Tennessee has shown an increasing trend, indicated in Figure 2.

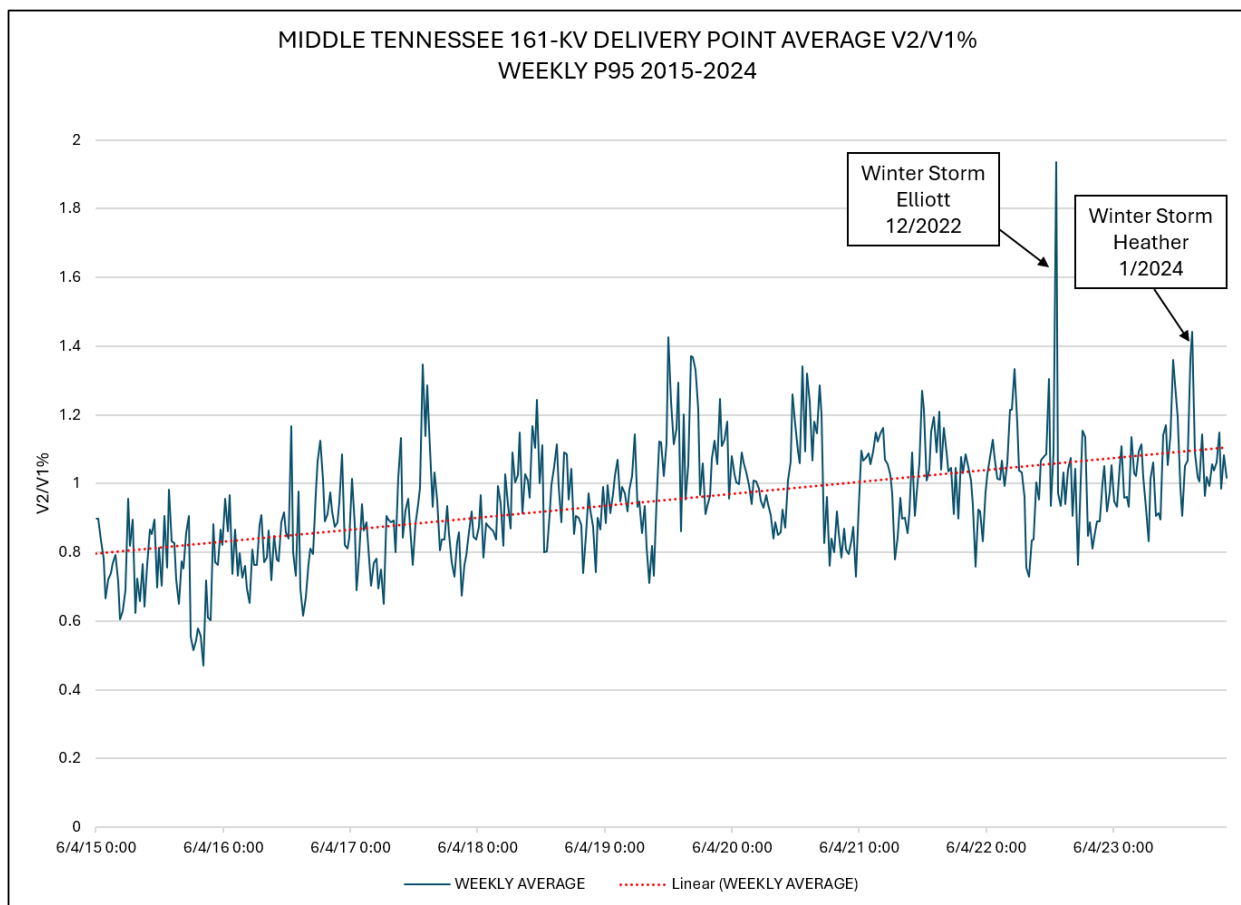


FIGURE 2 – MIDDLE TENNESSEE VOLTAGE UNBALANCE TREND

While the regional 161-kV system generally operates below the TVA 1.4% planning limit, it is becoming more common for the area average voltage unbalance to exceed the limit, particularly during extreme weather conditions.

161-kV A-phase to ground voltage across Middle Tennessee is consistently lower than B and C-phase to ground voltages. Figure 3 illustrates the ten-minute average phase-to-ground voltages on the primary side of one Middle Tennessee 161/25-kV LPC-owned step-down transformer for August 1 to August 8, 2023. There is an approximate 2-kV difference in the magnitude of the A-phase to ground voltage and the B and C-phase to ground voltages. The 95th percentile voltage unbalance at this station during this week was 1.36%.

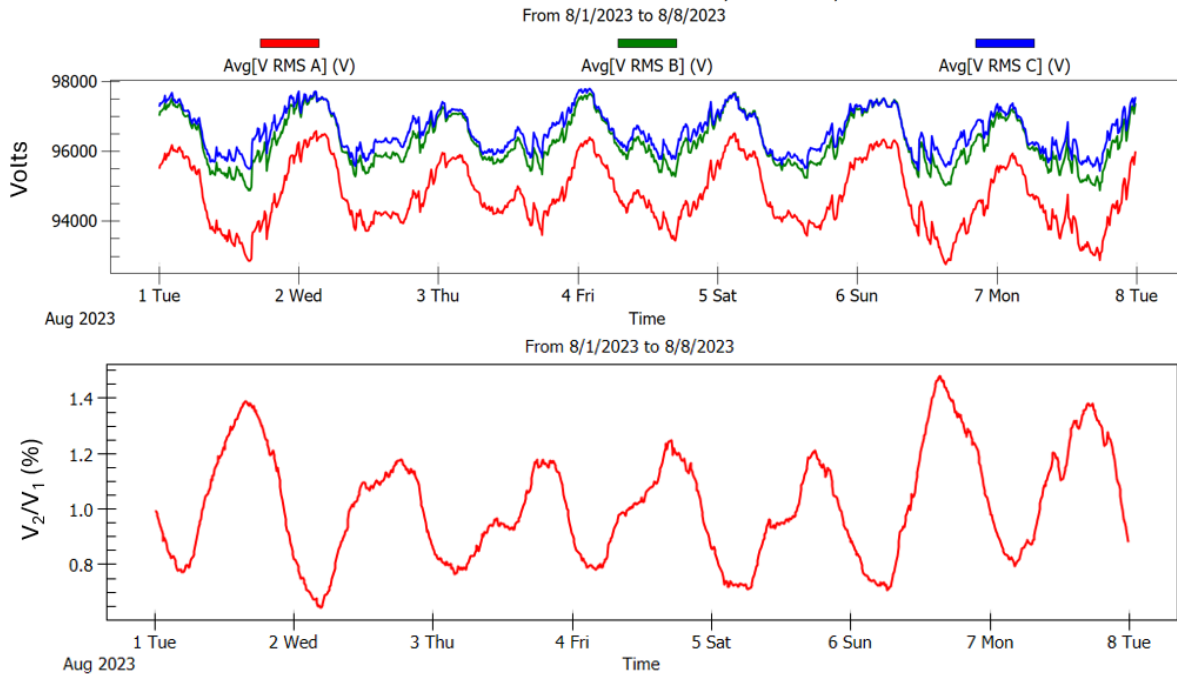


FIGURE 3 – 161-kV VOLTAGE MAGNITUDE DIFFERENCE AND VOLTAGE UNBALANCE

Most LPC step-down transformers are configured with a delta primary and grounded wye secondary. The delta-wye transformation of unbalanced 161-kV voltages with A-phase as the lowest phase results in LPC transformer secondary C-phase to ground voltage being higher than A and B-phase to ground voltages. Maintaining A and B-phase voltages within ANSI C84.1 range A limits at the end of a distribution line frequently resulted in undesirably high C-phase voltage at the LPC substation. Figure 4 shows the 25-kV line-to-ground voltage at the secondary side of the same LPC-owned transformer referenced in Figure 3. C-phase voltage reached a maximum of approximately 15.3-kV, corresponding to 1.06 per unit (p.u.) line-to-neutral voltage.

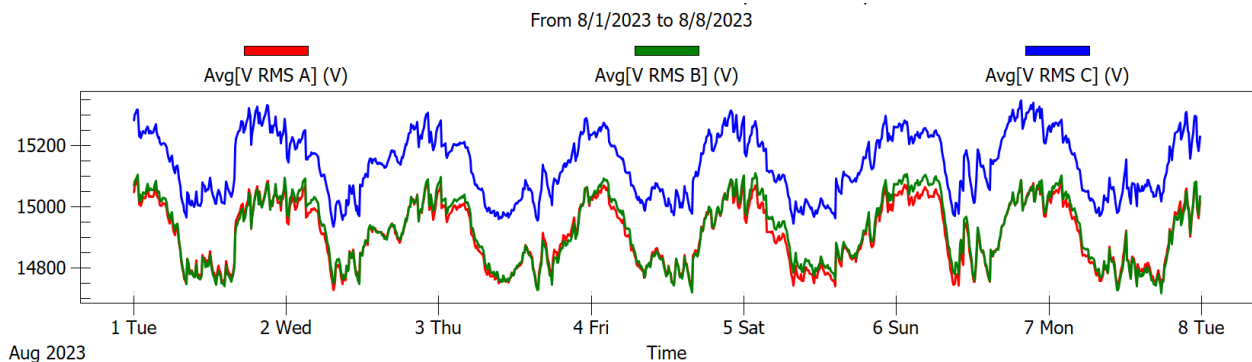


FIGURE 4 – LPC TRANSFORMER 25-kV SECONDARY LINE-TO-NEUTRAL VOLTAGE

IV. VOLTAGE UNBALANCE COMPLAINTS

A. High C-phase Distribution Voltage

During periods of higher TVA transmission system loading or planned generation outages in Middle Tennessee, the magnitude of C-phase distribution voltage frequently exceeded LPC

warning or alarm thresholds, prompting LPC personnel to contact TVA. LPC inquiries about high C-phase voltage in Middle Tennessee have become increasingly common during the past five years.

B. LPC Voltage Regulation Difficulty

ANSI C84.1 specifies that energy supply systems shall be designed and operated so that service voltages are within prescribed ranges, with only infrequent deviations. When C-phase voltage is significantly higher than A and B phase voltages at the substation, LPCs without single phase distribution voltage regulation capability have difficulty maintaining acceptable service voltage for customers on all phases for the length of the distribution line.

LPCs have complained that voltage unbalance impacts their use of conservation voltage reduction (CVR) technology. CVR increases energy efficiency of some equipment by intentionally lowering distribution voltage to the low end of the ANSI C84.1 range. During periods of higher voltage unbalance, LPCs have reported inability to maintain service voltages within ANSI C84.1 limits while the CVR systems are operational. In these cases, CVR must be curtailed or discontinued, which reduces the savings potential of the CVR technology investment.

C. End-Use Equipment Impacts

One Middle Tennessee LPC reported increased incidence of residential heating, ventilation, and air conditioning (HVAC) equipment failures on C-phase distribution circuits throughout their service area. They attributed this to the higher C-phase voltage caused by transmission voltage unbalance.

During extreme weather events and corresponding high transmission system load, Middle Tennessee LPCs have also reported occurrences of distribution-supplied end-use customer three-phase motor loads tripping on negative sequence protection due to elevated transmission and distribution system voltage unbalance.

V. CONVENTIONAL MIDDLE TENNESSEE VOLTAGE UNBALANCE MITIGATION STRATEGIES

The primary driver of increasing voltage unbalance in Middle Tennessee is increasing load flows on untransposed 500-kV and 161-kV networks. Conventional voltage unbalance mitigation techniques such as outage planning to avoid overlapping outages creating long radial lines or dispatching additional local generation to support regional voltage unbalance are not applicable in this case. Implementing 500-kV line transpositions on key lines supplying Middle Tennessee or adding additional generation to the area would be effective to improve Middle Tennessee voltage unbalance. However, the required engineering studies and projects to implement these improvements would require significant capital investment and have long lead times.

Flexible alternating current transmission systems (FACTS) may be configured to mitigate voltage unbalance. TVA has one existing static VAR compensator (SVC) at a 500-kV station in the Nashville area. Unfortunately, its existing controls cannot act on a per-phase basis. TVA is exploring modification of the SVC so it can act to reduce voltage unbalance in the future. Additionally, TVA has launched projects to install three static synchronous compensators (STATCOM) in Middle Tennessee to support dynamic voltage stability. As an auxiliary benefit, these new STATCOMs will be capable of providing continuous compensation to reduce voltage unbalance. The expected in-service date of the first Middle Tennessee STATCOM is 2029.

As LPC inquiries about high C-phase distribution voltage increased through the fall and early winter of 2024, Grid System Operations sought a low-cost solution that could be implemented quickly. The power quality team began exploring less conventional solutions.

VI. AN UNCONVENTIONAL VOLTAGE UNBALANCE SOLUTION

Power quality staff determined that the cause of the higher C-phase voltage on LPC distribution systems in Middle Tennessee is lower A-phase to ground voltage on the TVA 161-kV transmission system. To fix the problem, A-phase voltage magnitude would need to be increased to the level of B and C phase. Two options were evaluated.

Staff considered using 161-kV capacitor banks in Middle Tennessee to raise A-phase voltage to the level of B and C-phase voltages. This seemed sensible because the capacitor banks are typically in service at the highest load times when voltage unbalance is highest. However, there were clear problems with the approach. All 161-kV capacitor banks are gang-operated so individual phase switching is not possible without significant modification to existing equipment. Additionally, modifying the cap banks to have a constant megavar unbalance between A-phase and B and C-phases would require changes to capacitor bank protection schemes. Finally, operational control of the capacitor banks to regulate voltage levels and voltage unbalance in the area would become increasingly complex. Although not impossible, it became clear that this option had significant challenges.

A second option proved more feasible to implement. In Middle Tennessee, the TVA extra high voltage (EHV) and high voltage (HV) transmission systems are connected by nine intertie transformer banks, shown in Figure 5.

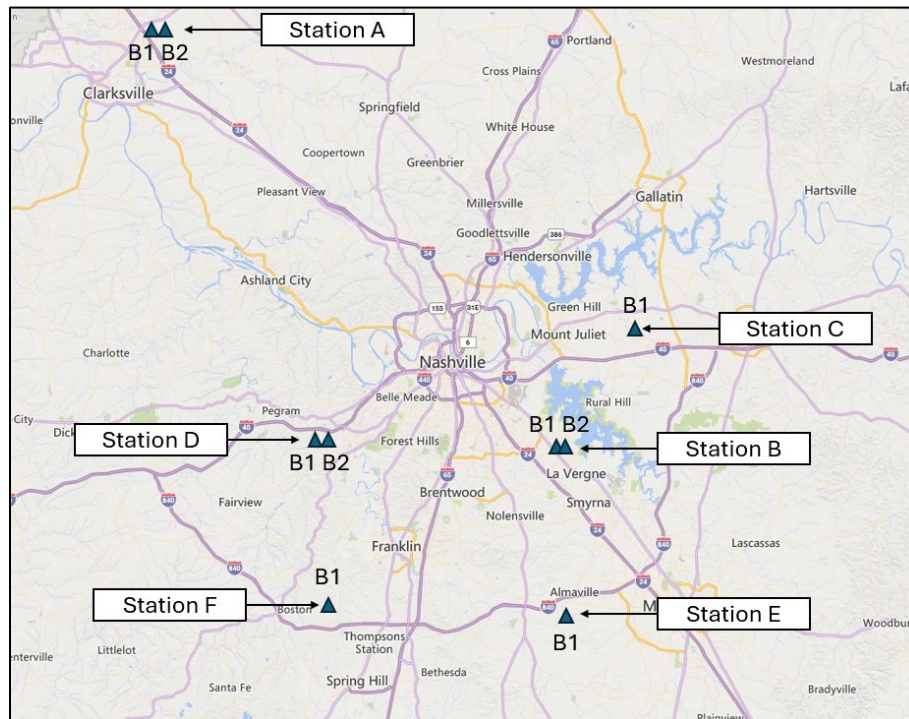


FIGURE 5 – MIDDLE TENNESSEE EHV/HV INTERTIE TRANSFORMER BANK LOCATIONS

Intertie transformer banks are typically comprised of three, single phase, three-winding, power transformers connected three-phase with a 500-kV wye-grounded primary, 161-kV wye-grounded

secondary, and 25-kV or 13-kV delta-connected tertiary windings. Each transformer is equipped with an on-load tap changer (LTC). The three phases of an intertie bank LTC are normally operated together for three-phase system voltage regulation. However, it is possible to manually manipulate the tap position of each phase independently. Manual adjustment is performed after an alarm alerts the transmission operator of the abnormal condition that an LTC has malfunctioned, and one phase has become “out of step”, or on a different LTC tap position, than the other two phases. In that case, remote LTC control is locked, and field personnel must manually correct the problem.

Power quality staff suggested adjusting only the A-phase tap at the 500/161kV intertie transformer banks around Middle Tennessee to raise the 161-kV A-phase line to ground voltage and reduce area voltage unbalance. This proposal was met with several concerns, discussed in section VII.

VII. IMPLEMENTATION CONCERNS

The intertie bank LTC proposal was met with legitimate questions and concerns from TVA personnel. Operating EHV transformer banks with LTCs out of step is not common utility practice. A literature review revealed one documented case of power transformer bank LTCs intentionally operated out of step [7]. This section discusses initial concerns with the strategy and power quality staff investigation of these issues.

A. Higher Intertie Bank Neutral and Tertiary Circulating Currents

In response to the intertie bank LTC proposal, TVA transmission planning staff noted that electromagnetic transient (EMT) models of the TVA 500-kV transmission system showed simulated 500/161-kV intertie transformer bank neutral current values that exceeded trip thresholds when the transformer LTCs were operated out of step. It was also unclear how the neutral current magnitude increases would vary with load after the LTC adjustments were made.

Fortunately, there was power quality data available from a previous event on a 500/161kV intertie bank where an LTC malfunctioned and became out of step. The actual response of the neutral current on the bank did not show the large increase suggested by the EMT models. This data alleviated some concern and provided a basis for moving forward with testing the LTC solution. Planning staff were satisfied the EMT models were not calibrated to accurately predict the expected increase in neutral current on the 500/161-kV intertie banks.

Another staff concern was the magnitude of the increase of the circulating currents in the intertie bank delta tertiary windings. Many Middle Tennessee 500-kV intertie banks have reactors connected on the tertiary bus that are used for voltage regulation. Staff were concerned that the intertie bank tertiary windings would become overloaded with the combination of increased circulating currents resulting from the LTC adjustments and the tertiary reactors in service. This would limit the ability of operators to employ the tertiary reactors to regulate system voltage. Staff agreed to place tertiary reactors out of service during initial testing of the LTC solution so the intertie bank tertiary circulating currents would not become a limiting factor.

B. Increase in 500-kV Voltage Unbalance

Staff expected that adjusting the intertie bank A-phase tap to increase 161-kV A-phase-to-ground voltage would increase 500-kV voltage unbalance by proportionally decreasing 500-kVA-phase-to-ground voltage. Staff was concerned that an increase in 500-kV voltage unbalance in

Middle Tennessee could transfer the higher unbalance levels to other areas of the transmission system. TVA has not adopted planning limits for voltage unbalance on the 500-kV system, so staff had to consider what increase in 500-kV voltage unbalance would be acceptable.

In Middle Tennessee, the 500-kV network is not directly connected to customer loads. The main concern was impact to generation on the 500-kV network. Staff concluded that if the closest 500-kV generation did not see significant change in voltage or current unbalance levels during testing, a small increase in voltage unbalance on the 500-kV network would be acceptable. Since adjusting LTCs would not alter the influence of the untransposed transmission lines on voltage unbalance, staff predicted that any local 500-kV voltage unbalance increase due to the LTC adjustment would not shift to other regions of the service territory.

C. EHV Transformer Out of Step Alarms

The TVA 500/161-kV intertie bank LTC out of step alarm is triggered when there is an odd number LTC step difference between any two individual phases. When the alarm is enabled, transmission operators are locked out of remotely adjusting the LTC. Field personnel must be called out to manually correct the issue. TVA's transformer subject matter expert suggested a workaround; to normally operate the LTCs out of step to correct voltage unbalance, the step difference between A-phase tap and B and C-phase taps would need to be an even number.

D. Previous LTC Adjustment Attempt was Unsuccessful

Staff recalled that a previous attempt to implement LTC adjustments in Middle Tennessee to mitigate voltage unbalance had increased area voltage unbalance. Power quality staff researched this claim and could not find corroborating data or documentation to explain the previous results. Given the lack of documentation of the previous attempt – including where the test had been performed, when it had been performed, what phase was adjusted, or the direction it was adjusted – staff agreed to attempt the adjustments again so the results could be documented and determine why the previous attempt had failed.

VIII. WIDE AREA LTC ADJUSTMENT PILOT IMPLEMENTATION AND RESULTS

This section discusses how TVA tested and implemented the LTC adjustments to correct wide area voltage unbalance.

Prior to implementing tests of the 500/161-kV intertie bank LTC adjustments, power quality staff configured web-based dashboards of phasor measurement unit (PMU) voltage and neutral current data from the 500-kV and 161-kV sides of each intertie bank. This enabled staff to monitor the impact of adjustments in real time and confirm that the tap changes were having the desired effect.

A. Proof of Concept: Initial LTC Adjustment Tests

Power quality worked with Grid System Operations and field staff to implement a three-hour test of the LTC adjustments at Substation D, Bank 1 and 2, and Substation F, Bank 1 (shown above in Figure 5), on February 21, 2024, from 11:00 CT to 14:00 CT. At 11:00 CT, A-phase tap of each bank was adjusted two steps to boost 161-kV A-phase voltage.

During the test, parameters of concern remained within acceptable limits. Staff used a handheld current transformer to measure the secondary circulating current in the delta-connected tertiary

windings at each intertie bank. The increase in tertiary circulating current at each bank varied but was well below the rating of the tertiary windings, which was considered acceptable. Bank neutral current increased by approximately 25 amps per A-phase LTC step change. Changes to 500-kV voltage unbalance were negligible.

The test proved the LTC adjustments are effective to reduce voltage unbalance over a wide area. Figure 6 indicates the 10-minute interval average 161-kV and 25-kV voltage and voltage unbalance for one LPC delivery point located approximately 20-line miles from substation D. During the test period, 161-kV A-phase to ground voltage increased, and LPC distribution C-phase to ground voltage decreased. At 14:00 when A-phase of each intertie bank was returned to be in step with B and C phases, 161-kV voltage unbalance increased by 0.28% (from 0.472% to 0.752%). 25-kV voltage unbalance increased by 0.22%, from (0.515% to 0.737%).

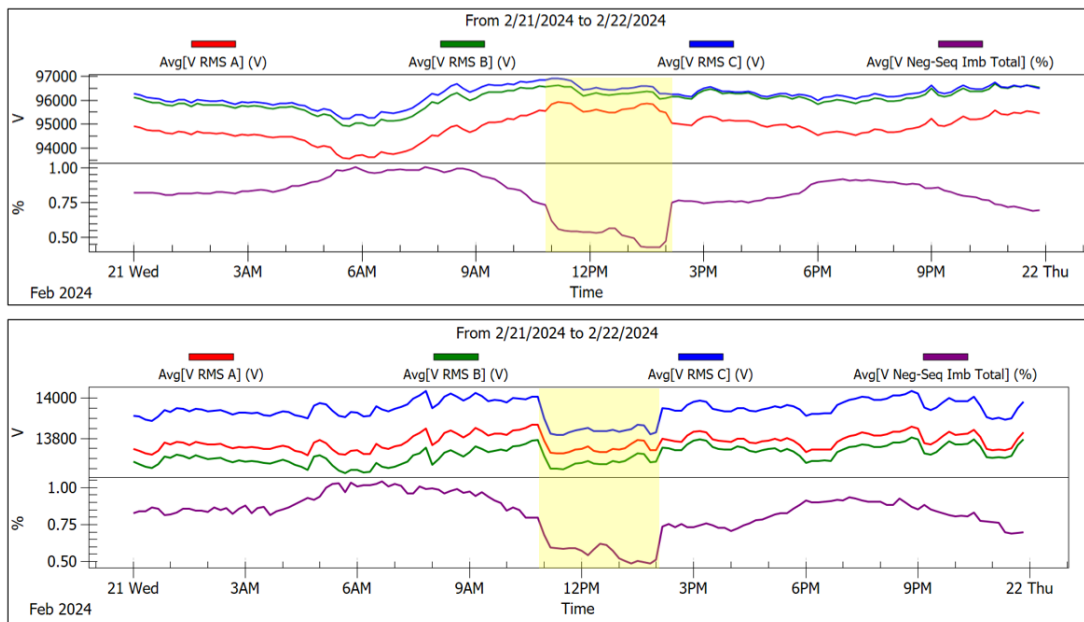


FIGURE 6 – FEBRUARY 21, 2024, LTC ADJUSTMENT TEST IMPACT AT LPC DELIVERY POINT

Figure 7 shows the voltage unbalance reduction (absolute difference) across 50 delivery points impacted by the test. Voltage unbalance improvements were greatest at stations within two busses of the intertie bank where the LTC adjustments were made.

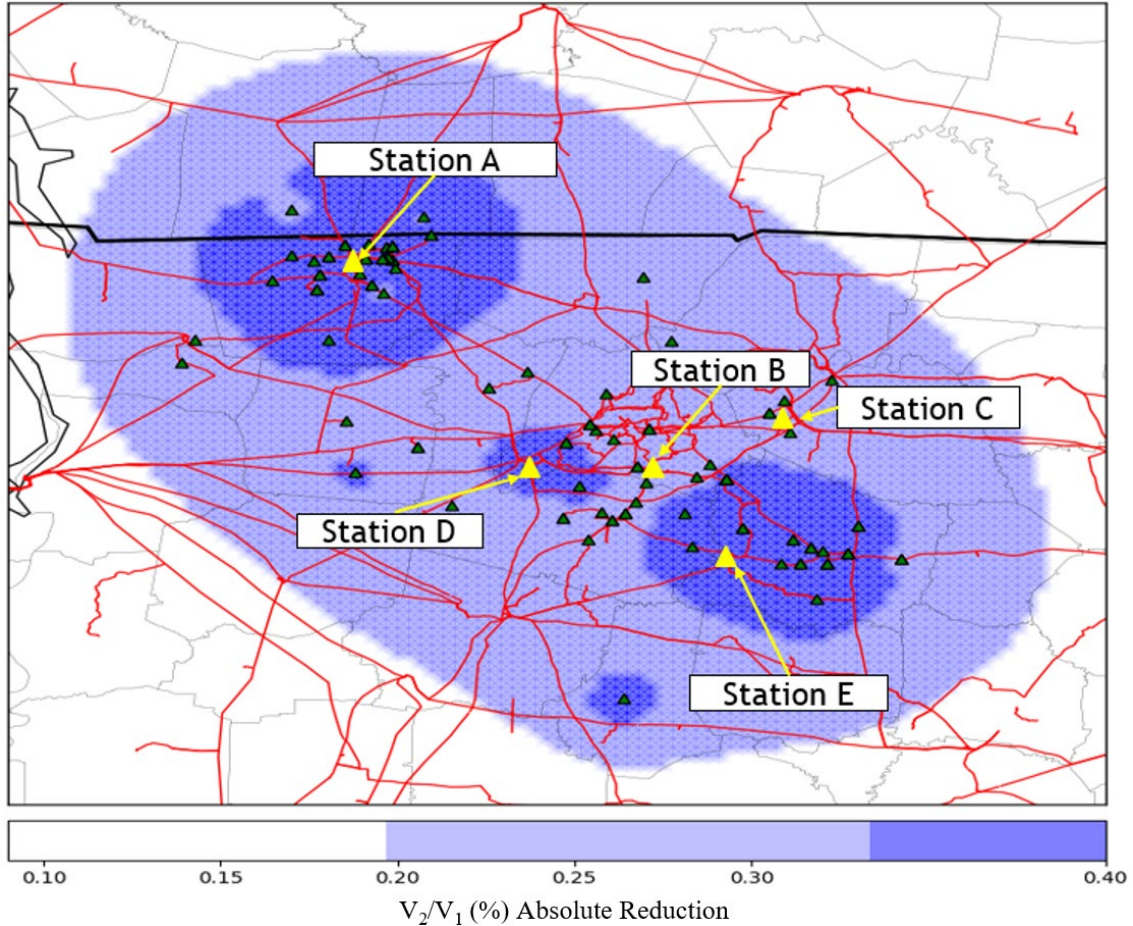


FIGURE 7 – FEBRUARY 2024 TEST VOLTAGE UNBALANCE REDUCTION

B. Middle Tennessee Area LTC Adjustment Pilot

The successful test provided a basis to move forward with a wide area LTC adjustment pilot to be implemented over a longer time. As with the initial test, the pilot project consisted of adjusting only the A-phase tap on each 500/161kV transformer at each 500/161-kV intertie bank in Middle Tennessee so the 161-kV A-phase to ground voltage would align with B and C-phase to ground voltages. On May 20, 2024, the LTC adjustments were made at eight 500/161-kV intertie banks listed in Table 1. These relative LTC positions have remained in effect for eleven months.

Transformer Bank	A-Phase Tap Position Difference from B and C-Phase
Station A Bank 1	-2
Station A Bank 2	-2
Station B Bank 1	+2
Station B Bank 2	+2
Station C Bank 1	-2
Station D Bank 1	+2
Station D Bank 2	+2
Station E Bank 1	+4

TABLE 1– LTC ADJUSTMENT PILOT RELATIVE A-PHASE TAP POSITION

Since these changes were implemented, approximately 110 LPC delivery points in Middle Tennessee have seen an absolute voltage unbalance decrease 0.25 percent or more. LPC delivery points within two busses of the 500/161-kV intertie banks with LTC adjustments saw most benefit. Figure 8 shows the wide area per unit voltage unbalance decrease across Middle Tennessee.

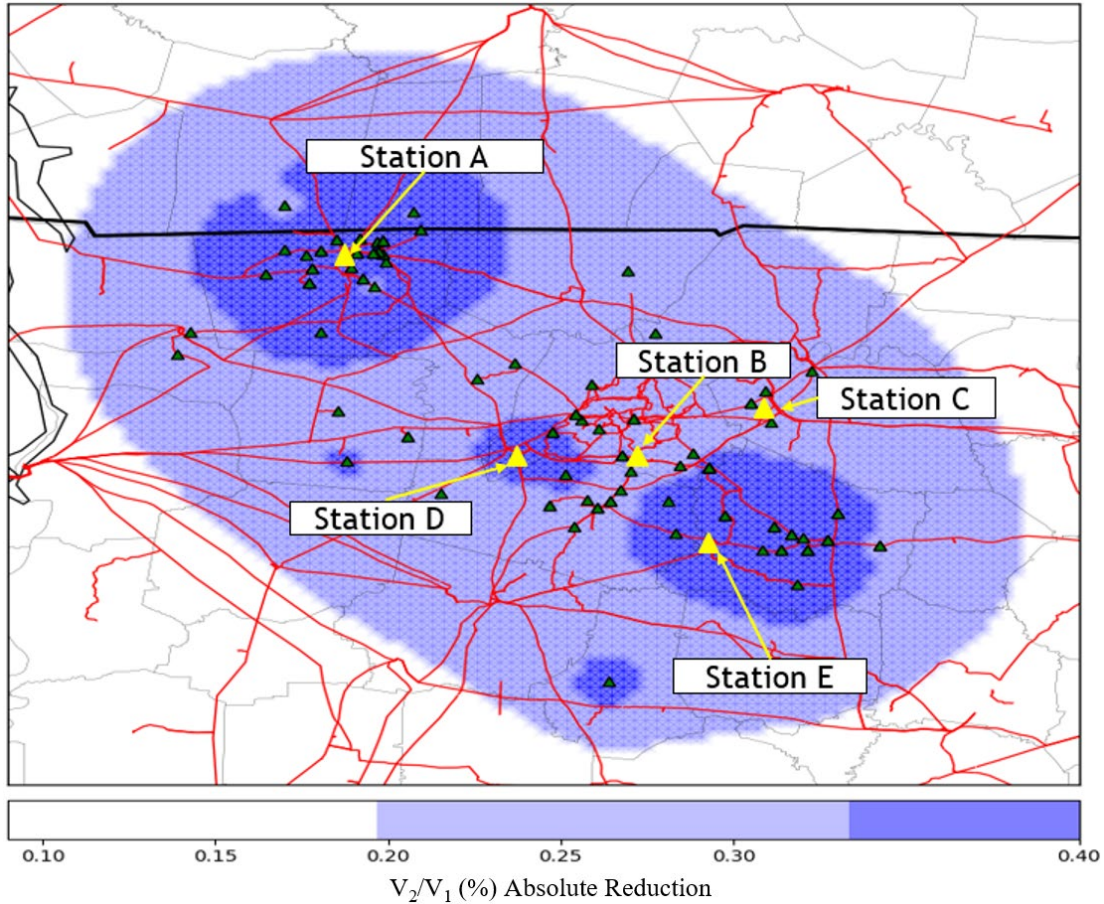


FIGURE 8 – MAY 2024 PILOT IMPLEMENTATION VOLTAGE UNBALANCE REDUCTION

Figure 9 illustrates the voltage unbalance improvement at one LPC medium voltage delivery point near Station E. LPCs have reported significantly improved C-phase voltage throughout the region.

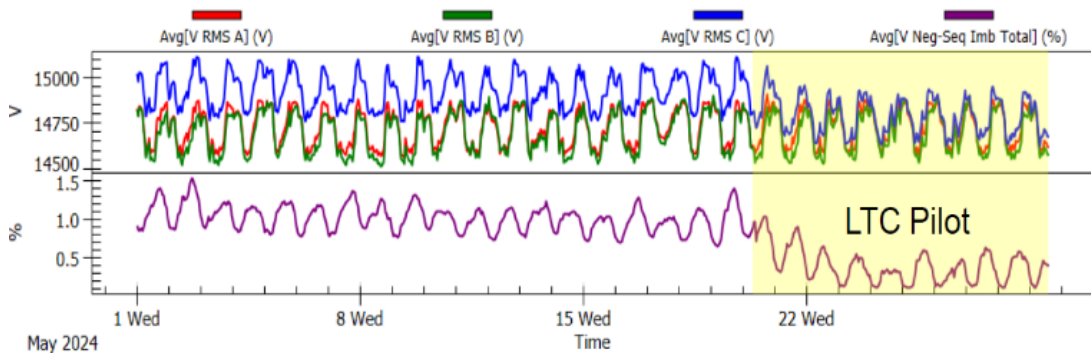


FIGURE 9 – LTC ADJUSTMENT PILOT IMPACT

As system load increased during the summer of 2024, voltage unbalance also increased. However, with the LTC adjustments in place, Middle Tennessee LPC delivery points saw lower voltage unbalance than they did in the summer of 2023. Figure 10 illustrates the average correlation between voltage unbalance and megawatt load at delivery points across Middle Tennessee for the summers of 2023 and 2024. In 2023, LPC delivery points serving 25 megawatt loads saw between 1.1% and 1.4% voltage unbalance. In 2024, such delivery points experienced between 0.65% and 0.90% voltage unbalance – a significant improvement.

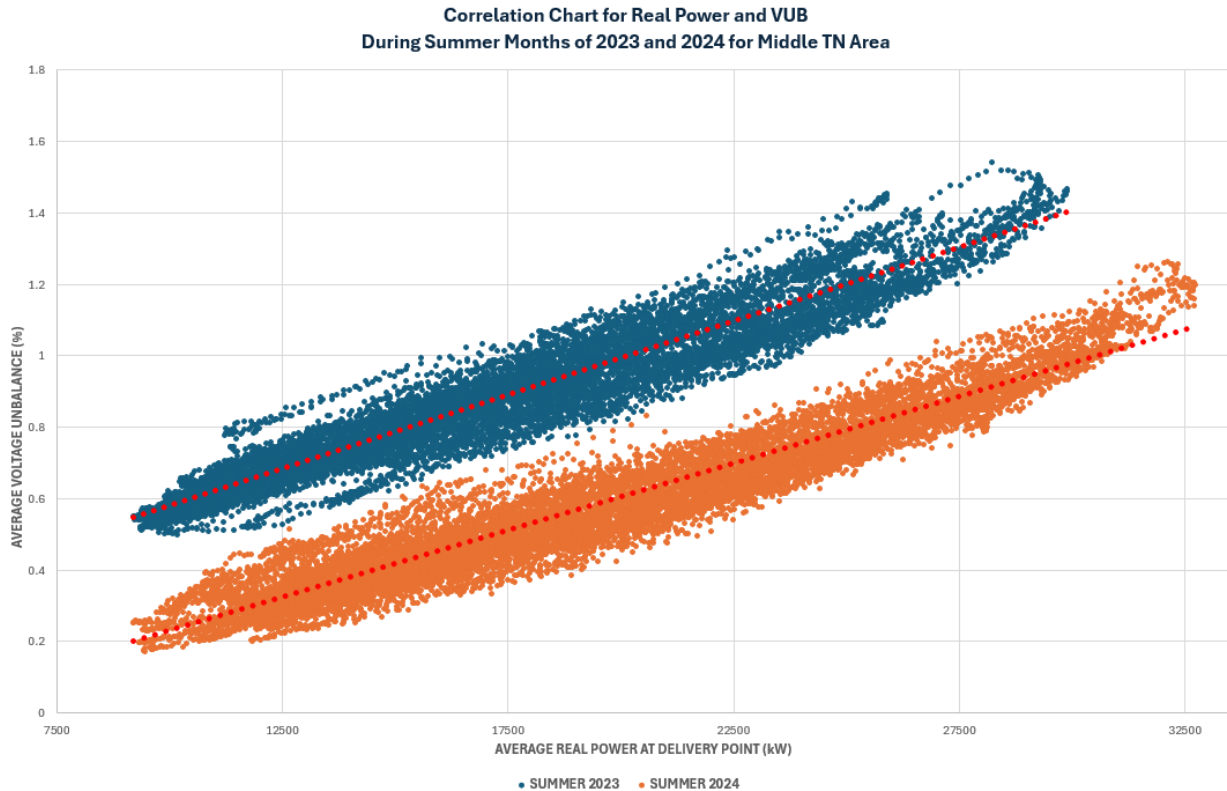


FIGURE 10 – 2023 AND 2024 LPC DELIVERY POINTS MEGAWATT LOAD AND VOLTAGE UNBALANCE CORRELATION

C. Addressing Initial Concerns

Staff concluded that the benefits of operating in the unbalanced LTC mode outweigh the downsides discussed in this section.

TVA has monitored 500/161-kV intertie bank neutral currents, delta tertiary circulating currents, and 500-kV voltage unbalance levels since the LTC adjustments were implemented on May 21, 2024, and found that all have remained within acceptable limits.

TVA observed that for each A-phase LTC step adjustment 500-kV neutral currents increased by approximately 20 to 25 amps. The largest 500-kV neutral increase observed was approximately 90 amps, seen at Station E, where A-phase LTC is 4 steps above B and C phase LTCs. This is well below the 400-A threshold where the bank may trip.

The changes in delta tertiary circulating currents varied for each LTC step change and changes were not as consistent as the neutral current increases. At Station E, the circulating current went

up to 330A for a four-step difference in the taps, corresponding to approximately 15-MVA of delta tertiary capacity. This is well below the rating of the winding.

500-kV voltage unbalance levels were increased proportionally to the 161kV voltage unbalance level decreases for stations with one 500/161kV intertie bank. At locations with two 500/161kV intertie banks, the voltage unbalance increase on the 500kV system was about 50% of the decrease on the 161kV system during the voltage unbalance pilot. These increases, however, have not caused problems to TVA or customer equipment. No customers are directly connected to the 500-kV system in Middle Tennessee. The increased voltage unbalance at TVA generation sites near Middle Tennessee is deemed insignificant. Phase-to-ground voltages TVA 500-kV stations have remained within acceptable limits.

Operating the transformer taps an even number out of step proved effective to avoid out of step alarms locking out operators from remote control of the intertie banks in most cases. Station F proved to be an exception which is discussed in Section IX.

IX. AN EXPECTED/UNEXPECTED PROBLEM DURING TESTING

TVA has configured controls to trigger an out-of-step (OOS) alarm when taps between EHV transformer phases vary by an odd number of steps for a specified time delay. This will prevent remote operation of the LTC until personnel report to the substation to return the transformers to balanced tap positions. The team assumed this scheme could be bypassed by adjusting the A-phase tap at each transformer bank an even number of steps from the other phases. However, this solution proved inadequate due to an idiosyncrasy of the typical LTC mechanism design.

Station F lacks capacitive compensation, generation, or a nearby SVC, so the Station F 500/161-kV intertie bank LTCs move frequently to maintain bus voltages within schedule. This was not expected to be problematic if an even step difference was maintained between A-phase LTC and B and C-phase LTCs. However, on May 21, 2024, shortly after implementing the adjustment at the Station F A-phase transformer LTC, the control system locked out. Staff learned that when the taps are at an even number out of step and the LTC progresses to tap 9, an out of step alarm will assert, locking out remote operation of the LTC.

The OOS alarm is triggered when the transformer moved to step 9 because there are two tap positions (9A and 9C) on either side of step 9 that are wired to the odd limit switches thus placing the step 9 position on the even limit switch, as shown in Figure 11. Operating on steps 7 and 9 or steps 9 and 11 is therefore seen logically as an odd step difference that will trigger an OOS alarm after a short time delay. These extra step positions are designed to be used for polarity reversal on the transformer moving from nominal voltage (step 9) to boosting or bucking mode of operation. This issue is present on all pilot sites but did not become apparent at additional sites due to lack of operation of the load tap changers through the problematic range.

VOLTS LINE TO NEUT.	448000 KVA AMPS.	LOAD TAP CH CONNECTIO	
		DIAL POS.	TAP SELECTOR CONNECTS A TO
317543	1411	17	1
313934	1427	16	2
310325	1444	15	3
306717	1461	14	4
303109	1478	13	5
299500	1496	12	6
295892	1514	11	7
292283	1532	10	8
288675	1552	9C	9
288675	1552	9	K
288675	1552	9A	1
285066	1572	8	2

FIGURE 11 – LTC NAMEPLATE POSITIONS

To eliminate operational issues arising from this design, multiple departments across TVA discussed the rationale for the odd LTC step lock out protection and whether it was necessary going forward. Staff theorized that early generation communications to remote substations caused operational problems with the LTCs necessitating the lockout protection in case of a “runaway tap changer” without proper visibility to the operator. This would require the operator to contact field personnel who could then verify operability, current step setting, and correct an abnormal LTC configuration, if needed. With modern communication pathways and increased grid visibility for remote operations, it was determined that the lockout feature could be eliminated given the OOS alarms would remain in place. TVA’s current design standard uses the OOS alarm without the lockout function. Operating with LTCs intentionally out of step has highlighted the importance of Operator visibility of single phase LTC position for transformer banks across the fleet.

X. CONCLUSION

Voltage unbalance on the TVA HV transmission system in Middle Tennessee has increased over the past decade due to increased power flows on untransposed EHV and HV transmission lines. While regional voltage unbalance is typically below TVA’s 1.4% planning limit, it is becoming more common for area average voltage unbalance to exceed the limit during periods of high load, causing problems for LPC distribution systems and end-use consumers. Conventional methods for managing transmission system voltage unbalance require significant capital

investment and have long lead times. LPCs in Middle Tennessee asked TVA for a solution that could be implemented quickly.

In 2024, the TVA Grid System Operations power quality team implemented a pilot project to adjust LTCs at eight Middle Tennessee 500/161-kV intertie banks to correct wide area voltage unbalance. During the pilot, LPC delivery points have experienced significant voltage unbalance improvement. Reductions in voltage unbalance were greatest at stations within two busses of the intertie bank where the LTC adjustments were made. TVA observed that the absolute decrease in voltage unbalance magnitude at delivery points when the LTC adjustments were made was maintained for that delivery point across all load levels.

In winter 2025, TVA implemented the 500/161-kV LTC adjustment strategy in another area of the TVA system to address increased voltage unbalance and voltage regulation issues during overlapping planned outages of TVA and customer equipment. That effort was successful, illustrating that the LTC adjustment strategy can be deployed strategically to address abnormal system conditions.

TVA must manage transmission voltage unbalance as the grid continues to evolve to serve our region. The 500/161-kV intertie bank LTC adjustment discussed in this paper has proven to be an effective, flexible, and low-cost method to reduce wide area voltage unbalance for heavily congested load areas. Given the success of the LTC adjustment pilot and positive response from customers, TVA plans to maintain the LTC adjustments in Middle Tennessee until more conventional solutions, such as increased deployment of FACTS devices, can be implemented.

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XII. BIOGRAPHIES

J. Sides received his B.S. in Electrical Engineering from Auburn University in 2009 and his M.S. in Electrical Engineering from Arizona State University in 2018. He is a registered professional engineer. He has been employed by the Tennessee Valley Authority for 9 years and currently serves as a Power Systems Engineering Specialist for Power Quality within the Grid System Operations organization.

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