TVA Power Quality Evaluation of Inverter Based Resource Impact on High Voltage Transmission Operations

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Abstract – **As part of system interconnection studies for inverter-based resources, TVA evaluates key power quality impacts of IBR operations. In a four-year period, TVA power quality staff have evaluated over 200 proposed utility scale solar and battery storage sites with total generation capability of over 31,000 Megawatts. A typical site size is 200-MW, proposed to interconnect to TVA's 161-kV transmission system. For various reasons (many not related to power quality) it is estimated that only a small fraction of these sites will be developed.**

The two significant power quality issues evaluated are 1) Rapid Voltage Change occurring when the inverter-based resource systems energize large transformers interconnected to the transmission system, and 2) Harmonic currents flowing from the inverter-based resource systems creating total harmonic voltage distortions exceeding the IEEE Std. 519 voltage limits. Power quality staff uses electromagnetic transient software to simulate the expected impact of RVC and harmonics on the TVA transmission system.

The power quality evaluation occurs early in the interconnection planning process, well before final site design. This allows engineers to consider the results of the power quality evaluation throughout the design process and incorporate power quality mitigation as required.

A relevant case study will be presented as well as discussion of power quality mitigation schemes and general recommendations for consideration by utilities and independent power producers. To date, TVA has recommended rapid voltage change mitigation in approximately 50% of evaluations and harmonic mitigation in approximately 35% of evaluations.

Keywords – Inverter Based Resources, harmonic, distortion, rapid voltage change, power quality

I. INTRODUCTION

The Tennessee Valley Authority (TVA) [1] is a generator and transmission owner/operator serving 153 local power companies and 60 transmission-connected large industries and federal facilities in the watershed of the Tennessee River Valley. TVA provides power through one of the largest transmission systems in the nation; a network that includes 16,000 miles of high voltage transmission lines, 69 interconnections with neighboring transmission systems, and 2,300 substation buses across a seven-state footprint, shown in Figure 1.

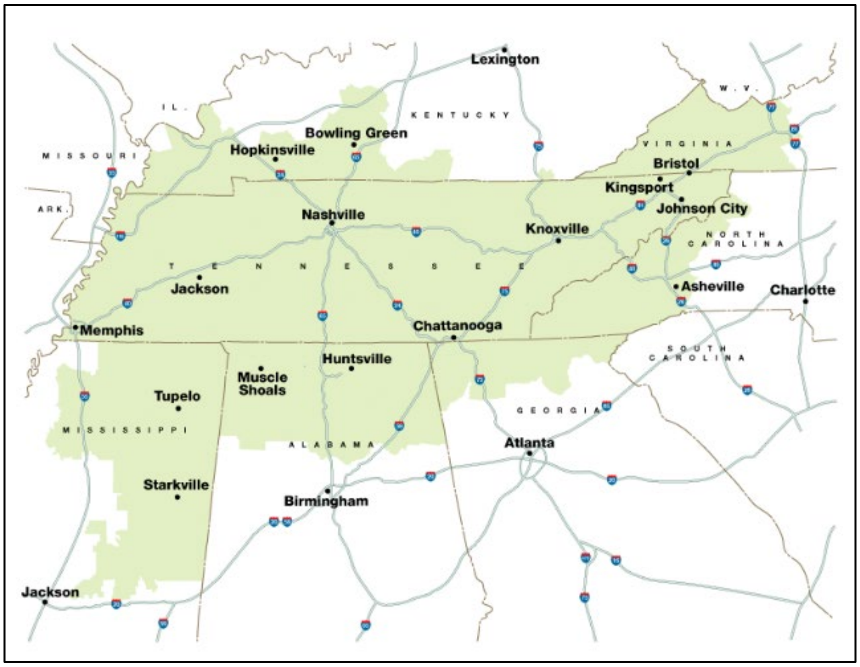

FIGURE 1 – TVA SERVICE TERRITORY

Providing reliable, clean, and affordable energy to the people and industries in the service area is at the core of TVA's mission. TVA is the nation's largest public power provider, operating a diverse generation fleet that includes a mix of nuclear, hydroelectric, coal-fired, gas and solar energy sites. In Fiscal Year 2024, solar generation accounted for approximately 4% of TVA's total generation portfolio. TVA is working to add up to 10,000 megawatts of solar energy to the TVA system by 2035.

As an owner/operator of an open-access transmission network, TVA regularly receives interconnection requests from independent power producers (IPP) for inverter-based resources (IBR) including solar and battery energy storage sites [2]. An important component of the interconnection process is the System Impact Study (SIS), during which TVA's Transmission Planning organization performs analyses for load flow, short circuit strength, and transient stability for the proposed site. All projects reaching the SIS are speculative in nature, and many sites will not develop through full implementation. Because of their large size, most IBR sites are proposed as interconnections to the TVA nominal 161-kV transmission voltage in locations selected by IPP based on factors not necessarily related to optimal power system interconnection. As a result, the strength of the transmission system may be less than ideal at proposed generation sites.

TVA SIS for proposed IBR facilities include an evaluation of power quality considerations related to the operation of the site at the proposed point of interconnection (POI) with TVA. In particular, the power quality study evaluates the potential for the IBR site to introduce objectionable rapid voltage change (RVC) and harmonic distortion to the transmission system. TVA power quality staff use an electromagnetic transients (EMT) computer program to complete the analysis. Accurately modeling the proposed transmission interconnection configuration yields a predictive simulation that serves as a key input to determining the necessary project parameters for a successful design and implementation.

During a four-year period from 2021 to 2025, TVA power quality staff completed system interconnection study power quality evaluations on a project set of over 200 proposed IBR sites. TVA has recommended rapid voltage change mitigation in approximately 50% of evaluations and harmonic mitigation in approximately 35% of evaluations. This paper will present best practices and TVA lessons learned developed through evaluation of the project set. Findings contained herein include:

- EMT model methodology, including pertinent transmission and IBR facility assumptions.
- Considerations for evaluation of sites near voltage disturbing systems including other existing or proposed IBR sites or large industrial facilities; and
- Mitigation strategies commonly used to eliminate or limit the negative power quality impacts identified in the analysis.

II. DETERMINING NETWORK REQUIREMENTS FOR INVERTER BASED RESOURCES

After a solar project has entered the interconnection queue, TVA performs interconnection studies as due diligence to identify the POI and the system requirements to support IBR operation. The strength of the area transmission system and the solar generation peak size are the primary drivers to determine the most efficient means of interconnection. For projects 75 megawatts or smaller, TVA permits interconnection through a tap on an existing transmission line. This configuration often presents the least cost and shortest duration for site interconnection but will not protect the solar site from experiencing an outage in the event of a fault on the transmission line.

For projects larger than 75 megawatts, TVA typically requires interconnection through construction of a ring bus. This applied to most of the project set. Commonly, facility requirements included opening an existing transmission line and re-terminating into a three-position ring bus. In the normal operation of this configuration, a line fault would not create an outage for the solar site. In some cases, system strength deficiencies required the addition of one or more new breaker positions and transmission lines to this ring bus, essentially creating a new bus. If a solar site of any size is proposed at an existing TVA bus, a new breaker would be added to that bus to serve the solar site.

It is prudent to determine network interconnection requirements and potentially challenging locations as early as possible. Evaluating these projects earlier in the process may require a greater dependence on assumption, but TVA power quality simulation results have shown problematic conditions when the ratio of short circuit capacity to peak generation is low. In these instances, power quality consults with TVA interconnection planning for advice on additional network requirements necessary to allow the proposed solar site to operate within acceptable limits.

III. POWER QUALITY EVALUATION OVERVIEW

TVA defines voltage disturbing systems (VDS) as equipment interconnected to the TVA transmission system that may cause objectionable voltage disturbances or fluctuations for TVA or other interconnected power systems. TVA considers disturbances to be objectionable if they result in stakeholders providing valid power quality complaints to TVA. TVA has adopted limits for power quality phenomenon based on established industry guidelines to ensure that connected VDS will not adversely impact other interconnected stakeholder systems. These limits are published in the TVA Transmission Planning Energy Supply Facility Interconnection Requirements document, publicly available on the OASIS website [3]. This section describes the key power quality parameters and applicable limits pertinent to the SIS for IBR systems.

A. Rapid Voltage Change

Rapid voltage changes (RVC) associated with operating transmission-connected IBR sites have the potential to impact other transmission-connected stakeholders. Operations commonly producing RVC include:

- Energizing large generator step-up (GSU) transformers; and
- Energizing medium voltage (typically 34.5-kV) inverter or battery feeder circuits.

TVA RVC limits are based on IEEE Std. 1453-2015 [4]. For a 161-kV POI, RVC is limited to less than 5% in the all-ties-closed or worst-case N-1 transmission configurations. For 500-kV POIs, RVC is limited to less than 3%. Table 1 indicates the IEEE 1453, Table 3 RVC planning limits. TVA evaluates RVC compliance using line-to-line voltages.

Number of Changes, *N*	**$\Delta V/V_r$ (%)**	
	MV	**EHV-HV**
$N \leq$ per day	5-6	3 - 5
$N \leq$ per hour	4	3
$2 < N \leq 10$ per hour	3	2.5

TABLE 1: ADAPTED FROM IEEE 1453-2015, TABLE 3

When EMT simulations for a site indicate RVC exceeds these planning limits, the power quality SIS report provides the IPP with commonly used mitigation schemes to allow for site operation at the proposed POI without exceeding the RVC limit.

B. Harmonic Voltage Distortion

Harmonic current flows associated with the operation of IBR systems on the transmission system may create objectionable voltage distortion at the POI. TVA has adopted the IEEE Std. 519-2014 [5] Table 1 limits for voltage total harmonic distortion (V_{THD}) and individual voltage harmonic distortion. The limits are shown in Table 2.

Bus voltage V at PCC	**Individual Harmonic (%) h ≤ 50**	**Total harmonic distortion THD (%)**
$V \leq 1.0$ kV	5.0	8.0
1 kV $< V \leq$ 69 kV	3.0	5.0
69 kV $< V \leq$ 161kV	1.5	2.5
161 kV $< V$	1.0	1.5

TABLE 2: ADAPTED FROM IEEE 519-2014 TABLE 1

TVA evaluates interconnection requests to ensure new systems do not increase voltage distortion above the IEEE 519 limits. For 161-kV POIs, IEEE 519 limits V_{THD} to 2.5% and individual harmonics to 1.5% of the fundamental voltage magnitude.

When series resonance occurs, TVA system voltage may be well below the individual harmonic limit, but the addition of the IBR network creates a low impedance to a particular harmonic, acting as a sink for any such harmonics already present on the transmission system. This can cause excessive voltage distortion at the medium voltage level. This paper discusses the IBR network components that can create series resonance including the medium voltage IBR network capacitances. Of particular concern are capacitors added to the medium voltage busses.

Parallel harmonic resonance can create voltage distortions above the IEEE 519 voltage limits when the TVA network presents a high impedance to a particular harmonic. TVA capacitors at the 161-kV level change the harmonic tuning points of the transmission system, while N-1 radial feeds to IBR systems reduce available transmission system short circuit current. One or both conditions can create voltage distortions at the point of interconnection that exceed TVA's V_{THD} limits during IBR operation.

The SIS power quality analysis uses EMT software to identify potential parallel and series resonant conditions created by the IBR site and the TVA system at the POI. This paper discusses the EMT simulation methodology and one mitigation strategy for V_{THD} levels that are expected to rise above the IEEE 519 limits.

IV. RAPID VOLTAGE CHANGE EVALUATION

A. RVC Modeling of GSU Inrush Currents

At the SIS stage, no actual GSU nameplate data is available for the project. Given that solar GSUs only operate loaded during daylight hours, they do not need to be base rated for 100% of generation rating. IPPs typically submit GSUs that are base-MVA rated at 75% of the solar/battery site peak megawatt operation with 8% to 10% impedance. For example, a 150-MW solar generation site may have a 103-MVA base-rated transformer. GSUs modeled for study purposes have voltage ratings of 161-kV primary, 34.5-kV secondary, and 13-kV tertiary voltage.

TVA uses GSU excitation characteristics from base EMT models to evaluate RVC. TVA has determined that multiple EMT software packages provide similar results when using typical excitation for normal three-winding transformer designs.

TVA has received complaints from local power companies when large transformers have been energized in the past. As such, power quality staff conservatively models IBR GSU energization with remanent flux 180 degrees out of phase when the GSU is energized in the simulation. This is easily done by beginning the simulation with the GSU energized, opening the GSU primary (eg.161-kV) breaker, and reclosing the GSU breaker one half cycle (0.08333 milliseconds) later. This approach was adopted to simulate the worst-case energization scenario and minimize the probability of impact to neighboring systems. IEEE 1453 allows 3-5% RVC for HV systems. For 161-kV POIs, TVA accepts the higher 5% RVC value, but evaluates sites based on peak remanent flux during the EMT simulations.

B. Additional IBR Operating Requirements to Minimize RVC events Exceeding Limits

While commissioning IBR sites on the TVA system, TVA has learned that medium voltage (typically 34.5-kV) inverter feeders at IBR sites must be de-energized and isolated from the GSU at the time the GSU is energized. Otherwise, inrush associated with energization of the 34.5-kV inverter transformers will be added to the inrush of the GSU creating a large RVC. During early solar site commissioning tests, PQ staff recorded RVC of 10% or greater when the GSU and multiple connected 34.5-kV inverter feeders were simultaneously energized from the IBR site 161-kV bus. To prevent this occurrence at new solar sites, TVA requires that the IPP implement control interlocks to prevent GSU energization when the 34.5-kV feeder breakers are closed. Additionally, 34.5-kV feeders must be energized one at a time to minimize RVC at the 161-kV POI.

C. Mitigation Strategies to Maintain RVC below 5% during GSU Energization

If any transmission configuration leads to more than 5% RVC for GSU energization, TVA requires IPP developers to add RVC mitigation to the project. There are two standard methods to reduce RVC impacts.

One mitigation approach is to add pre-insertion resistance (PIR) to a transformer primary breaker or switch to temporarily add resistance to the circuit to dampen the inrush current flow when the GSU is energized. Breakers (and some switches) are commercially available with integral PIR inserted temporarily during closing. Power quality EMT simulations conducted during the SIS provide a preliminary minimum value of resistance ohms temporarily inserted during GSU energization to maintain RVC below the 5% limit.

Another mitigation strategy is to utilize synchronous closing of breaker poles by phase sensing control. This approach requires a breaker with individual phase breaker contacts (not gang-operated phase breaker poles). When the breaker and its controls are properly configured, each phase can be energized in a manner that the minimizes the transformer inrush transients creating RVC disturbances. Configuration of breakers and phase sensing control occurs during commissioning of the solar site during the all-ties-closed transmission configuration.

V. HARMONIC EVALUATION

This section discusses how TVA simulates the expected harmonic impact of proposed IBR facilities on the transmission system. EMT simulation strategies for identifying problematic parallel and series resonance conditions are discussed. Also presented are common mitigation recommendations when simulations indicate a site is likely to exceed TVA's limits for voltage total harmonic distortion.

A. EMT Modeling of IBR Harmonic Contributions

TVA requires V_{THD} to be below the IEEE 519 Table 1 values at the POI during IBR system operation. At 161-kV POIs, the limit is 2.5%. Prior to commissioning the solar site, the only way to estimate the impact of harmonic distortion at the IBR site is by computer simulation. TVA uses EMT modeling to estimate the IBR's impact on the TVA and IBR networks.

Detailed EMT models of the IBR facility under study are not available at the SIS phase, so power quality staff must model a reasonable approximation of the harmonic current injection of the proposed solar site to the TVA system. TVA has considered inverter manufacturer harmonic data and actual measured current harmonic data from active solar sites to arrive at reasonable harmonic current injection profiles.

IBR equipment normally generates pulse width modulated (PWM) currents to create power flows onto the transmission grid. Ideally, these currents will not contain low-order harmonics, but TVA routinely measures fifth and seventh harmonic components at operating IBR sites. These harmonics are characteristic of six-pulse rectification systems. Six pulse systems are related to full wave conversion (2X) and three phase conversion (3X) working together to make six pulses.

IEEE 519 defines current distortion limits in terms of total demand distortion (TDD) which is the root sum square of harmonic currents up to the 50th order, excluding interharmonics, expressed as a percent of the maximum demand current. Individual harmonic distortion values are also expressed as a percentage of the site maximum current.

Table 3 provides one inverter manufacturer's specification for the total current distortion of one 4.4 MVA inverter model. In this case, total harmonic current distortion is 1.63% and the fifth and seventh harmonics comprise 69% of the total harmonic distortion created by the single inverter.

Inverter simulation specifications: 645 V_{rms}, 3.939 kA, 4.40 MVA, 100% load									
TDD	6th Multiple TDD	5th	7th	11th	13th	17th	19th	23rd	25th
1.63%	1.48%	0.73%	0.87%	0.59%	0.52%	0.33%	0.38%	0.16%	0.10%

TABLE 3: MANUFACTURER SPECIFICATION FOR INVERTER CURRENT DISTORTION

TVA has observed significant variability in inverter harmonic current distortion levels, even among different inverter models from the same manufacturer. The manufacturer of the 4.4 MVA inverter referenced in Table 3 also offers a 4.2 MVA inverter with 0.82% TDD—a significant improvement over the data presented in Table 3. It is likely that some harmonic filtration is incorporated in the 4.2 MVA offering. IPP developers may have the opportunity to specify inverter systems with lower current distortion, but cost and limited availability of equipment may force developers to install units with relatively high current distortion levels. If this is the case, other filtering may be possible.

At active, transmission-connected, IBR sites that aggregate the output of multiple inverters, TVA has recorded IBR currents with lower levels of harmonic distortion than indicated in Table 3, but the measured harmonic currents generally conform to the same pattern of dominant fifth and seventh harmonics.

Table 4 includes current harmonic values calculated from the digital frequency transform (DFT) of current waveforms captured at the 161-kV POIs for three active solar sites on the TVA system. Typical current distortion ranges from 0.74% to 1.03% current TDD. Lower order harmonics dominate the recorded TDD, with n-1and n+1 harmonics at multiples of 6 comprising 88-95% of the TDD.

	Solar Site A	**Solar Site B**	**Solar Site C**
Rated MW	75	129	227
TDD	0.74%	0.91%	0.98%
5th harmonic	0.42%	0.80%	0.68%
7th harmonic	0.49%	0.32%	0.34%
11th harmonic	0.14%	0.11%	0.08%
13th harmonic	0.07%	0.09%	0.01%
17th harmonic	0.08%	0.09%	0.62%
19th harmonic	0.11%	0.11%	0.05%
23rd harmonic	0.01%	0.07%	0.00%
25th harmonic	0.02%	0.04%	0.01%
6th Multiple TDD	0.68%	0.89%	0.98%

TABLE 4: MEASURED 161-KV CURRENT DISTORTION AT ACTIVE TVA IBR SITES

For proposed IBR sites, TVA models the harmonic current injection by scaling the current waveform data indicated in Table 4 to the maximum megawatt output of the IBR site under study and injects the scaled current values at the 34.5-kV side of the GSU in the EMT model of the proposed solar network.

TVA acknowledges that this method is not a perfect predictor of harmonic performance of the proposed IBR site. One weakness in this approach is that the measured current waveforms may be influenced by the background harmonics and tuning of the transmission network at the measurement location. For example, if harmonic resonance near the 5th harmonic exists at an active solar site, the measurements indicated in Table 4 overstate the 5th current harmonic contribution of the IBR. Despite this concern, TVA's experience has shown that in the absence of detailed EMT models of a proposed solar site, this approach is a reasonable approximation of IBR current injection performance and is suitable for use in SIS studies to screen for conditions creating V_{THD} exceeding TVA's limits at the POI.

TVA has not adopted the harmonic current distortion limits in IEEE Std. 2800-2022 [6]. IEEE 2800 defines IBR current distortion as total rated-current distortion (TRD) which is non-fundamental frequency RMS current flowing between the transmission system and the IBR plant, expressed as a percentage of rated current of the site. IEEE 2800, Table 17, allows IBR odd harmonic TRD of up to 2.5% of rated IBR current, which is significantly higher than TVA has observed at any active IBR site.

If TVA injected harmonic currents including the 5th and 7th harmonics at levels resulting in 2.0% TDD in SIS power quality simulations, it is estimated 75% of evaluated sites would require harmonic mitigation instead of 35%. When EMT simulations show operation of an IBR site will cause voltage harmonic distortion to exceed IEEE 519 limits at the TVA POI, it is commonly due to IBR medium voltage capacitors or TVA 161-kV capacitors that tune the network to a problematic harmonic resonant frequency, not the harmonic current contribution of the IBR.

B. Modeling System Capacitance

TVA HV Capacitor Banks

Transmission-connected capacitor banks alter transmission system tuning and may contribute to parallel resonance conditions as they are switched in and out of service. Figure 2 indicates the locations of over one hundred 161-kV capacitor banks on the TVA transmission system. EMT simulations for IBR SIS include all combinations of nearby multi-stage 161-kV capacitor banks.

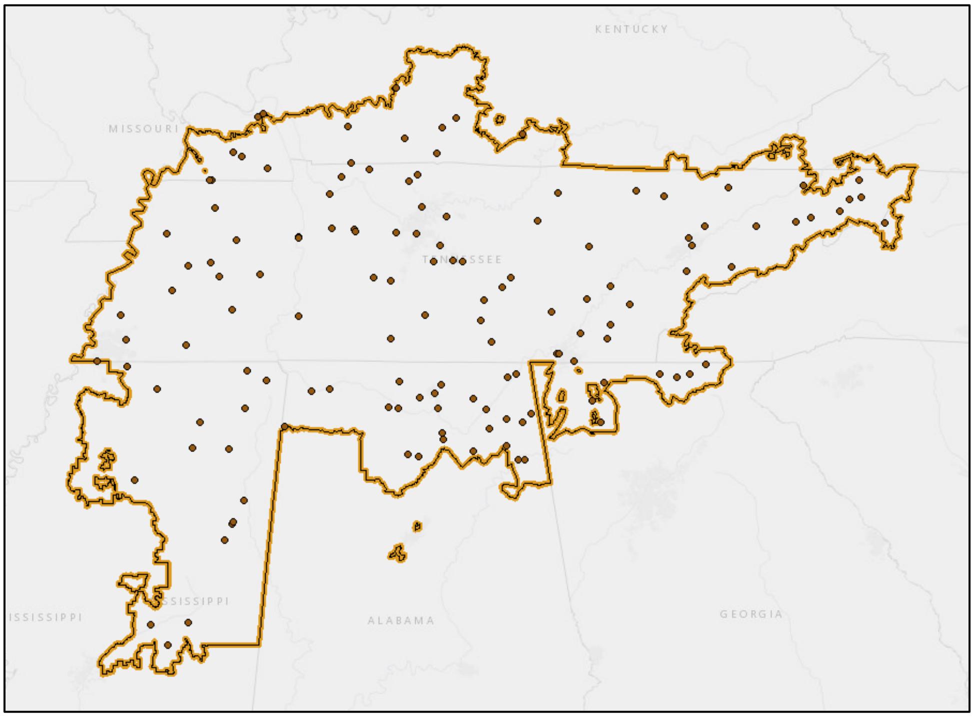

FIGURE 2: LOCATIONS OF TVA HV CAPACITOR BANKS IMPACTING HARMONIC TUNING

IBR Medium Voltage Collector Cable Capacitance

A typical utility-scale IBR site has multiple inverter units (typically sized at 4.4-MVA) interconnected to a 34.5-kV collector system through medium voltage step up transformers. TVA has observed that when the IBR inverter system is not in operation, such as during overnight hours, the medium voltage collector cables typically remain energized. The cabling of the 34.5-kV system is capacitive in nature and contributes megavars (MVAR) sufficient to alter the series resonance tuning point at the site. The MVAR contribution of the collector cables will vary depending on the rating, physical layout, and collector cable installation method at the site. These details are not known at the SIS phase, so TVA power quality staff have used actual measurements from existing solar sites to develop reasonable estimates of collector cable MVAR contribution for use in SIS evaluations. Measured MVAR contributions attributed to the collector cable network of five TVA solar sites are provide in Table 5, below. Using this data, collector cables at a proposed 150-MW solar site would be allotted 150 MW x 14.4 = 2,160 kVAR in an SIS EMT model.

IBR Site Rated MW	Measured 35-kV Collector Cable kVAR	Measured kVAr/Site Rated MW Ratio
70	920	13.11
100	1,700	17.00
173	3,500	20.23
200	2,300	11.50
227	2,300	10.13
	Average kVAR/MW Ratio:	**14.40**

TABLE 5: MEASURED MEDIUM VOLTAGE COLLECTOR CABLE MVAR CONTRIBUTIONS

IBR Medium Voltage Capacitor Banks

Some IPP developers install medium voltage capacitors to allow the IBR generation to meet TVA's voltage schedule requirements. Typically, these systems are 10 to 30-MVAR units. In some cases, these capacitors tune the 34.5-kV bus to problematic harmonics (usually lower order harmonics like the 5th and 7th) when energized. When this occurs, background harmonic currents flowing on the TVA system that normally do not create voltage distortion exceeding IEEE 519 Table 1 values may create significant voltage distortion at both the 161-kV POI and IBR 34.5-kV bus level.

A. Identifying Parallel and Series Resonance

During SIS power quality analyses, TVA power quality staff routinely identify potential problems with parallel and series resonance at proposed IBR sites. A quick way to identify a critical resonant frequency is using the following calculation to locate the harmonic turning point:

$$H_r = \sqrt{}(\frac{MVAsc}{MVAR})$$

FORMULA 1: RESONANT FREQUENCY

Where H_r is the harmonic resonant tuning point, MVAsc is the available short circuit MVA of the system under study and MVAR is the total MVAR rating of capacitive elements connected in the system.

Parallel resonance typically occurs when inverter currents (typically at 34.5-kV) are injected into a network with high impedance at a significant harmonic. For example, a 150-MW IBR site may have 792-MVAsc at 35.5-kV. If the 34.5-kV bus has three stages of 10-MVAR capacitor banks installed, the harmonic tuning point with all capacitors energized will be 5.1 and a high impedance to the 5th harmonic is likely to occur. This creates high oscillating 5th currents leading to high voltage distortion showing up on the 34.5-kV bus.

An example of series resonance occurs when the combination inductive and capacitive impedances of the TVA transmission network and the IBR site network result in a low impedance to a given harmonic frequency. When background harmonic currents at the series resonant harmonic frequency exist on the TVA system, they will flow to the low impedance at the IBR network, creating objectionably high voltage distortion. For example, the 150-MW IBR site with 792-MVAsc may have 34.5-kV collector cables with equivalent total capacitance 1.27-MVAR, creating a series resonance at the 25th harmonic. Any 25th harmonic present at the 161-kV level may see a near short circuit through the IBR system creating voltage high distortion at 34.5-kV.

B. Harmonic Mitigation Recommendations

When simulations indicate the IBR site is likely to introduce V_{THD} exceeding IEEE 519 limits at the IBR site POI, power quality staff typically simulates IBR operation with one or more high pass 5th harmonic filters in operation. Figure 3, below, illustrates an example EMT model with the high pass filter highlighted in yellow. The EMT simulation shows that the filter reduced the V_{THD} less than 2.0% at both POI sites (QXXX and QYYY). Trapping low order harmonics on the IBR medium voltage bus limits the injection into the 161-kV POI. Many times, adding capacitance to the 34.5-kV bus is needed for the site design. Usually adding a filter works better than adding capacitors alone.

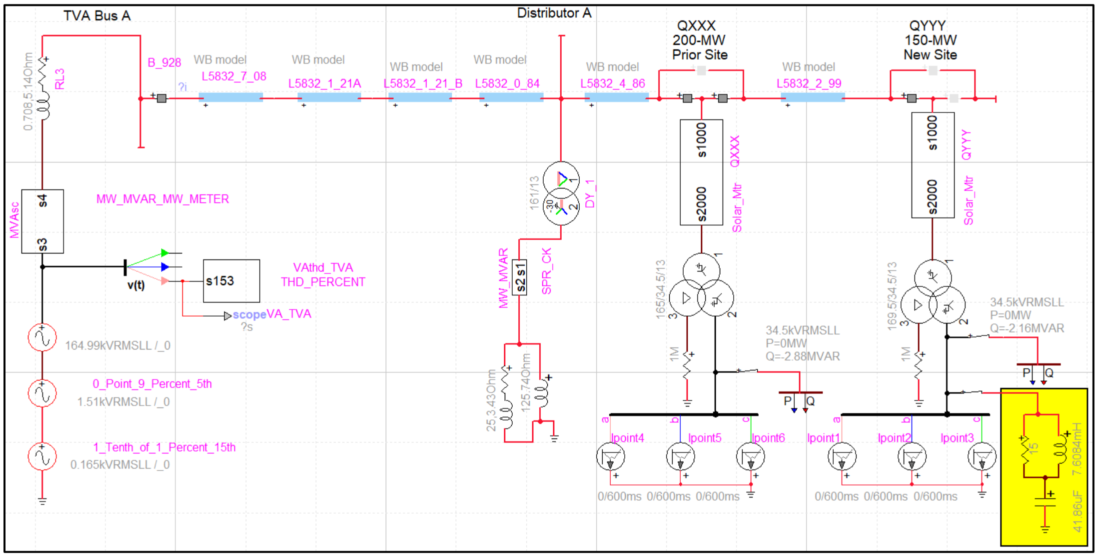

FIGURE 3: HARMONIC SIMULATION EXAMPLE WITH FILTER

When 34.5-kV capacitors are added to any IBR design, TVA recommends installing capacitors rated higher than 34.5-kV in case the capacitor bank needs to be modified into a filter after site commissioning. Adding the series reactor required for filtering will raise the operating capacitor voltage. Specifying higher voltage capacitors at the outset will allow the capacitors to be repurposed in the modified filter design.

C. Considering Power Quality During IBR Site Design and Commissioning

The interconnection SIS occurs years before a solar site is commissioned and the data provided by developers early in the interconnection process is subject to change. When a site proceeds to sign a power purchase agreement (PPA) with TVA, subsequent harmonic and RVC studies submitted by IPP developers commonly reflect mature system designs that may include significant changes from the site considered during the SIS. For example, GSU transformer impedance may be significantly different, or the design may include two GSU transformers instead of one. The size and quantity of medium voltage capacitor banks may have also changed. Given the risk of problematic harmonic resonance conditions, modifications to the size or quantity of IBR system medium voltage capacitors following the original SIS power quality study are of particular concern.

Additionally, the TVA system at the POI may have changed since the SIS was completed. The addition of new 161-kV capacitor banks, transmission lines, other IBR sites, or industrial loads near the POI could impact harmonic current flow or expected RVC. These considerations require that power quality staff carefully review the harmonic and RVC study materials submitted by the IPP to ensure that all required power quality considerations have been incorporated in the final site design.

TVA power quality staff have learned to identify IBR sites likely to be built and work with IPP consultants to ensure they have enough detailed transmission system configuration data to allow for a quality harmonic analysis. For example, 161-kV capacitors (size and locations) and nearby line characteristics need to be provided to the IPPs harmonic consultant firm. Background harmonic distortion levels at nearby TVA system busses must also be supplied to the consultants.

During IBR site commissioning, TVA ensures harmonic and RVC limits are not exceeded. The SIS is reviewed prior to commissioning to see what power quality issues may be present when the solar site starts. Often, the N-1 condition with the least MVAsc is the worst-case transmission configuration for harmonics and RVC identified in the original PQ study. If needed, the EMT models can be modified and simulated with pertinent changes to site or the TVA network to assist in the commissioning process. The goal is for a successful site startup with minimal surprises.

D. Continuous Improvement to TVA Power Quality Evaluation of IBR Harmonics

In 2025, the TVA power quality team has changed the SIS evaluation process to better include background voltage harmonics at nearby TVA busses. Also, line configurations are supplied in a study appendix for consultants including providing line configurations need to include all key TVA system configurations on the front-end including N-1 configurations, circuit configurations, and known 161-kV capacitances and filters. Also, consultants need details on other prior solar generation and their harmonic mitigation schemes. Finally, the power quality group is planning of following up as needed to provide details to study consultants early in their study process.

VI. CASE STUDY

TVA's recent experience commissioning a 173-megawatt solar site provided lessons learned that have informed subsequent SIS power quality evaluations.

The solar site is connected to the TVA system at a new 3-position ring bus on an existing 32.84-mile 161-kV transmission line between two TVA switching stations. The line serves one existing wholesale delivery point. A large industrial customer is supplied at 161-kV Switching Station A, 10.6-line miles from the solar site. Switching Station B includes two, 36-MVAR, 161-kV capacitor banks. Switching stations A and B are both strong busses, with over 12-kA available short circuit current at 161-kV. The configuration of the line is shown in Figure 4, below. The SIS for this site was conducted in 2019 and was one of the first to be evaluated using an early iteration of the process discussed in this paper.

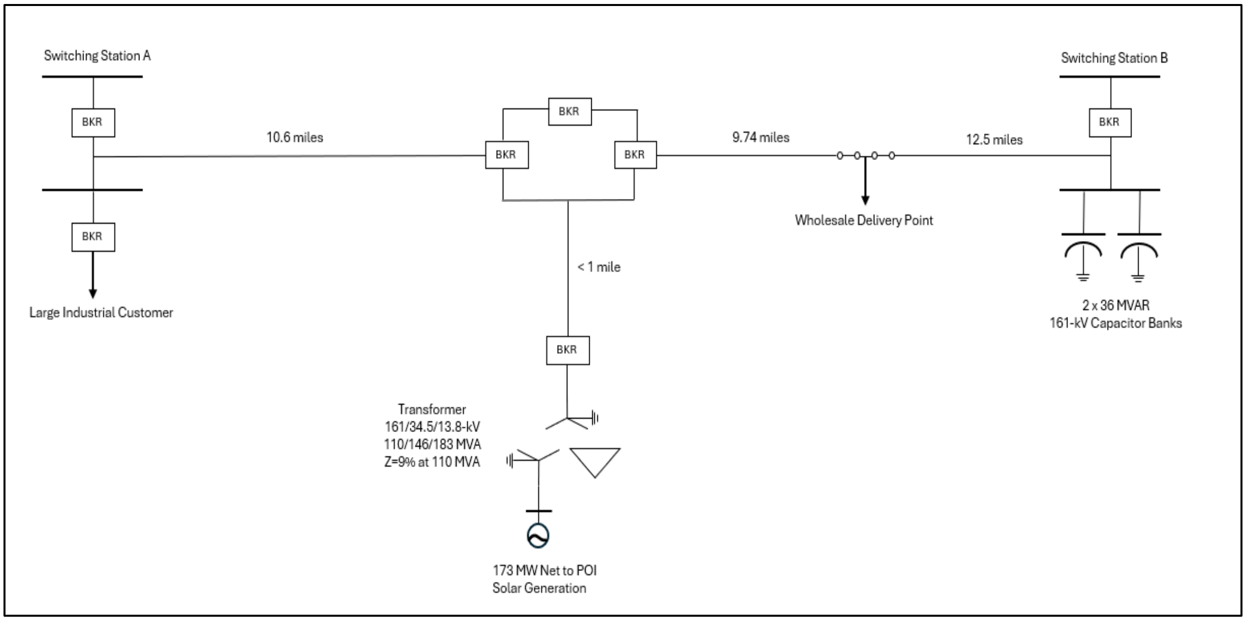

FIGURE 4 – IBR COMMISSIONING CASE STUDY ONE LINE DIAGRAM

The SIS identified that with all-ties-closed, RVC for energization of the solar GSU is below the TVA limit of 5% at 161-kV. However, when supplied radially from Switching Station A or B, RVC at the 161-kV POI for the solar site was expected to exceed the 5% limit, with potential to impact the large industrial customer located at Switching Station A. The IPP chose to implement independent phase closing with phase sensing control at the GSU primary breaker. During commissioning and configuration of the breaker closing controls, RVC was confirmed to be above the 5% limit when in the radial configuration. When configured, the independent phase closing of the breaker was effective keep RVC below 5% in all transmission configurations.

The SIS harmonic analysis injected current corresponding to the site nameplate 173 MW including 0.74% TDD comprised of 0.42% 5th and 0.49% 7th harmonic currents (reference Table 4, Site A). No background harmonics were included in the analysis. Megavars associated with the 34.5-kV collector cables at the solar site were neglected. With all-ties-closed, the harmonic simulation indicated V_{THD} at the 161-kV POI below the 2.5% limit. When radial from switching station A or B, the simulation indicated V_{THD} may exceed 2.5%.

In 2021, the IPP provided TVA with an EMT model of the aggregated current harmonic distortion for the 173-MW site. EMT simulation with the updated harmonic data resulted in less simulated voltage distortion than the generic data. With the IPP-provided harmonic data, the only transmission configuration resulting in simulated V_{THD} above 2.5% was the case where the generation is supplied radially from Switching Station B and no capacitor banks are online at Switching Station B. Results of the 2019 and 2021 harmonic analyses are included in Table 6.

Mode	Switching Station B 36 MVAR Units	V_{THD} at POI Site A Generic Current Harmonic Data	V_{THD} at POI IPP Current Harmonic Data
All-Ties-Closed	0	1.5%	0.68%
	1	1.6%	0.44%

	2	1.0%	0.62%
Radial from SS-B	0	3.9%	2.53%
	1	2.2%	1.10%
	2	2.8%	1.20%
Radial from SS-A	0	5.7%	1.70%

TABLE 6: HARMONIC SIMULATION RESULTS, GENERIC AND IPP-PROVIDED DATA

When the solar site began generation, power quality staff noted elevated V_{THD} recorded by two power quality-capable revenue meters obtaining voltage signals from separate windings of one magnetic potential transformer and current transformer combination unit at the 161-kV side of the solar GSU transformer. During solar generation with all-ties-closed, V_{THD} frequently exceeded 2.5%, as shown in Figure 5:

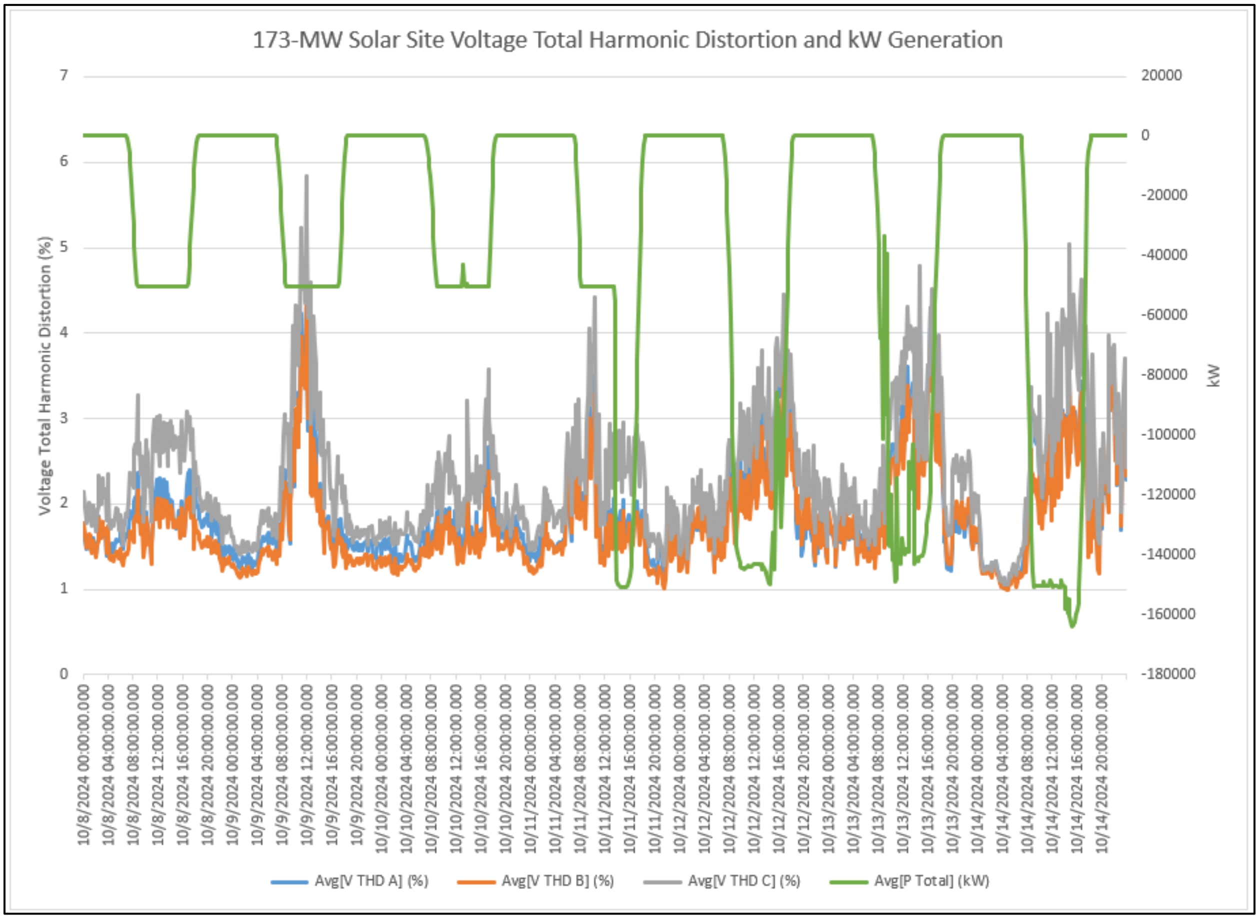

FIGURE 5: 173-MW SOLAR SITE V_{THD} AND GENERATION

The magnitude of the harmonic distortion initially appeared to vary with generation at the solar site. PQ staff observed changes in harmonic distortion both with and without the site medium voltage collector cables energized. Investigation revealed that the voltage distortion was caused by elevated 23rd and 25th harmonic voltages. The industrial site at Switching Station A is known to inject 23rd and 25th harmonic to the TVA system, however power quality monitoring at Switching Station A confirmed voltage harmonic distortion and current harmonic distortion for the industry complies with IEEE 519 limits.

TVA engaged the Electric Power Research Institute (EPRI) to perform in-situ frequency response testing of the potential transformer/current transformer combination unit providing the high harmonic distortion measurements [7]. EPRI injected known signals from 50 Hz to 150 kHz into the potential transformer with the primary side isolated and both with and without secondary burden connected. The measured frequency response is shown in Figure 6. EPRI's testing demonstrated that the potential transformer in this combination unit had a parallel resonance point near the 23rd and 25th harmonic (around 1,500 Hz). The high measured harmonic distortion was verified to be the result of the frequency response of the voltage transformer, not an issue with operation of the IBR generation.

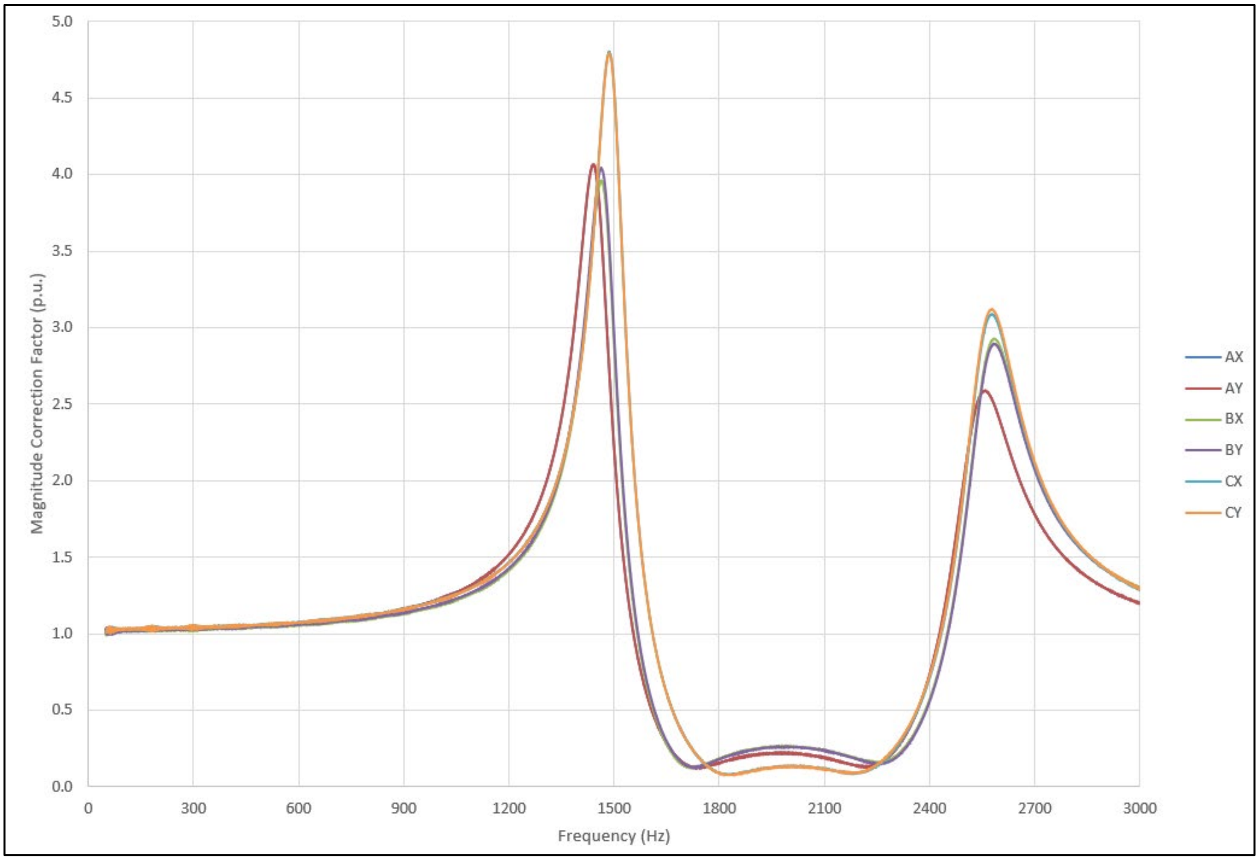

FIGURE 6: FREQUENCY RESPONSE OF CT/PT COMBO UNIT (COURTESY OF EPRI)

TVA employs the same make and model potential transformer and current transformer combination unit at multiple other utility scale solar sites. None of these sites have recorded voltage total harmonic distortion exceeding the IEEE 519 voltage distortion limits. The presence of the industrial site at Switching Station B injecting small amounts of 23rd and 25th harmonic to the TVA system caused the elevated harmonic distortion measurements.

TVA's experience commissioning this solar site highlighted the importance of considering transmission system background harmonics including the proximity of other harmonic producing loads, frequency response of measurement devices, and the harmonic tuning produced by IBR medium voltage capacitances, including collector cabling in the SIS power quality evaluation. Considering these factors early in the SIS power quality analysis will facilitate early identification of harmonic issues requiring mitigation during detailed design of the site. Having these considerations top of mind during commissioning will make surprises less likely and facilitate diagnosis of harmonic issues that do arise.

VII. CONCLUSION

TVA is soliciting IPPs interested in providing IBR power resources through purchase power agreements. The transmission planning process requires analysis of system impacts for requests to connect IBR to the TVA system. TVA performs power quality evaluations early in the interconnection process to screen proposed IBR sites for rapid voltage change and harmonic distortion issues that are likely to impact nearby stakeholders on the transmission system.

TVA has adopted IEEE standards for rapid voltage change and harmonic voltage distortion limits as the basis for the evaluating the impact of proposed IBR operations at the TVA POI. Through evaluation of 200 proposed IBR sites, TVA power quality has recommended rapid voltage change mitigation in approximately 50% of projects and harmonic mitigation in approximately 35% of projects.

TVA has successfully employed EMT software to identify cases where IBR GSU transformer energization will result in RVC exceeding IEEE 1453 limits on the transmission system. In such cases, TVA requires IPP developers to install appropriate mitigation.

Through EMT analysis and harmonic measurements at active solar sites, TVA has learned that power system resonance conditions and low transmission system strength due to N-1 outage conditions are the primary drivers of voltage harmonic distortion that exceeds IEEE 519 limits at the POI. The addition of medium voltage capacitor banks at solar sites is a common IPP practice that frequently results in harmonic resonance conditions requiring mitigation in the form of installing harmonic filters instead of capacitors alone.

As additional IBR are commissioned in the service territory, TVA power quality staff continue to apply lessons learned and modify the SIS power quality analysis process. Incorporation of background harmonics, consideration of nearby harmonic producing loads, consideration of IBR medium voltage capacitance, and understanding the frequency response of instrument transformers during system commissioning are recent process improvements.

VIII. REFERENCES

[1] Tennessee Valley Authority, www.tva.com.

[2] Tennessee Valley Authority, Integrated Resource Plan 2025, Volume 1, Draft Resource Plan. Available Online: 2025 Draft Integrated Resource Plan Volume 1 (Accessed April 1, 2025).

[3] Tennessee Valley Authority, "Energy Supply Facility Interconnection Requirements," available online: www.oasis.oati.com/tva.

[4] IEEE Std. 1453-2015, *Recommended Practice for the Analysis of Fluctuating Installations on Power Systems.*

[5] IEEE Std. 519-2014, *Recommended Practice and Requirements for Harmonic Control in Electric Power Systems.*

[6] IEEE Std. 2800-2022, *IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems.*

[7] G. Singh, J. Johns, A. Murphy, and N. Hooker, "In-Situ Frequency Response Measurements for Medium Voltage Sensors and Their Applications," Georgia Tech FDA Conference, Atlanta, April 2024.

IX. BIOGRAPHIES

J. Rossman received a B.S. in Electrical Engineering from the University of Tennessee and an MBA from Austin Peay State University. After 45 years working with TVA, he retired as a TVA Senior Program Manager of Power Quality, helping coordinate both TVA's end-use and transmission-related PQ efforts. He is currently assisting the power quality group within Grid System Operations as a contractor for TVA. Jim is a registered professional engineer in Kentucky and awarded the 2008 TVA's Engineer of the Year and recognized as one of the top 10 2008 NSPE Federal Engineers of the Year.

T. Fritch earned a B. S. in Electrical and Electronics Engineering from Tennessee Technological University and is a registered professional engineer. Tim has been employed by the Tennessee Valley Authority for 20 years and currently serves as the Manager of Power Quality in the Grid System Operations organization. Tim has served as Chair, NERC Synchronized Measurement Working Group, Vice-Chair, Synchronized Measurement Subcommittee, and led the NERC investigation for the 2022 Eastern Interconnection wide-area oscillation event. In 2024, Tim was recognized as the TVA Engineer of the Year and a top 10 finalist for the NSPE Federal Engineer of the Year award.

G. Piercy earned B. S. in Electrical Engineering and Juris Doctor degrees from the University of New Brunswick. She is a registered professional engineer in Tennessee and Maine. She has been employed by the Tennessee Valley Authority for 9 years and currently serves as Senior Program Manager for Power Quality within the Grid System Operations organization.