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Frequency Response of Voltage Transformers for Harmonic Measurement in South African Renewable Grids [†]

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Abstract

Voltage transformers (VTs) are part of the power quality (PQ) measurement system in renewable energy installations where harmonic distortion (HD) exists. Although they are designed for fundamental-frequency operation, VTs exhibit frequency-dependent behaviour that causes ratio and phase errors at harmonic frequencies. These errors decrease measurement accuracy and impact compliance verification under South African grid code standards. International standards such as IEC TR 61869-103 and IEEE 519 do not specify harmonic-frequency accuracy classes or correction methods. This paper examines published research on VT frequency response and considers its effects on harmonic measurement in South African renewable networks. The review highlights technical and regulatory challenges that affect the reliability of harmonic measurements and emphasises the need for structured frequency-response testing under local operating conditions. A complementary methodological study addressing this need has been submitted for publication.

Keywords: voltage transformer; frequency response; harmonic measurements; power quality; grid code compliance; renewable energy

1. Introduction

The integration of renewable energy sources (RESs) in South Africa has increased the demand for reliable harmonic measurements in power quality (PQ) monitoring. As the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) expands, accurate harmonic assessment remains essential for grid code compliance [1].

Voltage transformers (VTs) are used in medium- and high-voltage (MV and HV) networks to scale electrical signals for PQ analysis. Under harmonic-rich conditions, VTs display frequency-dependent behaviour that causes deviations in ratio and phase [2,3]. These deviations reduce measurement accuracy and potentially lead to incorrect compliance assessments [1,3]. IEC TR 61869-103 [4] acknowledges the existence of VT-induced errors but does not specify procedures for harmonic-frequency accuracy [2,3].

Inductive voltage transformers (IVTs) can exhibit ratio errors greater than 5% at various harmonic orders [1,4,5]. These errors are affected by core material, winding configuration, burden impedance, and resonance effects [1,6,7].

South Africa's grid code requires Independent Power Producers (IPPs) to adhere to harmonic emission limits set by Network Service Providers (NSPs). Standards like NRS 048-4 [8] and IEC 61000-3-6 [9] specify acceptable distortion levels at the Point of Connection (POC).

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Limited published data exists on VT frequency response in South African networks. Most available results are based on European (EU) VT designs, which may not reflect local design and manufacturing characteristics [2]. This paper reviews published research on VT frequency response. It assesses its relevance to South African renewable energy networks, highlighting technical and regulatory limitations that influence the reliability of harmonic measurements under local operating conditions.

2. Overview of the Frequency Response of Voltage Transformers

An accurate harmonic voltage representation depends on the VT's frequency response. Assessment of this behaviour requires consideration of applicable international and South African standards that define emission limits and measurement requirements.

2.1. Standards and Compliance Requirements

VTs are part of the PQ measurement chain and directly influence the accuracy of harmonic assessments in inverter-based renewable installations. IEC 61000-3-6 sets harmonic emission limits for high-power installations at the POC based on short-circuit capacity [9]. NRS 048-4 applies similar principles within South African networks and establishes short-term (24 h) and long-term (seven days) harmonic limits for renewable energy producers [8]. Compliance verification uses Class A instrumentation, as defined in IEC 61000-4-30 [10].

IEC TR 61869-103 recognises the impact of ITs on PQ measurements but does not define harmonic-frequency accuracy classes or correction procedures [4]. IEEE 519 specifies distortion limits at the POC and defines acceptable harmonic levels in terms of system fault-current ratios [11].

These standards define harmonic emission thresholds but rely on the accuracy definitions specified at the fundamental frequency. None explicitly accounts for frequency-dependent VT behaviour under harmonic excitation. Table 1 summarises key PQ standards relevant to harmonic compliance.

Table 1. Comparison of selected PQ standards.

Standard	Region	Key Parameters
IEEE 519 [11]	North America	Harmonic voltage and current limits at PCC. THD $\leq$ 8.0% ($\leq$1 kV), THD $\leq$ 1.5% ($\geq$161 kV).
IEC 61000-3-6 [9]	International	Harmonic emission limits for high-power installations across voltage levels.
EN 50160 [12]	Europe	Voltage characteristics for public distribution networks.
NRS 048-2 [8,13]	South Africa	Limits for voltage unbalance, flicker, and harmonic limits across LV and MV systems.
IEC 61000-4-30 [10]	International	Class A and S for PQ measurement.

Without definitions of harmonic-frequency accuracy, compliance verification may reflect transformer transfer limitations rather than actual grid distortion. Structured evaluation of VT frequency response is therefore necessary to support reliable PQ assessment in South African renewable networks.

2.2. VT Technologies and Harmonic Behaviour

VTs used for PQ measurement differ in construction and operating principles. In South African grids, the primary technologies include IVTs, capacitive voltage transformers (CVTs), and Electronic Voltage Transformers (EVTs), each exhibiting distinct frequency response characteristics that affect harmonic accuracy [4,10].

IVTs are the most widely used devices in MV and HV networks. They depend on magnetic coupling between primary and secondary windings. IVTs show frequency-dependent deviations at higher harmonic orders [1,4,5]. Under typical loading conditions, ratio errors can exceed 5% between the 7th and 49th harmonics [1,4,6,7].

CVTs are commonly used in HV and Extra-High-Voltage (EHV) transmission networks and employ a capacitive divider and an intermediate transformer to scale voltages. CVTs provide improved high-frequency behaviour compared with inductive units but remain sensitive to tuning, temperature variation, and stray capacitance [10,14].

EVTs use sensors, signal conditioning, and digital processing to provide extended bandwidth and low distortion [15]. Deployment in South African MV networks remains limited due to infrastructure compatibility and cost considerations [3].

Comparative studies show that IVTs typically experience a sharp degradation in accuracy beyond 1 kHz, while EVTs and Resistive-Capacitive Divider (RC) dividers maintain a stable response across the harmonic range [4]. The frequency response profiles of VT technologies, which illustrate how construction affects harmonic fidelity, are available in IEC 61869-103 [4].

IVTs remain dominant in South African MV installations due to existing infrastructure and cost considerations. Their frequency-dependent behaviour therefore has direct implications for the reliability of harmonic measurements in renewable energy networks.

2.3. Design Factors Influencing Frequency

Transformer design and construction affect performance under harmonic conditions. Core material, winding geometry, burden impedance, and tank configuration interact to shape the frequency response and error characteristics [1,4,6].

Core material determines magnetic behaviour and hysteresis losses. Grain-oriented silicon steel offers low loss at 50 Hz but exhibits nonlinear magnetisation and hysteresis at higher frequencies. Eddy-current and hysteresis losses increase with frequency, leading to distortion and phase lag beyond the 13th harmonic [1,4].

The winding layout influences leakage inductance and parasitic capacitance. These parasitic elements interact with burden impedance and external cabling, forming resonant circuits that alter harmonic magnitude [1,7]. The burden directly influences the ratio and phase error. An increased burden modifies the secondary voltage drop and phase displacement. Table 2 outlines permissible voltage error and phase displacement limits for different VT accuracy classes under defined burden conditions.

Table 2. Permissible voltage error and phase displacement limits for VT accuracy classes [16].

Class	Voltage (Ratio) Error $\epsilon_u \pm\%$	Phase Displacement $\Delta\varphi$ ±Minutes	±Centiradians
0.1	0.1	5	0.15
0.2	0.2	10	0.3
0.5	0.5	20	0.6
1.0	1.0	40	1.2
3.0	3.0	Not Specified	Not Specified

These limits apply only at the rated frequency and under specified burden conditions. They do not extend to harmonic frequencies. Consequently, a VT may comply with Class 0.5 or Class 1.0 at 50 Hz while exhibiting undefined ratio and phase errors at higher harmonic orders.

Phase displacement is the angular difference between the primary and secondary voltages and affects the accuracy of power and energy measurements. Resonance between internal inductance and capacitance typically occurs between 800 Hz and 1.2 kHz [2,3]. Maintaining rated burden conditions reduces additional frequency-dependent distortion.

The tank construction and magnetic shielding affect stray flux coupling and damping. Shielding and damping influence high-frequency impedance and harmonic stability [4]. The winding configuration further influences performance. Open-delta and three-phase banks assembled from single-phase units may introduce unequal phase response under harmonic excitation [4]. Collectively, design factors and burden conditions define resonant behaviour and harmonic accuracy of VTs [4,17]. These interactions influence transformer transfer characteristics under harmonic excitation and directly affect the interpretation of measurements [4].

2.4. Measurement Errors and Correction Techniques

When operating beyond the rated frequency range, VTs introduce ratio and phase errors that distort harmonic magnitude and phase-angle measurements. The size of these errors depends on transformer design, burden impedance, and operating conditions [1,4,7]. As harmonic order increases, error magnitude increases sharply, often exceeding standard accuracy limits [1,4,5]. Table 3 summarises typical error ranges for IVTs under varying burden conditions.

Table 3. Typical IVT error ranges at selected harmonic orders.

Harmonic Order	IVT Ratio Error	Phase Displacement	Burden Influence
Fundamental	<0.2%	<0.1 crad	Minimal if at rated burden
3rd–13th	Up to +4.5%	Up to −1.2 crad	Increases with burden deviation

Ratio error is the deviation between the measured and theoretical secondary voltage, while phase error is the angular displacement between primary and secondary voltages. At higher frequencies, leakage inductance and parasitic capacitance dominate the transfer characteristic, causing attenuation and delay.

Correction techniques aim to compensate for frequency-dependent deviations and improve measurement accuracy. Analytical methods use a frequency-dependent equivalent circuit to derive correction factors from impedance parameters [4].

Empirical approaches use measured frequency-response data to generate correction profiles for post-processing or real-time implementation [18]. Hybrid techniques combine analytical modelling with experimental data to balance precision and practicality.

Despite these developments, IEC TR 61869-103 acknowledges VT-induced PQ errors but does not prescribe standardised correction procedures. In South Africa, no defined protocol exists for harmonic-frequency calibration or compensation [2–4]. This regulatory gap introduces uncertainty in compliance assessments and limits confidence in PQ data from renewable installations.

Effective correction methods must account for variations in burden, temperature effects, and transformer ageing to remain valid under field conditions. Without a valid transfer characterisation, measured harmonics may reflect transformer behaviour rather than actual network distortion.

2.5. South African Grid Conditions and Research Gaps

South Africa’s renewable energy expansion has introduced operating conditions that differ significantly from those in traditional grids. Inverter-based generation introduces harmonic components that interact with network impedance and influence transformer behaviour [1].

Environmental factors further complicate measurement accuracy. High temperatures, humidity, and airborne dust accelerate insulation ageing, modify stray capacitances, and shift resonance frequencies [19]. Table 4 outlines how these influences degrade VT performance during PQ assessments.

Table 4. PQ challenges from renewable energy integration and effects on VT measurements.

PQ Challenges	Source of Challenge	Impact on VT
Harmonic distortion	PV/Wind inverters	Excites resonance, reduces amplitude and phase accuracy.
Supraharmonics	High-speed inverter switching	Outside VT design range. Not reliably measurable.
Voltage fluctuations	Intermittent solar irradiance	Alters transient response and steady-state gain.
Environmental exposure	Temperature and humidity	Alter magnetic properties and introduce leakage paths.
Nonlinear loading	Inverter-generated waveforms	Affects coupling and phase shift, distorts harmonic ratios.

Despite the increasing deployment of renewables, research on VT frequency response under South African conditions remains limited. Most published studies focus on CVTs or current transformers (CTs), while conventional MV VTs remain under-characterised in local networks [4,5]. Table 5 compares the structural and operational differences between EU and South African VT applications.

Table 5. Comparison of European and South African VT applications.

Category	European Context	South Africa
Voltage Level–MV	1 kV to 35 kV	Up to 33 kV
Voltage Level–HV	Up to 150 kV	132 kV to 220 kV
Voltage Level–EHV	Up to 400 kV	Up to 765 kV
Environmental Impact	Moderate ambient temperatures.	Higher ambient temperatures.
Harmonic Standards	EN 50160 [12], IEC 61000-4-30 [10], IEC 61869 [4].	NRS 048 [9], SANS equivalents. Limited frequency accuracy classes.
Tolerance Bands	95% quantile, THD < 8% (EN 50160)	THD < 8%, short-term THD up to 11% (NRS 048) [8].
VT Deployment	IVT in MV CVTs and LPITs in HV/EHV	CVTs are common in HV. Some IVTs and LPITs are rarely used.
Testing Limitations	On-site methods available with limited access	Limited infrastructure. Frequency response is often unknown.

International investigations have examined VT-induced harmonic errors in EU systems [19]. Differences in equipment design and operating conditions limit direct transfer to South African networks.

Currently, no national standard defines procedures for evaluating VT accuracy at harmonic frequencies. IEC TR 61869-103 acknowledges the issue but does not define thresholds for harmonic-frequency performance [4]. This regulatory gap introduces uncertainty in PQ compliance assessment.

Addressing these gaps requires a structured characterisation of VT frequency response under representative South African operating conditions. Reliable transfer verification is necessary to support accurate harmonic assessment in renewable networks.

3. Discussion: Implications for PQ Measurement and Grid Compliance

The literature consistently shows that VTs, particularly inductive types, introduce frequency-dependent errors that distort harmonic voltage measurements. These deviations stem from core non-linearity, winding parasitics, and burden interaction, and are influenced by environmental exposure and installation conditions [4,17]. While several international studies propose analytical and empirical correction methods, their direct applicability to South African transformer designs remains uncertain. The absence of local frequency response data limits the reliability of PQ assessments in renewable networks.

South African renewable power plants operate under environmental and network conditions that differ significantly from those in Europe. Elevated ambient temperatures and outdoor exposure influence magnetic and capacitive behaviour [4]. These effects increase distortion at higher harmonics and can lead to noncompliance with measurement requirements [4]. Recorded distortion may therefore reflect transformer behaviour rather than actual network emission levels.

The South African grid code allows a 50% HD tolerance band, yet IVTs have demonstrated ratio errors exceeding this margin between the 7th and 49th harmonics. Such errors can exceed permissible tolerances, leading to an incorrect interpretation of compliance [4]. IEC TR 61869-103 acknowledges the influence of ITs but does not define procedures for harmonic-frequency verification, leaving NSPs and IPPs without consistent criteria for verification [4].

Reliable PQ assessment requires verification of the transformer's transfer behaviour under representative operating conditions. Structured harmonic-frequency evaluation methods have been proposed to address this need [4,17].

VT-induced errors are systematic rather than incidental. Compliance verification must therefore consider transformer-specific frequency response behaviour rather than assuming ideal transfer characteristics. Recognising this limitation strengthens the interpretation of harmonic measurements in renewable energy networks.

4. Conclusions

VTs are essential components in PQ measurement chains, yet their frequency-dependent behaviour limits the accuracy of harmonic assessment in renewable energy networks. This paper reviewed the literature on VT frequency response and examined how design characteristics, burden conditions, and environmental factors influence ratio and phase errors. Inductive transformers, although widely used in South African grids, display significant deviation at higher harmonic orders that can compromise grid code compliance.

International standards such as IEC TR 61869-103 and IEEE 519 acknowledge the impact of ITs on PQ measurement but do not specify harmonic-frequency accuracy classes or correction procedures. In South Africa, the absence of validated VT frequency-response data and standardised correction methods creates uncertainty when verifying compliance for renewable installations. Most available research is based on EU equipment, which differs in design and operating context from local infrastructure.

Structured evaluation of VT frequency response under representative South African operating conditions is therefore necessary to support reliable harmonic measurement. A complementary methodological study addressing harmonic-frequency evaluation procedures has been submitted for publication [20]. Recognising transformer-specific transfer limitations strengthens the interpretation of PQ data and improves confidence in assessing grid code compliance.

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