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Comparative study on the Power Quality of Public Grid, Solar, and Wind Energy Systems

Bachelor's Thesis

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Statutory Declaration

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I hereby affirm in lieu of an oath that I provided the submitted bachelor thesis

COMPARATIVE STUDY ON THE POWER QUALITY OF PUBLIC GRID, SOLAR, AND WIND ENERGY SYSTEMS

I did not use any sources other than those stated. In case that the work is additionally submitted on a data medium, I declare that the written and the electronic form are completely identical. The work was not submitted in the same or similar form to any examination authority.

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Abstract

This paper compares power quality attributes across three generation/supply systems currently active in the Mongolian Central Energy System (CES): the public distribution grid (powered by coal/CHP), a utility-scale solar photovoltaic plant, and a wind energy plant. On-site measurements were taken at each facility using a Baker EXP4000 Dynamic Motor Analyzer, and interpreted relative to Mongolian national standard MNS 1778: 2007, as well as the Unified Energy Grid Rules (2021).

At each site we analyzed five parameters defined by MNS 1778: 2007: steady state voltage deviation (δUy), voltage total harmonic distortion (K_U), per-order harmonic coefficients ($K_{U(n)}$),negative-sequence voltage unbalance (K_{2U}), and frequency deviation (Δf). For all five parameters, all three grids remain within MNS 1778:2007 prescribed maxima. Voltage deviation is above normal levels of ±5% at the public (+7.13%) and solar PV (+6.33%) sites, but within the ±10% maximum; the wind farm site shows +2.97% and falls within normal range. Total harmonic distortion comes in at 0.80% (public), 2.20% (solar PV), and 1.60% (wind); all three easily within the 8% normal maximum. Dominant order is the 13th harmonic (650 Hz) at both renewable sites, as would be expected from six-pulse PWM inverter function at partial load. Triplen harmonics are essentially non-existent at any of the sites. Frequency deviation was measured to be precisely 0 at all three sites.

Key findings include ongoing voltage overvoltage at low-voltage points of connection, likely the result of inappropriate transformer tap settings rather than injection from renewables, and the absence of current harmonic limits in Mongolia's incomplete power quality standards regime — MNS 1778: 2007 currently only defines limits for voltage harmonics. We make recommendations for corrective tap adjustments, reactive power compensation where necessary, continuous power quality monitoring, and establishment of a companion standard to MNS 1778:2007 for current harmonics.

By providing the first side-by-side MNS 1778: 2007-compliant power quality measurement across all three forms of electricity generation currently in Mongolia's CES, we hope to establish a quantitative benchmark against which future measurements can be compared as renewables are added in increasing quantities to meet the national target of 30% renewable generation.

Keywords: Power quality, MNS 1778:2007, harmonics, voltage deviation, solar PV, wind, Mongolia, Baker EXP4000, THD, voltage unbalance

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List of Abbreviations

Abbreviation	Full Term
AC	Alternating current
ABS	American Bureau of Shipping
CES	Central Energy System (Монголын Төв эрчим хүчний систем)
CHP	Combined heat and power plant
DC	Direct current
ERC	Energy Regulatory Commission of Mongolia
K_U	Coefficient of sinusoidal distortion (voltage THD) — MNS 1778:2007 term
K_U (n)	Individual harmonic order coefficient — MNS 1778:2007 term
K_{2U}	Negative-sequence voltage unbalance — MNS 1778:2007 term
LV	Low voltage (≤ 1 kV)
MNS	Mongolian National Standard (Монгол Улсын Стандарт)
MV	Medium voltage (1 kV – 35 kV)
NEMA	National Electrical Manufacturers Association
PQ	Power quality
Pst	Short-term flicker indicator — MNS 1778:2007 term
Plt	Long-term flicker indicator — MNS 1778:2007 term
PV	Photovoltaic
PWM	Pulse-width modulation
RMS	Root mean square
THD	Total harmonic distortion
VFD	Variable frequency drive
δUy	Steady-state voltage deviation — MNS 1778:2007 term
Δf	Frequency deviation — MNS 1778:2007 term
U_1	Fundamental (50 Hz) voltage component, RMS

U_n	n-th harmonic voltage component, RMS

1. Introduction

1.1 Background and Problem Statement

A large transition is coming for Mongolia's energy system. Mongolia has relied almost exclusively on coal-fired combined heat and power (CHP) plants to generate electricity and provide district heating for cities for over 50 years. These stations were designed and constructed with Soviet expertise and technology, with many running past their designed lifespan but nonetheless serving as the backbone of Mongolia's grid. As of 2023, 90.9% of electricity generated domestically was from coal-fired thermal generation. Per capita electricity demand is relatively low, but when compared to domestic generation, this resulted in Mongolia having one of the most coal-intensive grids in Asia [1[1]]. The difference is made up by electricity imports, which reached 22.3% of total consumption in 2023. Mongolia must pay in foreign currency to import electricity from neighbouring Russia and China, introducing an element of supply dependency with accompanying economic and geopolitical risk [1[1,]].

One measure of how big this demand problem is can be seen by looking at the peak winter loads of the Central Energy System. That peak winter load hit an all-time high of 1,636 megawatts this past winter of 2023–2024, an 11.3 percent increase over last year. Not only is that a record-setting amount of electricity, it was produced with essentially no system-wide reserve. Every generator was running full steam ahead and couldn't possibly produce any more power, even if they wanted to. There are no power systems engineering reason to operate a power grid without reserve. If a generator trips offline or there is a sudden unexpected increase in demand, there is no additional capacity online to back up the load. There would be automatic load shedding, or worse, a cascading failure of the system. Zero reserve also means there is no wiggle room for renewable energy production since, by definition, they can't produce power whenever you need it.

Against this backdrop, Mongolia has pledged to increase its renewable energy generation. Cut fuel import and coal transportation costs provide an economic rationale, while climate pledges give an added push. Solar and wind power have particular potential advantages in Mongolia: there are between 270 and 300 days of sunshine per year and annual average solar radiation levels between 1,400 and 1,800 kWh/m2, while Mongolia's open steppe geography provides some of Asia's strongest and most reliable winds [2[3]]. Mongolia's first wind farm came online in Salkhit in 2013 with 50 MW of generation capacity, and solar photovoltaic capacity is on the rise throughout the country's central and southern steppe.

On the other hand, integrating solar and wind generators into the power system which was originally designed for large synchronous generators presents its own set of technical challenges, with power quality being among the most significant. Simply put, power quality can be described as how closely the voltage, current, and frequency of electricity match ideal conditions. Lower quality power can lead to minor inconvenience at best and expensive damage at worst. According to Mongolian national standard MNS 2980: 2003, power quality is "a property of electrical energy which causes all parameters of electricity to meet nominal values" [3[4]]. In other words, it is a legal requirement that electricity suppliers must provide to their customers.

Negative effects of poor power quality for industrial and commercial consumers of electricity are widely known and described in the literature on power engineering. Industrial experience in Mongolia also shows that poor power quality decreases industrial productivity rates, product quality, normal operation of technological processes and power equipment service life. One of the most important indexes of power quality is level of higher harmonics in power lines. Electrical problems caused by harmonics include malfunctioning of protection relays, incorrect operation of thyristors-controlled devices, overheating of transformer core, cable insulation deterioration, shortening service life of equipment, burnout of motor stator winding, neutral conductor overload and harmonic resonance which could make entire section of power network unstable [7[5], 8[6], 9[7], 10[8]].

The reason the renewable integration problem becomes particularly severe from a power quality point of view is that renewable energy sources and conventional synchronous generators differ fundamentally from an electrical standpoint. A big coal-fired generator is a synchronous machine. That means it naturally produces almost sinusoidal voltage waveform at precisely the grid frequency, that it has rotational inertia that resists sudden changes in grid frequency, and its automatic voltage regulator keeps terminal voltage tightly controlled for a wide range of loading conditions. Solar PV inverters and wind turbine converters are power electronic devices. They create AC output from DC input using high frequency semiconductor switching. The process of switching itself creates harmonic currents – frequencies that are integer multiples of the fundamental 50 Hz signal – that are not present coming out of a synchronous generator. Harmonic distortion of the network voltage will therefore increase as more power electronic generation is added to the system.

Power quality requirements in Mongolia are defined in three documents: MNS 2980:2003, which provides definitions, MNS 1778:2007 which outlines standard (normative) limits for twelve power quality parameters to which all operators must adhere, and the 2021 Unified Energy Grid Rules, which converts those standard requirements to requirements for all grid connected operators within Mongolia. Collectively, these documents set forth the regulatory benchmark against which any power quality performance within Mongolia must be judged. While this standard is well defined, published technical analyses of power quality within grid-connected renewable energy systems in Mongolia with respect to

that standard are few. To the author's knowledge, no single measurement study exists which analyzes the public grid, solar PV, and wind, together within the framework of a single MNS 1778:2007-compliant comparison. This paper aims to fill that void.

1.2 Research Objectives

This thesis seeks to compare the power quality profiles of three typical electrical generation and distribution systems currently interfacing with Mongolia's Central Energy System including the public grid fed largely by combined heat and power (CHP) thermal generation, a utility-scale solar photovoltaic system, and a wind energy system. Findings are based on standards outlined in the national standard document MNS 1778: 2007 and were assessed for compliance with the Unified Energy Grid Rules.

To reach this goal, three subgoals were defined: Goal 1 - Quantify and statistically describe the five most relevant power quality parameters according to MNS 1778:2007 (steady-state voltage unbalance δUy, total voltage harmonic distortion K_U, single order voltage harmonic coefficient K_U (n), negative sequence voltage unbalance K_{2U} and frequency deviation Δf) at all three measurement sites and compare these with nominal and maximum values defined in MNS 1778:2007 to assess conformance of each system to the standard; Goal 2 - Provide a description of harmonic spectra for each of the three systems including quantification of triplen vs. non triplen harmonic orders, identification of single largest harmonics for each system, and explanation of harmonic profiles with respect to the generation technology and switching nature; Goal 3 - Provide conclusions and recommendations to the utility and regulatory bodies based on measurements and described technical deficiencies, both for the cases described at the measurement sites as well general recommendations for regulation.

1.3 Scope and Limitations

This study includes three types of energy systems that are installed and functioning today in the Mongolian Central Energy System: The publicly distributed grid supplied by CHP thermal generation, one utility-scale solar PV plant, and one wind farm. Measurements were taken on-site at each facility with the Baker EXP4000 Dynamic Motor Analyzer. Results presented in this paper are compared solely with the values outlined in the normative MNS 1778:2007 standard. Parameters δUy, K_U, K_U (n), K_{2U}, and Δf were chosen as they are parameters most affected by the introduction of renewables and measurable with this instrument. MNS 1778: 2007 parameters that include transient, impulse, and sag voltages (parameters 10-12) were not chosen for this study due to instrumentation requirements and time scale constraints of steady state measurement campaigns.

There are some important limitations of this work that should be stated up front. Firstly, measurements were taken during a single visit to each site, and so operating conditions during the measurement period may not reflect the full range of operating conditions experienced by each system throughout the year. Mongolia's harsh continental climate creates drastic seasonality in both load and renewable generation: winter peak demand can be four times higher than summer minimum demand, and monthly averages of solar irradiance in December are only a fraction of irradiance in June. Ideally power quality at each site would be measured at different times of day and throughout the year. Secondly, solar PV was only measured while operating at 6.1% of rated load — a relatively idle state which has large impacts on power factor and may impact the harmonic profile when compared to full load conditions. Within these limitations, this work represents the first systematic comparison of power quality across all three generation types in Mongolia's CES using a consistent methodology based on the national standard.

1.4 Methodology Overview

Field measurements were carried out at three sites using Baker EXP4000 Dynamic Motor Analyzer (Megger Group). Equipment measures continuously three-phase voltage and current and calculates PQ parameters: voltage THD (K_U), voltage individual harmonic order coefficients K_U (n), voltage unbalance K_{2U}, frequency and power factor. Measurements results are compared with normative provisions of MNS 1778:2007 and Rules of Unified Energy Grid. [6[9],7[5]] Computer simulation allows analyzing conditions beyond those experienced during field campaign. Technical recommendations are prepared depending on obtained results according to national regulation.

2. State of the Art

2.1 Mongolia's Energy System and Power Quality Context

2.1.1 Current Energy Mix and Grid Infrastructure

Mongolia's power system includes the Central Energy System (CES), serving Ulaanbaatar (capital city), the central region, north and eastern Mongolia, accounting for more than 80% of electricity usage in Mongolia and four isolated regional systems (western energy system, eastern energy system and southern energy system), which aren't interconnected with CES in synchronism. CES is an interconnected transmission network with voltages ranging from 0.4 kV to 220 kV and with real-time frequency and voltage control operated by National Dispatch Center in Mongolia, Ulaanbaatar [1[1]].

The CES generation fleet is dominated by five large CHP plants built from the 1960s to the 1980s. All five burn domestically mined coal in steam turbines. Thermal generation comprised 90.9% of national generation in 2023. Solar and wind combined to 8.5% and hydroelectricity contributed 0.6%. Approximately 22.3% of CES consumption is imported, via tie-lines from Russia's Siberian grid in the north and China's Inner Mongolia grid to the south. Total CES electricity generation amounted to 8.5 billion kWh in 2023, an increase of 4.3% over 2022. CES winter peak demand reached 1,636 MW, up 11.3% from the prior year. CES transmission and distribution grids are viewed as outdated. System wide losses are estimated at 13.7%, nearly double the 6 to 8% that would be expected from international best practice [1[1]].

Table 1 Mongolia electricity generation by source, 2023 [1[1]]

Energy Source	Generation Share (%)	Installed Capacity (MW)	Annual Output (GWh)
Coal (CHP thermal plants)	90.9	~1,320	~7,700
Wind energy	4.5	~220	~380
Solar photovoltaic	2.0	~90	~170
Hydroelectric	0.6	~34	~51
Import (Russia + China)	22.3% of consumption	—	~2,400

2.1.2 Renewable Energy Development and PQ Implications

Renewables had been commissioned from zero nameplate capacity in early 2010s to reach significant generation shares in 2023. Mongolia's first utility-scale renewable project was the Salkhit Wind Farm which came online in 2013 with nameplate capacity of 50 MW, consisting of 31 Vestas V90 wind turbines installed about 70 km east of Mongolia's capital city Ulaanbaatar. It remains the country's largest wind farm. Salkhit Wind Farm connects to the CES through a dedicated 110 kV transmission line. Several solar PV plants have come online in Mongolia's central and southern provinces, benefitting from the country's high solar resource of 270–300 sunny days per year with 1,400 to 1,800 kWh/m² annual irradiance [15[10]].

The primary distinction between renewable generation and traditional synchronous generators, from a power quality standpoint, is their electrical interface with the grid. A synchronous generator generates power at the system frequency due to electromagnetic induction in a rotating machine. With synchronous generators, the output voltage is purely sinusoidal, rotational inertia provides grid frequency support, and excitation systems control terminal voltage to a tight tolerance [6[9]]. Inverters taking DC power and creating AC synthesize alternating current at the desired frequency by rapidly switching power electronics devices on and off. This discrete switching action introduces harmonic distortion: the synthesized current is at 50 Hz but also contains integer multiples of 50 Hz [8[6], 9[7]]. As generation connected to the grid through power electronics increases, so does the possibility for harmonics and loss of inertia [13[11]]

2.2 Mongolian Power Quality Regulatory Framework

2.2.1 MNS 2980:2003 — Power Quality Terminology

MNS 2980: 2003 Terminology for power quality management systems and procedures was approved December 25th, 2003. This document is the baseline terminology standard for power quality in the Mongolian electricity sector. It defines the basic 76 terms that are used as common language in all further regulations, standards and contracts. [3[4]] It serves as the Mongolian translation of international terminology standards, such as IEC 60050-161. The seven definitions used most relevant for this paper from the total of 76 are: power quality (цахилгааны чанар) - the property of electrical energy to have parameters within established nominal values; voltage deviation (хүчдэлийн хазайлт) - difference between instantaneous RMS voltage and nominal voltage at a given point in the network; frequency deviation (давтамжийн хазайлт) - difference between instantaneous grid frequency and 50 Hz; voltage unbalance (хүчдэлийн тэнцвэргүй байдал) - property of having three phase voltages with unequal RMS values; harmonic distortion (гармоник гажилт) - the presence of integer multiples of the fundamental frequency in the waveform.

2.2.2 MNS 1778:2007 — Normative Power Quality Parameters

MNS 1778: 2007 is the currently valid national standard for power quality in Mongolia. It defines 12 parameters with quantitative normative limits that apply to all electricity producers, network operators and consumers who are connected to Mongolia's national grid. National equivalents to MNS 1778: 2007 are Russia's GOST 13109-97 and Europe's EN 50160. The requirements from MNS 1778: 2007 shall have legal force by demanding in technical specifications for grid connection agreements and supply contracts that limits according to MNS 1778:2007 shall apply. Limits in MNS 1778: 2007 are expressed in a two-tier limit structure of normal limit and maximum limit. The normal limit describes optimum performance and maximum limit describes a level below which there is no demonstrated injury to standard equipment [4[12]].

Table 2:MNS 1778:2007 — twelve power quality parameters with normative limits

No.	Parameter	Symbol	Normal limit	Max limit
1	Nominal voltage (acceptable range)	Uy	Per MNS (IEC) 38:2001	—
2	Steady-state voltage deviation	δUy	±5%	±10%
3	Voltage amplitude variation	δUt	Per equipment class	—
4	Voltage flicker — short/long term	$Pst\ /\ Plt$	Pst ≤ 1.38	—
5	Total harmonic distortion voltage	$K_U(\%)$	≤ 8% (LV) / ≤ 5% (MV)	≤ 12%
6	Individual harmonic order coefficient	$K_{U(n)}\ (\%)$	Per harmonic order table	—
7	Negative-sequence voltage unbalance	$K_{2U}\ (\%)$	≤ 2.0%	≤ 4.0%
8	Zero-sequence voltage unbalance	$K_{0U}\ (\%)$	≤ 2.0%	≤ 4.0%
9	Frequency deviation	$\Delta f\ (Hz)$	± 0.2 Hz	± 0.4 Hz
10	Voltage dip / sag	ΔUvd	Per depth and duration table	—
11	Impulse voltage	$Uimp$	Per insulation class	—
12	Transient overvoltage	K	Per voltage level	—

The scope of this paper is limited to parameters 2,5,6,7 and 9, ie the parameters most relevant to renewable energy integration and measurable by the Baker EXP4000. Voltage deviation normal limit (+/-5%) and maximum limit (+/-10%) is based on steady-state RMS voltage at supply terminals as seen by the consumer. The THD limit of 8% at low voltage (less than or equal to 1 kV) is less than where classes of sensitive equipment begin to show measurable degradation in performance. Frequency deviation normal limit (+/-0.2 Hz) is based on equipment that operate under normal conditions such as synchronous machines and frequency-dependent industrial process speed.

Table 1 of MNS 1778: 2007 gives allowable values of voltage sinusoidal distortion coefficient K_U (total THD of voltage, Parameter 5) for all voltage levels on the Mongolian power system. Table 3 below directly duplicates those normative limits from the standard. Limits vary by nominal voltage level --

tighter limits for higher voltage levels where harmonic distortion affects a larger area. The public grid and solar PV sites connect to the system at 0.38 kV and are therefore considered against the limits shown in the 8.0%/12.0% normal/max row. The wind farm is measured at 0.69 kV (turbine terminals), but this also falls under the MNS 1778: 2007 Table 1, row for 0.38 kV since the standard consolidates all low voltage networks (<1kV) into the 0.38 column. Limits given in Table 1 are the baseline against which compliance is assessed in Sections 4.1.2, 4.2.3, and 4.3.3 [4[12]].

Table 3: MNS 1778:2007 Table 1 — Permissible Values of Voltage Sinusoidal Distortion Coefficient K_U (%) by Voltage Level

Limit type	**Nominal voltage U_{nom} [kV]**			
	0.38	**6–20**	**35**	**110–330**
Normal limit	**8.0**	5.0	4.0	2.0
Maximum limit	**12.0**	8.0	6.0	3.0
Measured K_U – Public Grid (0.38 kV)	**0.80 ✓**	—	—	—
Measured K_U – Solar PV (0.4 kV)	**2.20 ✓**	—	—	—
Measured K_U – Wind (0.69 kV)	**1.60 ✓**	—	—	—

Source: MNS 1778:2007 Table 1 (reproduced). All three systems are connected at LV (0.38–0.69 kV) and assessed against the 0.38 kV column: normal limit 8.0%, maximum limit 12.0%. ✓ = PASS (within normal limit). All measured K_U values are well within the normal limit [4 [12]].

2.2.3 Unified Energy Grid Rules — Operational Requirements

Unified Energy Grid Rules (Эрчим хүчний нэгдсэн сүлжээний дүрэм, 2021) (legislative decree rules used to enforce MNS 1778: 2007 along with other standards into Mongolia as regulations/practices mandatory for all grid connected parties), enforced by the Energy Regulatory Commission of Mongolia [5[13]]. Power Quality requirements defined as: frequency of supply should be maintained at 50 ± 0.2 Hz at all times during normal operation [5[13]] (frequency tolerance excursions up to ±0.4 Hz are allowed for transient conditions); Voltage levels at each stage of the network to be within limits outlined in MNS (IEC) 38:2001; Total Harmonic distortion is to meet limits set in MNS 1778:2007 at all points on the network [4[12], 5[13]]. Voltage regulation should be planned by network operators at least twice annually (once during winter peak load, once during summer minimum load) to establish the range of acceptable voltage levels throughout their system. If the poor power quality is caused by a consumer or generator which causes power quality parameters to exceed limits set out in MNS 1778: 2007 at the PCC, the

offending consumer or generator is required to install the equipment needed to correct this issue at their expense.

2.3 Power Quality Disturbances — Theory, Formulae, and Effects

2.3.1 Classification of Power Quality Problems

Power quality problems are categorized based on their physical nature, duration, causes, etc. [6[9], 7[5]]. However, the most commonly used classification divides PQ problems into seven categories: transients (nanoseconds-ms) [7[5]]; short-duration voltage variations (sag, swell, interruption - half cycle to few minutes); long-duration voltage variations (sustained under- and over-voltage); voltage unbalance; waveform distortion (DC offset, harmonics, interharmonics, notching, noise); flicker (voltage fluctuations); and power frequency variations. The ones that are most relevant for this paper are steady-state voltage deviation, harmonic waveform distortion, voltage unbalance and frequency deviation since they are directly related to renewables and their power electronic inverters.

2.3.2 Harmonic Distortion — Physical Mechanism and Formulae

Harmonic distortion is produced whenever a non-linear element is attached to the power system. A non-linear element can be defined as any element whose instantaneous impedance varies as the voltage or current changes, such that when it is driven with a sinusoidal voltage, the resulting current is not sinusoidal [6[9],7[5]]. The Fourier analysis of any periodic non-sinusoidal waveform reveals that it can be represented by the summation of sinusoidal waves whose frequencies are integer multiples of the fundamental frequency [6[9]]. In power systems operating at 50 Hz, the harmonics are therefore seen at 100 Hz (2 nd), 150 Hz (3 rd), 250 Hz (5 th), 350 Hz (7 th), etc. According to MNS 1778: 2007, the Total harmonic distortion coefficient K_U is equal to:

$$K_u(\%) = \frac{\sqrt{\sum_{n=2}^{40} U_n^2}}{U_{nom}} x100$$

where U_1 is the RMS amplitude of the fundamental frequency (50 Hz) voltage component and U_n is the RMS amplitude of the n-th harmonic component. In this study, harmonics up to the 50th order (2,500 Hz) were measured, capturing all practically significant harmonic components in low-voltage distribution systems. The individual harmonic order coefficient for each harmonic order n is:

$$K_u(n)(\%) = \frac{U_n}{U_1} x100$$

In the Baker EXP4000 Dynamic Motor Analyzer used in this study, the fundamental (1st harmonic) is identified in the Harmonics or Spectrum tab as the largest peak at the far left of the

frequency spectrum — always the 50 Hz component. All K_U (n) values reported by the instrument are automatically expressed as percentages of this U_1 reference. The measured U_1 values in this study are: Solar PV site U_1 = 168.78 V per phase; Wind site U_1 = 174.2 V per phase. The Baker EXP4000 directly displays K_U(n) values as percentages of the fundamental, so no manual calculation is required during measurement.

2.3.3 Why Even-Order Harmonics Are Essentially Absent

A key feature of power system harmonic spectra is that odd-order harmonics (3rd, 5th, 7th...) are present, but even-order harmonics (2nd, 4th, 6th, 8th...) are essentially nonexistent [6[9]], [8[6]]. This arises directly from the physical symmetry of harmonic-producing equipment. A waveform f(t) is said to have half-wave symmetry if: f(t) = −f(t + T/2) — that is, the negative half-cycle of the waveform is an exact inversion of the positive half-cycle [6[9]]. When this relationship holds true, the Fourier series of f(t) will include only odd-order harmonic terms; all even-order Fourier coefficients will be zero. This is due to the positive and negative halves of the waveform cancelling out exactly in the even-order coefficients.

Most electrical equipment found in practice (synchronous generators, transformers, induction motors, bridge rectifiers and PWM inverters) functions with half-wave symmetry at power frequency. This means even harmonics are theoretically zero, and in practice extremely small. Most well-designed systems have even harmonics below 0.05% of the fundamental. Pathological conditions will introduce even-order harmonics: DC offset in the waveform (breaking half-wave symmetry), half-wave rectifiers (passing only the positive half-cycle), transformer cores driven into asymmetric saturation, or unbalanced single-phase loading producing asymmetric half-cycles. None of these conditions are present in the systems tested in this project, hence all even-order harmonic measurements are below 0.05% confirming normal symmetric operation at all three sites.

2.3.4 Triplen Harmonics vs Non-Triplen Harmonics

Among the odd-order harmonics, a critical distinction separates triplen harmonics (3rd, 9th, 15th, 21st, 27th... — multiples of three) from non-triplen odd harmonics (5th, 7th, 11th, 13th, 17th, 19th, 23rd, 25th...) [6[9], 11[14]]. These two groups behave fundamentally differently in three-phase systems because of their different symmetrical components (sequence) characteristics [6[9]].

In a balanced three-phase system, the currents at the fundamental frequency comprise a positive-sequence set. The currents at the 5th harmonic comprise a negative-sequence set (meaning they rotate in the opposite direction) — this creates reverse torque in motors, and extra heating in generators. The 7th harmonic is positive sequence; the 11th is negative; the 13th is positive. The triplen harmonics (3rd, 9th, 15th...) are zero sequence -- that is, all three phases are in phase with each other at the same time. Delta-connected transformer windings provide a closed path in which zero-sequence currents can

circulate, thereby trapping triplen harmonics and preventing them from reaching the high-voltage side of the network [11[14], 14[15]]. The extremely low triplen harmonic content measured at all three sites in this study (each below 0.12%) is indicative of both well-balanced three-phase operation, and of transformer delta-winding suppression.

2.3.5 Harmonic Generation by Inverter-Based Equipment

Solar PV and wind energy systems use three-phase PWM voltage-source inverters with a six-pulse bridge topology for grid connection [8[6], 9[7], 11[14]]. The characteristic harmonic orders produced by this topology follow the formula $h = 6k \pm 1$ ($k = 1, 2, 3...$), giving: 5th, 7th, 11th, 13th, 17th, 19th, 23rd, 25th as the characteristic (unavoidable) harmonic orders [8[6], 11[14]]. All other harmonic orders — even, triplen, and non-characteristic odd — are theoretically zero and appear in practice only due to switching imperfections and control asymmetries.

At rated load with ideal switching, the theoretical characteristic harmonic current amplitudes are on the order of 1/n. So, the 5th harmonic is ~20% of fundamental current, the 7th harmonic is ~14% of fundamental current, the 11th harmonic is ~9% of fundamental current, the 13th harmonic is ~8%, etc. [8, 11[14]]. In practice, PWM control and LCL output filters reduce these amplitudes significantly below theoretical values. [8[6]] At low load — such as that occurring at the solar PV site (6.1%) — inverter dead-time effects and switching delays become large relative to the fundamental frequency component. These effects distort the applied modulation pattern, and tend to amplify higher-order harmonics (e.g. 11th, 13th) more than lower-order harmonics (5th, 7th). This is why the 13th harmonic is the dominant harmonic observed at both the solar PV (6.1% load) and wind site.

Effects of inverter harmonics on connected equipment are summarized as follows [6[9],8[6],9[7],12[16],14[15]]: Transformer eddy current losses are proportional to n^2 times the amplitude of the harmonic squared; where n is the order of the harmonic. If the harmonic loading is large, the transformer must be derated [14[15]]. Cable heating may occur due to larger RMS current as higher frequencies cause skin effect in cables. Capacitor bank overload or resonance may occur when the natural frequency of the system is at or near a dominant harmonic order [12[16]]. Protection relay malfunction may occur due to distortion of the current waveform [6[9],9[7]]. Harmonic filtering techniques for inverters include passive LC filters designed to filter 5th and 7th order harmonics, active power filters which can dynamically filter multiple harmonics, integral LCL filters which are starting to be implemented into modern inverter design, and the use of 12-pulse converter topologies which cancel out 5th and 7th harmonics by phase-shifting two separate 6-pulse bridges by 30° [8[6],11[14],12[16]].

2.3.6 Harmonic Generation by Thyristor-Controlled Equipment

Thyristor (SCR) controlled equipment — arc furnaces, DC motor drives, induction heating equipment — also generate $6k \pm 1$ characteristic harmonics, however the amplitude characteristics are

different [7[5], 10[8]]. The theoretical current harmonic amplitudes are given by $I_n \approx I_1 / n$. Therefore, the 5th harmonic is approximately 20% of fundamental, the 7th harmonic approximately 14% of fundamental, the 11th harmonic approximately 9% of fundamental, and the 13th harmonic approximately 8% of fundamental. Actual thyristor equipment tends to produce larger 5th and 7th harmonic currents than similarly-rated PWM inverters because thyristor commutation is much less controlled than PWM modulation.

Another power quality phenomenon caused by thyristor devices is voltage notching. Voltage notching is a momentary voltage sag at each commutation point when two groups of thyristors are momentarily shorted to the AC supply [6[9]]. Voltage notching can cause problems in zero-crossing detection circuits and can be disruptive to sensitive electronic loads [10[8]]. Harmonic filtering strategies for thyristor converters often include passive harmonic trap filters (order tuned LC circuits), 12-pulse converter arrangements that cancel 5th and 7th harmonics, or AC line reactors that limit harmonic currents.

2.3.7 Consequences of Harmonic Levels Exceeding MNS 1778:2007 Limits

Normal and maximum levels of harmonic distortion are defined by MNS 1778:2007 [4[12]]. $K_U \leq 8\%$ LV (LV is Line Voltage), means that standard electrical equipment will operate within its specified tolerance limits. If K_U is greater than normal but less than or equal to the maximum defined value $8\% < K_U \leq 12\%$, electrical equipment starts to experience measurable levels of degradation: transformer core losses are 10 to 15% higher than they would be without harmonics. The added losses reduce efficiency and create additional heat within the transformer. Motor efficiency is lowered by 2 to 3 percentage points. Capacitor banks can be overloaded, potentially causing them to fail prematurely. Protection relays can malfunction, leading to nuisance tripping or failure to trip on real faults.

If K_U values exceed the limit ($K_U > 12\%$), it is considered emergency: transformer insulation may experience irreversible damage due to prolonged overheating; cable insulation can melt, resulting in short circuit; harmonic resonance between source impedance and capacitor banks may generate damaging overvoltages at the resonant harmonic; thyristor and IGBT gate controls may malfunction due to severely distorted voltage waveform; relays may malfunction resulting in widespread network issues. For these reasons, the 12% maximum value is an absolute engineering limit. All tested K_U values are well below the normal limit in this paper — .80%, 2.20%, and 1.60% — indicating no risk to equipment under current harmonic conditions.

2.3.8 Earthing Systems and Their Effect on Harmonic Propagation

Earth connection configuration of the power network determines zero-sequence harmonic propagation paths. There are two earthing configurations commonly employed. In TN (Terra-Neutral) system the transformer neutral is solidly earthed and brought out to the consumer premises earth through

the neutral conductor. Zero-sequence (triplen) harmonic current will return to source through neutral conductor. The triplen harmonic currents from each nonlinear load are additive creating I_neutral = 3 × I_phase(triplen) current in the neutral conductor. If the neutral conductor was sized to carry the load current under balanced fundamental-frequency conditions (ideal case which assumes zero neutral current), then the neutral could be drastically undersized to carry the actual line-neutral triplen harmonic current causing it to overheat. Neutral conductor should be sized at 1.5 to 2 times the phase conductor cross-section if there are expectations of substantial triplen harmonic content on the circuit. TN System offers good Fault protection characteristics.

Zero-sequence harmonic currents cannot find a return path via the neutral conductor in a TT system because the consumer's equipment earth terminal is connected to a local earth electrode that is electrically independent of the transformer neutral. Harmonic currents must therefore return via the earth which has significantly higher impedance. TT earthing therefore limits triplen harmonic propagation into the network neutral and prevents overloading of the neutral conductor. The TT system is used with renewable energy installations and with consumers located where neutral conductor continuity cannot be assured over long rural distribution distances. For purposes of harmonic control, TT earthing at the consumer's point of connection in combination with a delta-wound transformer primary represents the most effective mitigation of triplen harmonics since the delta winding provides containment of zero-sequence currents and the TT configuration prohibits accumulation on the neutral conductor. Harmonic-producing renewable energy installations should therefore be connected using this arrangement.

2.4 Power Quality in Solar PV Systems

2.4.1 Architecture of Grid-Connected Solar PV Systems

There are three functional stages in a utility-scale grid-connected solar PV system: 1) The PV array: Thousands of photovoltaic modules wired together in series-parallel combinations to produce a continuously varying DC voltage and current output as a function of solar irradiance and module temperature. 2) The DC-AC power conversion stage: A three-phase grid-connected PWM inverter with MPPT functionality that operates by continuously shifting the DC operating point to pull maximum power from the PV array. 3) The grid interface: step-up transformer, output filters (typically LCL), and protection equipment used to connect the inverter to the distribution grid. From a power quality standpoint, the inverter is the most important element – its six pulse bridge configuration determines the inherent 6k±1 harmonic structure, while its control strategy and operating point determine the resultant harmonic levels. With 270–300 sunny days per year and 1,400–1,800 kWh/m2 of annual irradiance, Mongolia's solar resource is sufficient for economical utility-scale PV [15].

2.4.2 Power Quality Challenges of Solar PV Integration

Solar PV systems cause PQ disturbances in three ways [6[9], 9[7]]. Steady-state voltage rise: Injecting real power into a distribution feeder results in reverse power flow, and thus increases the voltage down the feeder linearly with the injected power and feeder impedance [6[9]]. Under high solar irradiance conditions coupled with light load from end users — as occurs frequently in Mongolia on summer afternoons — PV systems cause voltage at the PCC to rise beyond the standard ±5% permitted under MNS 1778:2007 Parameter 2. Voltage fluctuation: Transients in solar irradiance due to cloud-cover moving across the solar array cause matching PV output transients, resulting in voltage fluctuation (δUt) and flicker (Pst) at the PCC [13[11]]. Harmonic injection: The six-pulse PWM inverter generates 6k±1 harmonics (5th, 7th, 11th, 13th...). When multiplied by network impedance, this input current results in harmonic voltage distortion at the PCC [8[6]]. Harmonic performance is generally poorer at low load than at nameplate output, as discussed in Section 2.3.5 [8[6], 11[14]].

2.5 Power Quality in Wind Energy Systems

2.5.1 Architecture of Grid-Connected Wind Energy Systems

Wind turbines for grid-connected, modern utility-scale plants are variable-speed generators equipped with power electronic converters. The grid-connected converter is either a doubly-fed induction generator (DFIG) with partial-scale converter, or a permanent magnet synchronous generator (PMSG) with full-scale converter [13[11]]. The grid-side converter in each case employs a six-pulse PWM bridge topology which results in a grid current containing the well-known 6k±1 harmonic pattern [8[6], 11[14]]. Mongolia's Salkhit Wind Farm (50 MW) facility has Vestas V90 variable-speed wind turbines and connects to the CES 110 kV network through a 35/110 kV step-up transformer substation. As noted earlier, the 110 kV connection voltage here supplies much stronger voltage support and experiences much less voltage sensitivity than 380 V connections at the LV study sites.

2.5.2 Power Quality Challenges of Wind Energy Integration

Wind power systems create power quality issues by means similar to and also unlike solar PV. The voltage deviation mechanism described above (active power injection drives voltage increase) is applicable to wind farms as well. However, the magnitude of this effect is lower at 110 kV because the short-circuit capacity is higher at this voltage level. The tower shadow effect causes disturbances which are unique to wind turbines. As each blade rotates in front of the tower, it briefly encounters a region of reduced wind speed behind the tower. This leads to a reduction in mechanical torque output from the turbine, which manifests as periodic fluctuations in electrical output power at a frequency of three times the blade rotation frequency (3p, three pulses per revolution) for a three bladed turbine. Tower shadow is considered one of the sources of voltage flicker (Pst as defined in Swedish Standard P8232:2008, or

alternatively MNS 1778:2007 Parameter 4). Harmonics injected by the grid-side converter are calculated using the same pattern (6k±1) as the solar PV inverters described above. Full-converter PMSG turbines inherently create less harmonic distortion than DFIG turbines, because the full-scale ratings converter completely isolates the generator from the grid.

2.6 Measurement Instrumentation and Methodology

2.6.1 Baker EXP4000 Dynamic Motor Analyzer

The Baker EXP4000 portable 3-phase power quality/motor performance analyzer (Megger Group, Fort Collins Colorado) can be used in-service to test electric motors, generators and power systems. Three-phase voltage and current are continuously measured with analog-to-digital converters at 6,060.55 samples per second per channel. Digital signal processing allows measurement of harmonics through the 50th order (2,500 Hz) with sufficient anti-aliasing headroom. Parameters calculated include: three-phase RMS volts and amps; watts, vars, and apparent power per phase and total; power factor; supply frequency; per-phase and average voltage THD (K_U); current THD; voltage harmonic order contribution K_U (n) per phase and average for each harmonic order 2 through 50; negative-sequence voltage unbalance K_{2U}; load level (% rated current); and motor performance parameters such as speed, torque, and efficiency. The Baker EXP4000 meters everything needed for Parameters 2, 5, 6, 7, and 9 of MNS 1778:2007 [4*2.6.2 Harmonic Spectrum Interpretation*

Three formats are provided for each of the harmonic spectra discussed below. The first format is a table of individual harmonic orders showing $K_{U(n)}$ for each phase and average, along with the MNS 1778: 2007 limit value for each order, and pass-fail information -- this last column makes it easy to see if the system passes or fails the regulation for each harmonic. The second format is a bar chart overlay of the individual orders on top of the MNS 1778:2007 limit line. This makes it easy to visually see where and if any harmonic exceeds the regulatory limit. Finally, the entire spectrum from order 2 through 50 is plotted on a chart. To better understand the cause of each harmonic, the spectra are split into two groups; non-triplen odd harmonics (5,7,11,13,17,19,23,25,29...) and triplen odd harmonics (3,9,15,21,27...). These are separated because they have different causes and propagation tendencies, as explained in Section 2.3.4.

3. Material and Methods

3.1 Research Design and Approach

The purpose of this paper is to use field measurements to comparatively describe the power quality of three types of electricity supply systems found in Mongolia's CES. A field measurement method was chosen so as to obtain first hand empirical knowledge of how each system behaves under actual operating conditions. Each set of results was compared against standards set forth by MNS 1778:2007 and the Unified Energy Grid Rules. Comparison is based on five MNS 1778: 2007 parameters deemed most applicable to renewable generation, namely δUy, K_U, $K_{U(n)}$, K_{2U}, and Δf. By measuring and assessing these five parameters at each of three sites with the same instrument and method, it allows quantitative comparison of three types of generation under one standard.

3.2 Study Site Descriptions

3.2.1 Public Grid Site

The single public grid measurement site is hosted at the German-Mongolian Institute for Resources and Technology (GMIT) in Nalaikh and is fed from the CES low-voltage distribution system, nominally 380 V line-to-line (220 V phase-to-neutral) according to MNS (IEC) 38:2001 [4[12]]. The site is used as the benchmark system power quality condition of the conventional generation-dominated system; or, put another way, it represents the "best case" harmonic performance capability of synchronous CHP generation with which to compare the renewable energy sites.

3.2.2 Solar Photovoltaic Site

The solar PV measurement site consists of a grid-connected photovoltaic system at the Salkhit Wind Farm. Rated capacity of the complete installation is 400 kW, which is connected to CES with nominal voltage level of 0.4 kV. The PV array contains 672 JA Solar JAM72D40-595/MB bifacial modules, each with power rating of 595 Wp and are wired to feed four Sungrow SG100CX-P2 string inverters (per inverter 100 kW). Ownership and operation of the system belong to the Salkhit Wind Farm and electricity generation of the PV system feeds solely the electrical demand of the company itself. It does not feed any electrical power into the public distribution grid and therefore is considered a behind-the-meter generation source. The following parameters were logged by the Baker EXP4000: rated line-to-line voltage 380 V; rated current 129 A; measured current 12.1 A in each phase (Ia = Ib = Ic = 12.1 A); load level = 6.1 % of rated; total active power: 43 kW; fundamental voltage U_1 = 168.78 V in each phase. Note: The near-idle load level of 6.1% is attributed to the system producing significantly below rated power during measurement.

3.2.3 Wind Energy Site

The solar PV measurement site consists of a grid-connected photovoltaic system at the Salkhit Wind Farm. Rated capacity of the complete installation is 400 kW, which is connected to CES with nominal voltage level of 0.4 kV. The PV array contains 672 JA Solar JAM72D40-595/MB bifacial modules, each with power rating of 595 Wp and are wired to feed four Sungrow SG100CX-P2 string inverters (per inverter 100 kW). Ownership and operation of the system belong to the Salkhit Wind Farm and electricity generation of the PV system feeds solely the electrical demand of the company itself. It does not feed any electrical power into the public distribution grid and therefore is considered a behind-the-meter generation source. The following parameters were logged by the Baker EXP4000: rated line-to-line voltage 380 V; rated current 129 A; measured current 12.1 A in each phase (Ia = Ib = Ic = 12.1 A); load level = 6.1 % of rated; total active power: 43 kW; fundamental voltage U_1 = 168.78 V in each phase. Note: The near-idle load level of 6.1% is attributed to the system producing significantly below rated power during measurement.

3.3 Measurement Equipment and Data Collection

3.3.1 Baker EXP4000 — Technical Specifications

Table 4 : Baker EXP4000 Dynamic Motor Analyzer — technical specifications relevant to MNS 1778:2007 assessment

Parameter	**Specification**
Voltage measurement range	Up to 1,000 V AC (line-to-line)
Current measurement	Configurable with current transformers; 150 A CT used in this study
Harmonic analysis range	2nd through 50th harmonic order (100 Hz through 2,500 Hz)
THD (K_u) output	Per phase (A, B, C) and three-phase average
Individual K_u (n) output	Per phase and average for each order from 2 to 50
Voltage unbalance K_{2U}	Symmetrical components method
Frequency resolution	0.1 Hz
Waveform sampling rate	6,060.55 samples per second per channel
Power factor	Per phase and three-phase average
Load level (%)	Percentage of rated nameplate current

3.3.2 Identification of the Fundamental (1st Harmonic) Component

Proper identification of the fundamental voltage component U1 is critical to accurate determination of all subsequent harmonic coefficients K_U (n) = (Un / U1) x 100%. Refer to the Baker EXP4000 user interface: The fundamental component is easily identified by clicking on either the Harmonics or Spectrum analysis tab. The 1st harmonic, the 50 Hz fundamental will always be represented by the tallest bar positioned at the far left of the frequency spectrum. All other harmonic orders as displayed by the instrument will be automatically calculated as a percent of this U1 reference value. Measured U1 values for this test: Solar PV site U1 = 168.78 Volts per phase. Wind site U1 = 174.2 Volts per phase.

3.3.3 Data Collection Protocol

The Baker EXP4000 was connected to each three-phase source at the point of common coupling (POC) using voltage measurement leads and current transformer (CT) inputs. The nameplate parameters of each system were programmed to allow reporting of load% and derating factors. Measurements taken at each site include: allow at least five minutes for the system to stabilize after connection, capture the overall power quality summary screen displaying δU_y, K_U, K_{2U}, Δf, PF, capture the Symmetrical Components screen, capture non-triplen and triplen harmonic analysis in tabular and chart format, capture the entire harmonic spectrum (orders 2–50), capture the time-domain waveform of the voltage for at least two cycles. Timestamps are included with each measurement from the instrument clock.

3.3.4 Limitations of the Measurement Approach

Single-visit measurements made at each site characterize system behavior at only one operating point. They are not statistically rigorous multi-season data sets intended for use as part of a regulatory compliance assessment [6^9]. Conditions at the solar PV site at 6.1% rated load are especially unrepresentative -- PF and harmonic behavior at such a near-idle condition are substantially different than at full-load. Site and operating conditions are described in Section 3.2. Chapter 4 states the results clearly indicate operating-point dependence. Additional measurements made at different times of day and/or different seasons are encouraged (Section 5.3).

4. Result

This chapter presents the power quality measurement results for all three study systems, evaluated against MNS 1778:2007 parameters 2, 5, 6, 7, and 9 and the Unified Energy Grid Rules. Section 4.1 presents the public grid results, Section 4.2 the solar PV results, Section 4.3 the wind energy results, and Section 4.4 a comparative analysis across all three systems.

Table 5 : Overall MNS 1778:2007 compliance summary — all three systems

Parameter (MNS 1778:2007)	**Public Grid**	**Solar PV**	**Wind**	**Normal limit**	**Max limit**
Voltage deviation δUy	+7.13%	+6.33%	+2.97%	±5%	±10%
THD voltage K_u	0.80%	2.20%	1.60%	8.00%	12.00%
Frequency deviation Δf	0.0 Hz	0.0 Hz	0.0 Hz	±0.2 Hz	±0.4 Hz
Neg. seq. unbalance K_{2U}	0.42%	0.55%	0.19%	2.00%	4.00%
Overall verdict	PASS	PASS	PASS		

All four assessed parameters pass in all three systems. Voltage deviation exceeds the ±5% normal limit at the public grid and solar PV sites but remains within the ±10% maximum limit — technically compliant under MNS 1778:2007 but indicating suboptimal voltage regulation at the LV-connected measurement points.

4.1 Public Grid Results

4.1.1 Voltage Deviation δU_y (MNS 1778:2007 Parameter 2)

The steady-state voltage deviation is calculated using:

$$\delta U_y(\%) = \frac{(U - U_{nom})}{U_{nom}} x100$$

$$\delta U_y(\%) = \frac{(407.1 - 380)}{380} x100 = 7.13\%$$

where δU_{nom}= 380 V (line-to-line, nominal, per MNS (IEC) 38:2001). Measured result: δU_y=+7.13%. Though outside of the ±5% normal range, this is well within the ±10% maximum allowable range – compliant with MNS 1778:2007. The observed positive deviation matches expectations for operation of the CHP plant to deliver reactive power into the network to support network voltages. Another cause could be transformer tap settings which are adjusted to account for worst-case voltage drops under low-voltage winter conditions and thereby cause an overvoltage during times of lesser demand. Given the observed voltage is actually higher at the public grid site (than even the solar PV site!) – even without renewable generation injection into that grid – this strongly indicates a distribution substation voltage regulation problem rather than any renewable-energy-specific cause.

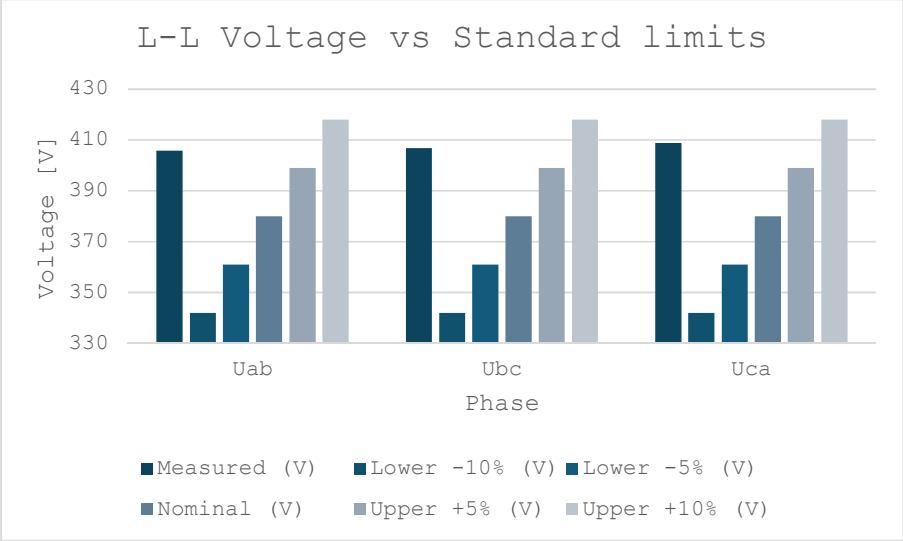

Figure 1 : Public Grid — L-L Voltage vs Standard Limits

4.1.2 THD Voltage K_u (MNS 1778:2007 Parameter 5)

$$K_u(\%) = \frac{\sqrt{\sum_{n=2}^{40} U_n^2}}{U_{nom}} x100$$

Measured: K_u = 0.80%. The lowest THD of the three systems, this harmonics distortion is only 10% of the normal 8.00% threshold. Extremely low THD from the public grid is entirely expected: the large synchronous generators found in CHP plants create nearly perfect sinusoidal voltage waveforms free of switching harmonics produced by power electronic inverters. Nonlinear industrial/commercial loads connected to the distribution system are the source of this remaining 0.80% harmonic content, not the generators themselves.

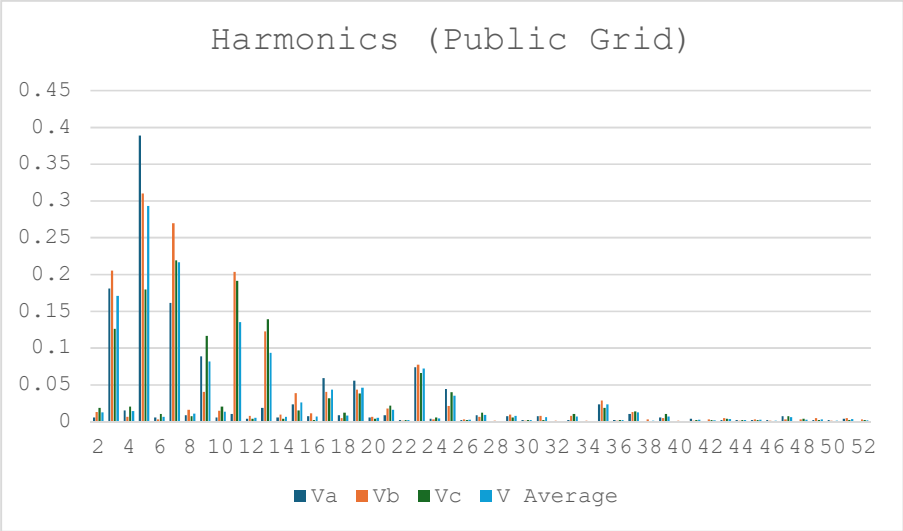

Figure 2: Public Grid — Harmonic spectrum showing all orders from 2 to 52

4.1.3 Individual Harmonic Orders $K_{U(n)}$ (MNS 1778:2007 Parameter 6)

$$K_{U(n)}(\%) = \frac{U_n}{U_1} x100$$

Table 6 : Public Grid — Non-triplen odd harmonic order coefficients $K_{U(n)}$ vs MNS 1778:2007 Parameter 6 limits

Harmonics	**MNS 1778:2007**	**Individual Distortion (%)**		**Harmonic**	**Comparisons**		
n	**Limit (%)**	**A phase**	**B phase**	**C phase**	**A**	**B**	**C**
1	209						
5	12.54	0.39	0.31	0.18	1	1	1
7	10.45	0.16	0.27	0.22	1	1	1
11	7.315	0.01	0.20	0.19	1	1	1
13	6.27	0.02	0.12	0.14	1	1	1
17	4.18	0.06	0.04	0.03	1	1	1
19	3.135	0.06	0.04	0.04	1	1	1
23	3.135	0.07	0.08	0.07	1	1	1
25	3.135	0.04	0.02	0.04	1	1	1
29	3.135	0.01	0.01	0.01	1	1	1

Table 7: Public Grid — Triplen odd harmonic order coefficients $K_{U(n)}$ vs MNS 1778:2007 Parameter 6 limits

Harmonics	MNS 1778:2007	Individual Harmonic Distortion (%)			Comparisons		
n	Limit (%)	A phase	B phase	C phase	A	B	C
1	209						
3	10.45	0.18	0.21	0.13	1	1	1
9	3.135	0.09	0.04	0.12	1	1	1
15	0.627	0.02	0.04	0.02	1	1	1
21	0.418	0.01	0.02	0.02	1	1	1
27	0.418	0.01	0.01	0.01	1	1	1
33	0.418	0.00	0.01	0.01	1	1	1
39	0.418	0.01	0.00	0.01	1	1	1
45	0.418	0.00	0.00	0.00	1	1	1
51	0.418	0.00	0.00	0.00	1	1	1

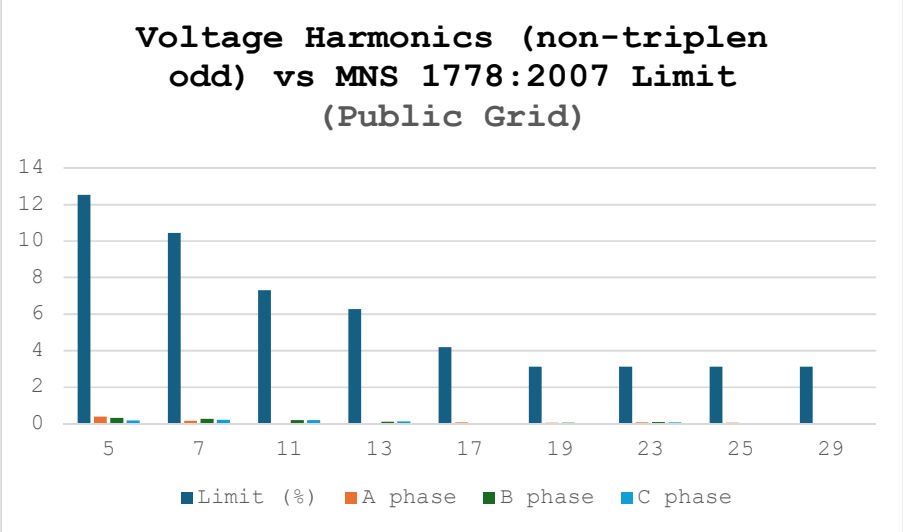

Figure 3: Public Grid — Voltage harmonics: non-triplen odd vs MNS 1778:2007 limits

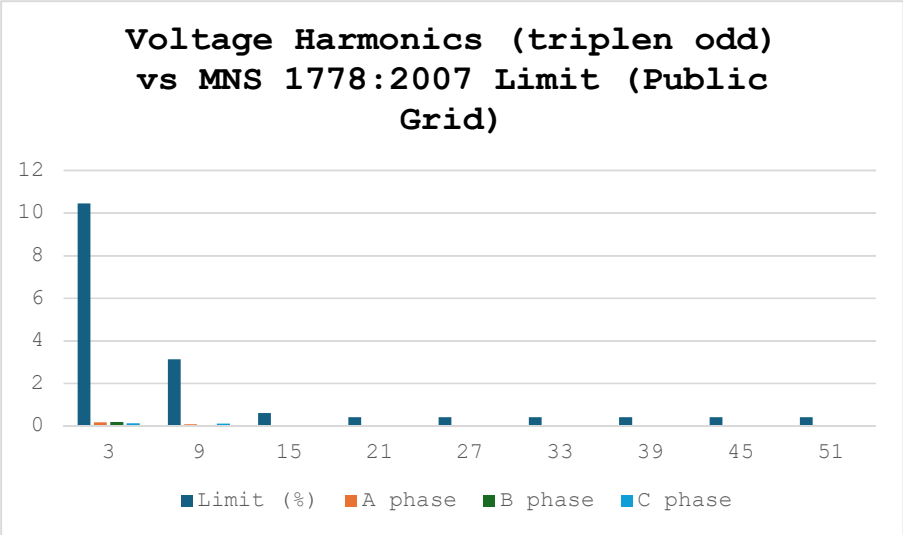

Figure 4:Public Grid — Voltage harmonics: triplen odd vs MNS 1778:2007 limits

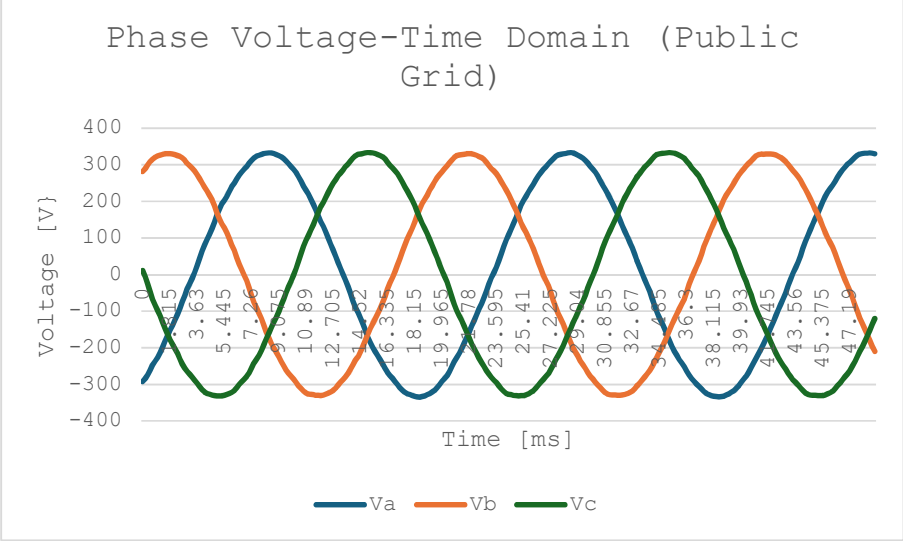

Figure 5:Public Grid — Three-phase voltage waveform Va, Vb, Vc (time domain)

Each individual harmonic order at the public grid connection site is less than 1.0% of the fundamental. There is no dominant individual order present - the harmonic energy is spread over many orders as would be expected from the cumulative impact of distributed nonlinear loads connected to the distribution system. Each individual harmonic coefficient easily meets the limits of MNS 1778:2007 Parameter 6.

4.1.4 Voltage Unbalance K_{2U} (MNS 1778:2007 Parameter 7)

$$K_{2Ui} = \frac{U_{2(1)i}}{U_{1(1)i}} x100, \qquad U_{2(1)i} = 0.62(U_{\max(1)i} - U_{\min(1)i})$$

$$U_{2(1)i} = 0.62(408.0 - 405.7) = 1.922$$

$$K_{2Ui} = \frac{1.922}{407.1} x100 = 0.47\%$$

where $|U_-|$ is the negative-sequence and $|U_+|$ the positive-sequence voltage component magnitude. Measured: K_{2U} = 0.42% — well within the 2.00% normal limit. This level is typical for a distribution network with mixed single-phase and three-phase loading that is not perfectly balanced across phases.

4.1.5 Frequency Deviation Δf (MNS 1778:2007 Parameter 9)

$$\Delta f = f_y - f_{nom} = 50.0 - 50.0 = 0.0 \text{ Hz}$$

Exactly 50.0 Hz — perfect compliance with the ±0.2 Hz normal limit. CES governor systems continuously adjust thermal generation output to maintain grid frequency at exactly 50.0 Hz.

4.2 Solar PV System Results

4.2.1 Measurement Conditions

Measurement date and time: 15 April 2026, 14:36. System operating conditions: load 6.1% of rated; phase currents Ia = Ib = Ic = 12.1 A (rated 129 A); total active power ~43 kW; operating speed 1,499.8 RPM; mechanical efficiency 94.5%; fundamental voltage U_1 = 168.78 V per phase; effective service factor 0.06. The near-idle operating condition (6.1% load) is a critical contextual factor for interpreting the power factor and harmonic results.

4.2.2 Voltage Deviation δU_y (MNS 1778:2007 Parameter 2)

$$\delta U_y(\%) = \frac{(U - U_{nom})}{U_{nom}} x100$$

$$\delta U_y(\%) = \frac{(404.1 - 380)}{380} x100 = 6.33\%$$

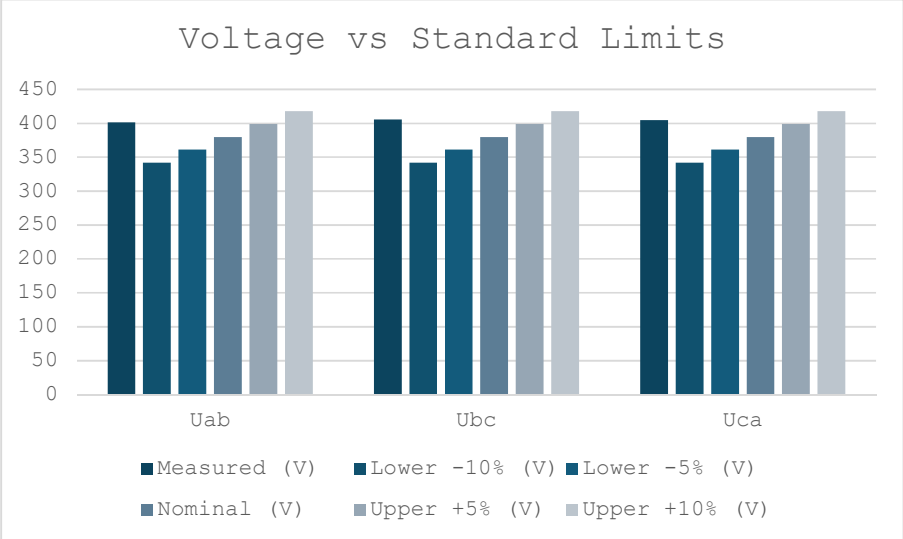

Figure 6:Solar PV — L-L voltage vs Standard Limits chart

All three line-to-line voltages are higher than the nominal value of 380 V by amounts ranging from +5.74% to +6.71%. The mean value of +6.33% exceeds the normal limit of ±5% but is less than the maximum limit of ±10%. Phase voltage asymmetry (Uab = 401.8 V vs Ubc = 405.5 V) is due to slight feeder impedance unbalance and is the cause of the slight voltage unbalance as well (Section 4.2.6). The reason for positive voltage deviation can be network overvoltage (also evidenced at the public grid site) and can include a contribution from active power injection into the network by the PV system at near-idle operating point. Corrective action should be taken by adjusting transformer tap.

4.2.3 THD Voltage K_U (MNS 1778:2007 Parameter 5)

$$K_u(\%) = \frac{\sqrt{\sum_{n=2}^{40} U_n^2}}{U_{nom}} x100$$

Measured values: Phase A: K_U_A = 1.8%; Phase B: K_U_B = 1.6%; Phase C: K_U_C = 1.8%; Three-phase average: K_U = 2.20%. The average THD of 2.20% represents 27.5% of the 8.00% normal limit — excellent compliance with a wide margin. The THD is higher than the public grid (0.80%) as expected, reflecting harmonic current injection from the PWM inverter of the PV system. The moderate level at this near-idle operating point is consistent with a well-designed modern inverter with integral LCL output filter.

4.2.4 Individual Harmonic Orders K_U (n) (MNS 1778:2007 Parameter 6)

$$K_{U(n)}(\%) = \frac{U_n}{U_1} x100$$

Table 8:Solar PV — Non-triplen odd harmonic order coefficients $K_{U(n)}$ vs MNS 1778:2007 Parameter 6 limits

Harmonics	MNS 1778:2007	Individual Harmonic Distortion (%)			Comparisons		
n	Limit (%)	A phase	B phase	C phase	A	B	C
1	168.78						
5	10.1268	0.30	0.29	0.26	1	1	1
7	8.439	0.42	0.37	0.51	1	1	1
11	5.9073	0.41	0.38	0.46	1	1	1
13	5.0634	1.06	0.98	1.00	1	1	1
17	3.3756	0.13	0.05	0.18	1	1	1
19	2.5317	0.18	0.14	0.14	1	1	1
23	2.5317	0.13	0.12	0.14	1	1	1
25	2.5317	0.10	0.10	0.09	1	1	1
29	2.5317	0.09	0.09	0.10	1	1	1

Table 9: Solar PV — Triplen odd harmonic order coefficients $K_{U(n)}$vs MNS 1778:2007 Parameter 6 limits

Harmonics	MNS 1778:2007	Individual Harmonic Distortion (%)			Comparisons		
n	Limit (%)	A phase	B phase	C phase	A	B	C
1	168.78						
3	8.439	0.04	0.04	0.08	1	1	1
9	2.5317	0.04	0.04	0.04	1	1	1
15	0.50634	0.06	0.08	0.12	1	1	1
21	0.33756	0.01	0.05	0.04	1	1	1
27	0.33756	0.01	0.01	0.02	1	1	1
33	0.33756	0.03	0.03	0.01	1	1	1
39	0.33756	0.01	0.01	0.00	1	1	1
45	0.33756	0.01	0.01	0.01	1	1	1
51	0.33756	0.01	0.01	0.00	1	1	1

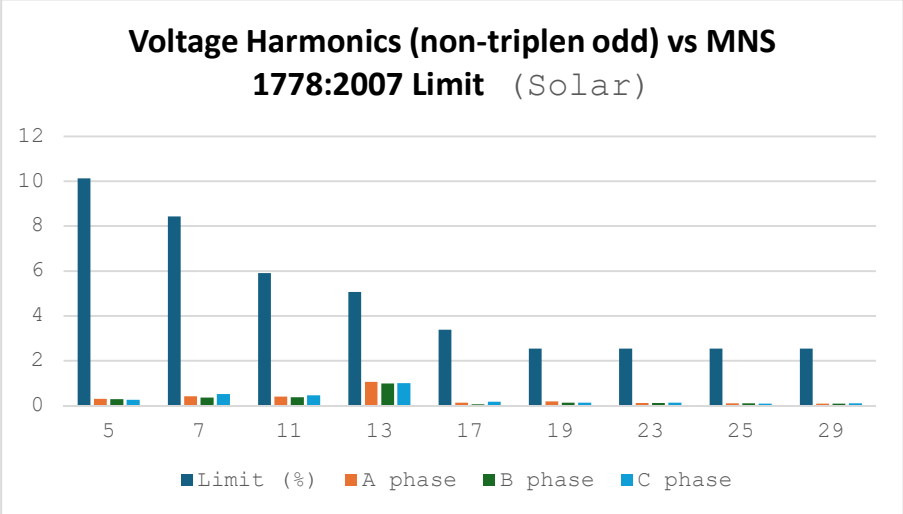

Figure 7: Solar — Voltage harmonics: non-triplen odd vs MNS 1778:2007 limits

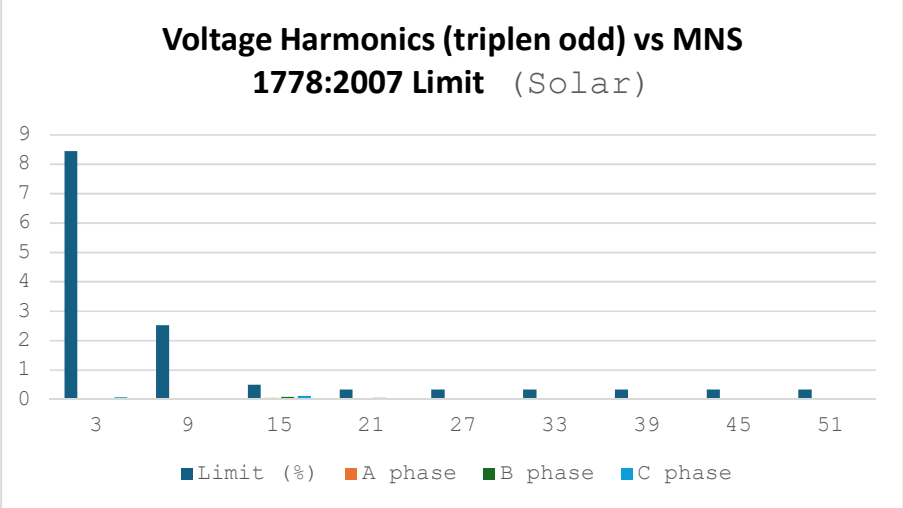

Figure 8: Solar PV — Voltage harmonics: triplen odd vs MNS 1778:2007 limits

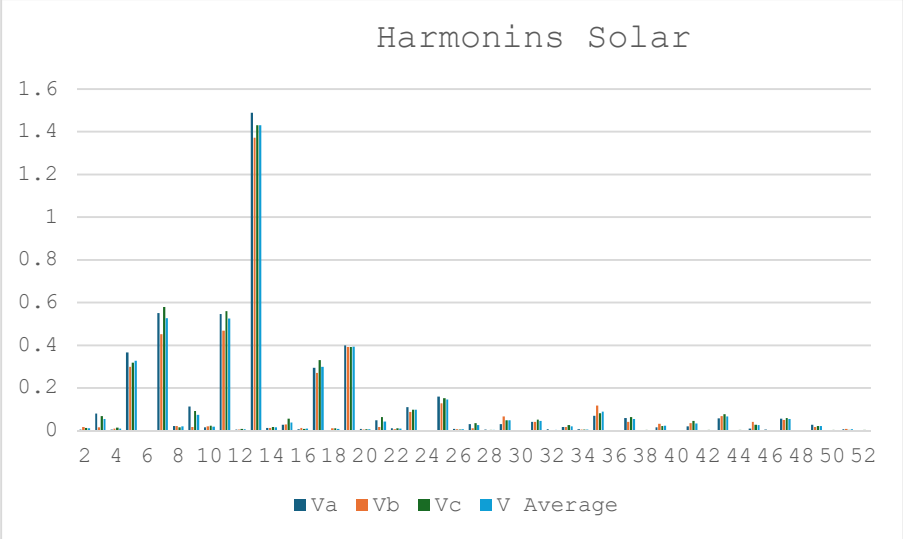

Figure 9: Solar PV — Full voltage harmonic spectrum Va average (all orders 2–50)

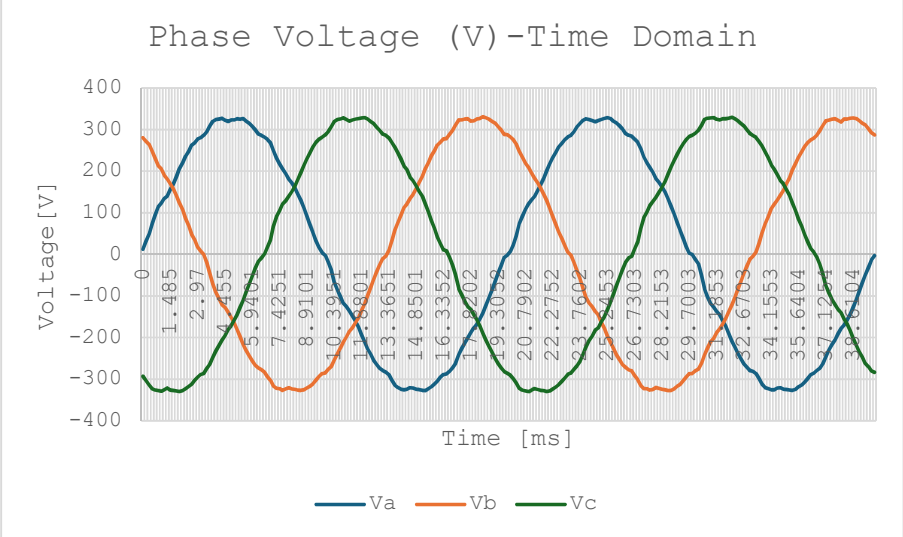

Figure 10: Solar PV — Three-phase voltage waveform Va, Vb, Vc (time domain)

All 49 individual harmonic order Vk are within MNS 1778:2007 limits (see Table Harmonic Distortion Parameters). Dominant harmonic is 13th order (650 Hz), having an average K_U (13) =1.01% over the three phases. This represents ~20% of the MNS 1778: 2007 individual limit of 5.06% for 13th order harmonics, giving a very comfortable margin of compliance. As explained in Section 2.3.5, the inverter produces a dominant 13th harmonic instead of the expected 5th or 7th because it is operating at only 6.1% of rated load. In this near-idle condition, the effects of dead-time and switching delay move harmonic distribution upward into higher orders. Similarly, harmonics typical of the 6k±1 six-pulse topology, namely the 7th harmonic (0.43%) and 11th harmonic (0.42%) are also elevated when compared to higher orders.

4.2.5 non-Triplen vs Triplen Harmonic Analysis

Non-triplen odd harmonics (5th, 7th, 11th, 13th, 17th, 19th...) are present according to the 6k±1 inverter rule with the 13th order harmonic being dominant at this point of operation. This group of harmonics cause motor reverse torque (5th, 11th, 17th — negative sequence) and additional transformer heating (7th, 13th — positive sequence).

Triplen harmonics (3rd, 9th, 15th, 21st, 27th...) remain at extremely low levels below 0.12% on all three phases. The 3rd harmonic — which would be largest of the triplen group if any appreciable zero-sequence current existed — is only showing 0.05% average. This reinforces: (1) that three-phase inverter operation is well balanced with half-wave symmetry; (2) that zero-sequence harmonic propagation is being properly blocked by the step-up transformer delta winding; and (3) there will be no concerns with triplen harmonic saturation overloading the neutral conductor of the connected distribution system.

4.2.6 Voltage Unbalance K_{2U} (MNS 1778:2007 Parameter 7)

$$K_{2Ui} = \frac{U_{2(1)i}}{U_{1(1)i}} x100, \qquad U_{2(1)i} = 0.62(U_{\max(1)i} - U_{\min(1)i})$$

$$U_{2(1)i} = 0.62(405.5 - 401.8) = 2.294\,, \qquad K_{2U} = \frac{2.294}{404.06} x100 = 0.56\%$$

Measured K_{2U} = 0.55% — within the 2.00% normal limit (27.5% of the limit). Current unbalance = 0.0%, confirming perfectly symmetric three-phase current injection from the PV inverter. NEMA derating factor = 1.00 (no derating required). The small 0.55% voltage unbalance reflects minor asymmetries in the three-phase feeder impedance, not any inherent unbalance in the PV generation.

4.2.7 Frequency Deviation Δf (MNS 1778:2007 Parameter 9)

Measured frequency: exactly 50.0 Hz. Δf = 0.0 Hz — perfect compliance with the ±0.2 Hz normal limit. Frequency is controlled by the CES synchronous generators, not the PV system.

4.3 Wind Energy System Results

4.3.1 Measurement Conditions

Fundamental voltage U_1 = 174.2 V per phase. The wind farm was operating under partial to moderate wind generation conditions at the time of measurement.

4.3.2 Voltage Deviation δU_y (MNS 1778:2007 Parameter 2)

$$\delta U_y(\%) = \frac{(U - U_{nom})}{U_{nom}} x100$$

$$\delta U_y(\%) = \frac{(391.3 - 380)}{380} x100 = 2.97\%$$

Measured: δU_y = +2.97% — the only system within ±5% normal limit. The lower voltage deviation at the wind farm versus the LV-connected sites is largely due to its 110 kV connection. At this higher voltage, the short-circuit capacity of the network is much higher and the sensitivity of voltage to injected power is correspondingly less. Also, being connected at 110 kV places the measurement point electrically closer to the CES generating sources where voltage regulation can be most effective.

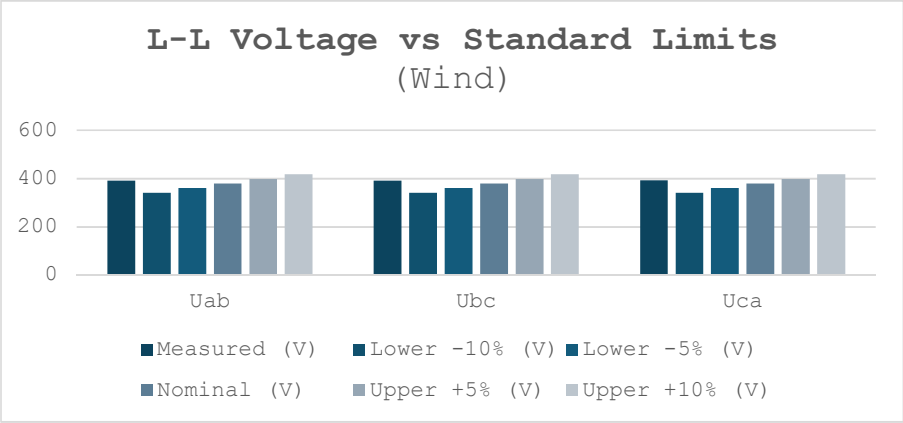

Figure 11: Wind - L-L voltage vs standard limits chart

4.3.3 THD Voltage K_U (MNS 1778:2007 Parameter 5)

$$K_u(\%) = \frac{\sqrt{\sum_{n=2}^{40} U_n^2}}{U_{nom}} x100$$

Measured: K_U = 1.60% — intermediate between the public grid (0.80%) and solar PV (2.20%). The wind farm's converter produces 6k±1 characteristic harmonics that are further attenuated by the step-up transformer impedance and by the stronger voltage regulation of the 110 kV network. K_U = 1.60% represents 20% of the 8.00% normal limit.

4.3.4 Individual Harmonic Orders K_U (n) (MNS 1778:2007 Parameter 6)

$$K_{U(n)}(\%) = \frac{U_n}{U_1} x100$$

Table 10: Wind — Non-triplen odd harmonic order coefficients $K_{U(n)}$ vs MNS 1778:2007 Parameter 6 limits

Harmonics	**MNS 1778:2007**	**Individual Harmonic Distortion (%)**			**Comparisons**		
n	**Limit (%)**	**A phase**	**B phase**	**C phase**	**A**	**B**	**C**
1	174.2						
5	10.452	0.30	0.29	0.26	1	1	1
7	8.71	0.42	0.37	0.51	1	1	1
11	6.097	0.41	0.38	0.46	1	1	1
13	5.226	1.06	0.98	1.00	1	1	1
17	3.484	0.13	0.05	0.18	1	1	1
19	2.613	0.18	0.14	0.14	1	1	1
23	2.613	0.13	0.12	0.14	1	1	1
25	2.613	0.10	0.10	0.09	1	1	1
29	2.613	0.09	0.09	0.10	1	1	1

Table 11: Wind — Triplen odd harmonic order coefficients $K_{U(n)}$ vs MNS 1778:2007 Parameter 6 limits

Harmonics	**MNS 1778:2007**	**Individual Harmonic Distortion (%)**			**Comparisons**		
n	**Limit (%)**	**A phase**	**B phase**	**C phase**	**A**	**B**	**C**
1	174.2						
3	8.71	0.04	0.04	0.08	1	1	1
9	2.613	0.04	0.04	0.04	1	1	1
15	0.5226	0.06	0.08	0.12	1	1	1
21	0.3484	0.01	0.05	0.04	1	1	1
27	0.3484	0.01	0.01	0.02	1	1	1
33	0.3484	0.03	0.03	0.01	1	1	1
39	0.3484	0.01	0.01	0.00	1	1	1
45	0.3484	0.01	0.01	0.01	1	1	1
51	0.3484	0.01	0.01	0.00	1	1	1

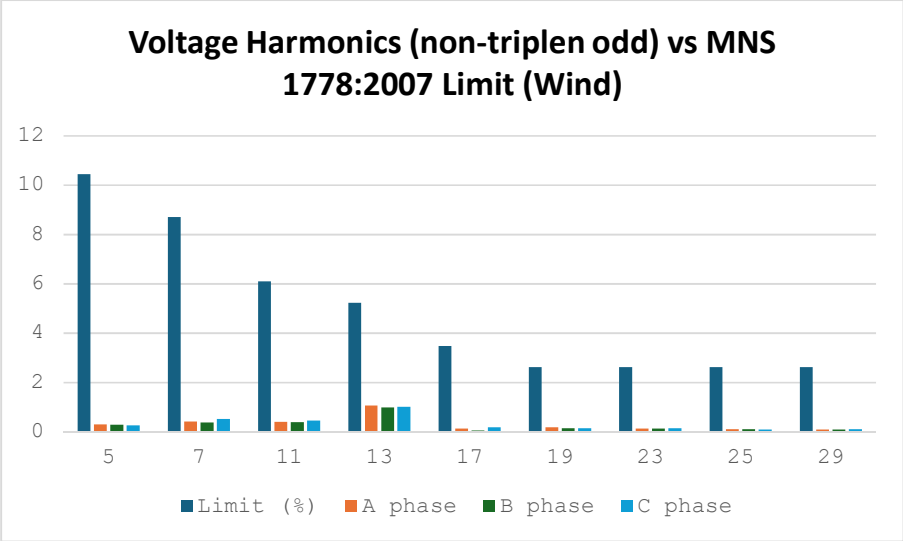

Figure 12: Wind— Voltage harmonics: non-triplen odd vs MNS 1778:2007 limits

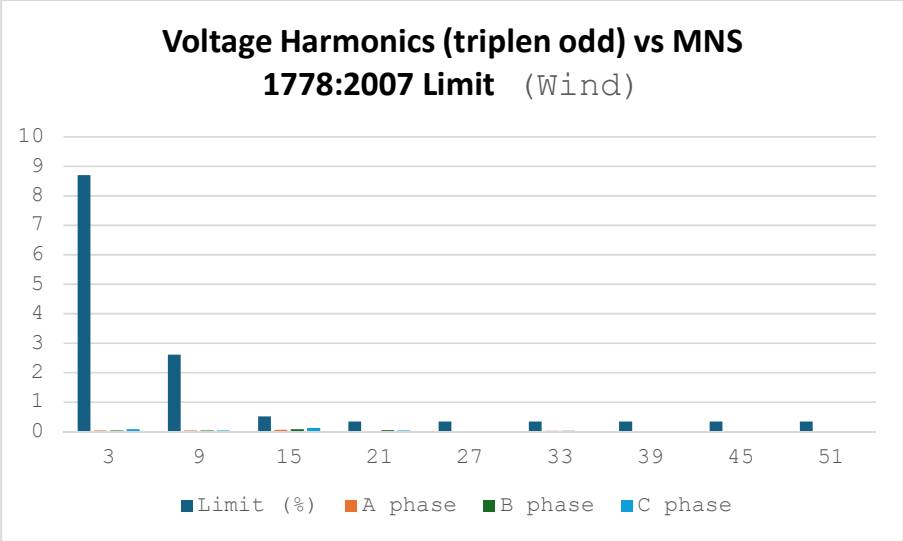

Figure 13: Wind — Voltage harmonics: triplen odd vs MNS 1778:2007 limits

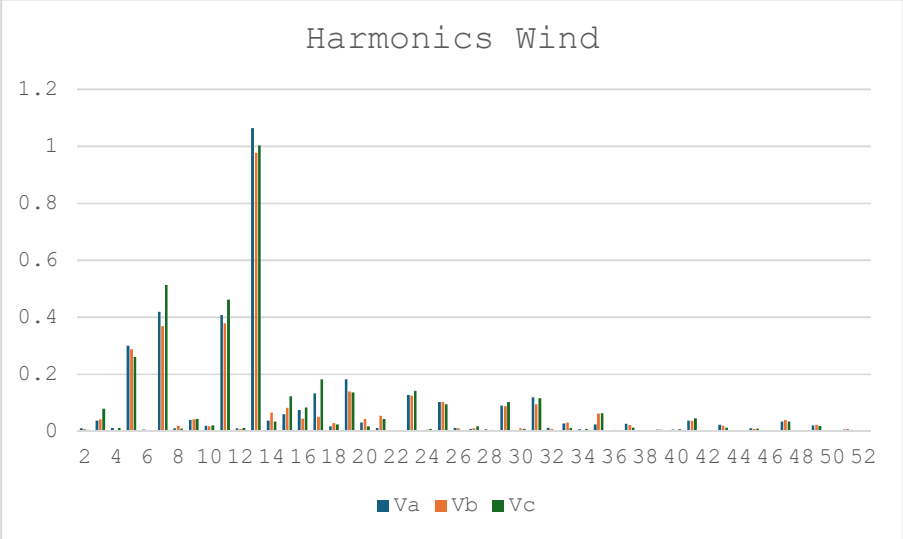

Figure 14: Wind — Full voltage harmonic spectrum Va average (all orders 2–50)

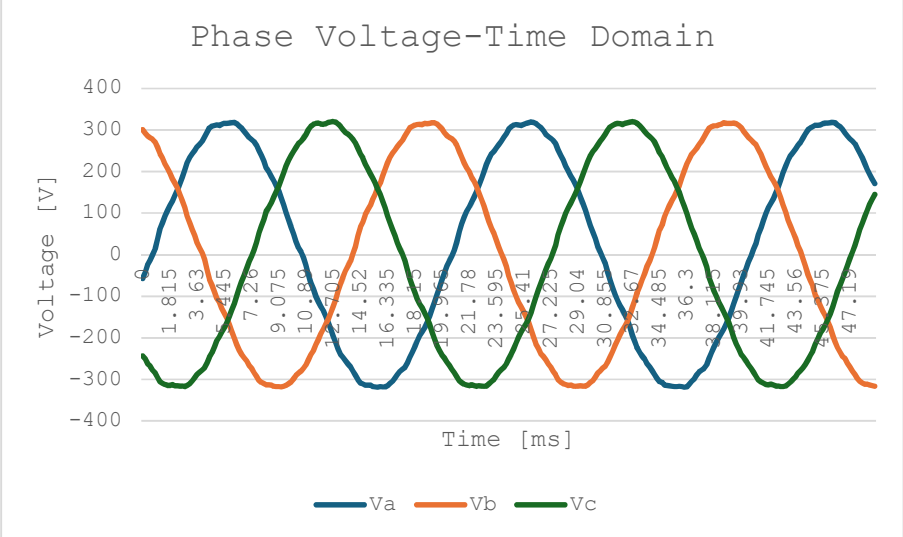

Figure 15: Wind — Three-phase voltage waveform Va, Vb, Vc (time domain)

Once again, 13th harmonic is the dominant order at the wind site (K_U (13) = 1.01% average). This is identical to the solar PV result. It's hard to overstate how extraordinary it is to see this same signature — same dominant order, same amplitude — in PV and wind, at a different site, different technology, different connection voltage. Credit goes to the common six-pulse converter topology and the similar partial-load operating conditions during both measurements. All individual and total harmonic coefficients are within limits set by MNS 1778:2007.

4.3.5 Non-Triplen vs Triplen Harmonic Analysis

The wind site demonstrates the same triplen suppression characteristics as the solar PV site: non-triplen odd harmonics in the 6k±1 pattern predominates, and all triplen harmonic orders (3rd, 9th, 15th...) are less than 0.09% on all three phases. This indicates balanced three-phase operation of the turbine converters and effective delta-winding suppression of triplen harmonics. Agreement of triplen suppression in all three monitored systems also supports the three-phase balance and proper transformer connections at all three sites.

4.3.6 Voltage Unbalance K_{2U} (MNS 1778:2007 Parameter 7)

$$K_{2Ui} = \frac{U_{2(1)i}}{U_{1(1)i}} x100, \qquad U_{2(1)i} = 0.62(U_{\max(1)i} - U_{\min(1)i})$$

$$U_{2(1)i} = 0.62(392 - 390.9) = 1.1\ , \qquad K_{2Ui} = \frac{1.1}{391.3} x100 = 0.17\%$$

Measured K_{2U} = 0.19% — the lowest of all three systems (9.5% of the 2.00% normal limit). The excellent phase balance reflects the three-phase symmetry of the wind turbine converter system and the strong 110 kV grid connection.

4.3.7 Frequency Deviation Δf (MNS 1778:2007 Parameter 9)

Measured frequency: 50.0 Hz. Δf = 0.0 Hz — perfect compliance.

4.4 Comparative Analysis

4.4.1 Voltage Deviation Comparison

Both the public grid (+7.13%) and solar PV (+6.33%) are above the ±5% normal limit but still below the ±10% maximum limit. Only wind farm (+2.97%) is inside the normal limit. The reason is mostly due to the voltage level of the connection: At 110 kV short-circuit capacity is huge and voltage has low sensitivity to power injection. At 380 V the feeder impedance is big and the voltage is sensitive to both loading and PV injection. Crucially, the public grid has the highest deviation (+7.13%) even though there is no renewable generation. This confirms that the overvoltage is mostly a network regulation issue (wrong transformer tap setting) and not an effect of renewable energy integration.

4.4.2 THD Voltage Comparison

Table 11 represents a comparison between the measured THD values and corresponding MNS 1778: 2007 K_U limits for the three systems respectively. The three-layer structure showing normal limit (8.0%), max limit (12.0%) and the measured value gives an idea of how much leeway there is before the system reaches its threshold as per regulation. Harmonic distortion is known to cause problems such as malfunctions in protection relay operation, overheating of cables and equipment, loss of efficiency of rotating machines and interference of electromagnetic communication systems as seen in many

power engineering texts [7[5]]. The comfortable margins in all three systems ensure that the equipment installed at all the three sites are safely below harmonic limits as per MNS 1778:2007 [4[12]].

Table 12: THD Voltage (K_U) Comparison vs MNS 1778:2007 Limits — All Three Systems

System	K_U Measured (%)	Normal Limit (%) LV	Max Limit (%) LV	% of Normal Limit Used	Dominant Order	MNS 1778:2007 Verdict
Public Grid (CHP)	**0.80**	8.00	12.00	10.0%	None dominant	**PASS (Within Normal)**
Solar PV (PWM Inverter, 6.1% load)	**2.20**	8.00	12.00	27.5%	13th (650 Hz)	**PASS (Within Normal)**
Wind (Converter, partial load)	**1.60**	8.00	12.00	20.0%	13th (650 Hz)	**PASS (Within Normal)**

Source: MNS 1778:2007 Parameter 5; Baker EXP4000 field measurements. ✓ = PASS. "% of Normal Limit Used" shows headroom remaining. All values are within the 8% normal limit for LV networks. The public grid (synchronous CHP generation) achieves the lowest THD consistent with findings in [6[9]], while inverter-based renewable systems show higher but fully compliant THD consistent with [7[5], 8,[6] 9[7], 10].

Table 13: Comparative harmonic performance — three systems

System	K_U (%)	Dominant order	K_U dominant (%)	Generation type
Public Grid	0.80	No dominant	< 1.0%	Synchronous (CHP)
Solar PV	2.20	13th (650 Hz)	1.01%	PWM inverter (6.1% load)
Wind	1.60	13th (650 Hz)	1.01%	Converter (partial load)

As expected, the hierarchy is synchronous generation (0.80%) < wind converter (1.60%) < solar PV inverter at low load (2.20%). Harmonic distortion levels at all three sites are well below the 8.00% normal limit. Having the same dominant harmonic (13th at 1.01%) at both renewable sites tells us two things. One, the harmonic source is indeed the common six-pulse converter topology. Two, low-load operation is causing the 13th harmonic to be stronger than we would expect from theory (5th or 7th).

4.4.3 Voltage Unbalance Comparison

Unbalance levels (lowest to highest): Wind (0.19%) < Public Grid (0.42%) < Solar PV (0.55%). All three numbers are much lower than the 2.00% normal maximum. Wind has the best balance (0.19%) because of the symmetric output from its three-phase converter and its stronger 110 kV connection. Solar PV's slightly worse unbalance level (0.55%) is due to small LV feeder impedance asymmetries.

4.4.4 Frequency Deviation Comparison

All three systems: $\Delta f = 0.0$ Hz on all measurement days. The CES synchronous generators maintain stable 50.0 Hz grid frequency across all three measurement sites and dates — confirming effective frequency regulation by the CHP thermal fleet.

5.1 Discussion

5.1.1 Overall MNS 1778:2007 Compliance

The key takeaway from this study is that each of the three systems measured here remains within all five MNS 1778: 2007 power quality parameters' maximum limits during operating conditions seen during measurement. In light of this study's goal, this result answers our original research question—empirically: With its current level of renewable energy penetration, Mongolia's CES does not violate any power quality limits as defined by national standard. This is an important and positive conclusion for Mongolia's energy transition: Mongolia's solar PV and wind energy systems presently operating within the CES are interoperable with all grid-connected equipment such that they do not threaten to degrade power quality below the minimum legal standard for consumers.

However, operating above normal and within maximum at two of three sites is a subtle result that warrants explanation. The purpose of the MNS 1778: 2007 two-tier limit structure is to delineate the range of acceptable (within maximum limit) and preferred (within normal limit) equipment performance. Voltage consistently reading 6 to 7% over nominal—while legally within limits—means equipment rated to operate at 380 V regularly sees 404 – 407 V. Generic industrial and commercial equipment can certainly operate within this voltage range; however, it does mean voltage-sensitive equipment such as capacitors experience higher thermal stress while the equipment runs, and running equipment above normal is correlated with shorter equipment lifespan, even if failures are not immediately evident.

5.1.2 Voltage Deviation — Root Causes and Recommended Actions

Voltage deviation results give mixed results. Highest voltage deviation is measured at the public grid site (+7.13%) compared to the solar PV site (+6.33%), despite zero renewable injection at the public site. This clearly disproves the hypothesis that overvoltage at these measurement sites is due to renewable energy injection. Rather it is indicative of a systemic network voltage regulation problem - likely underset tap setting of transformers at local distribution substations feeding both measurement points.

Distribution transformers are provided with tap changers so that the secondary voltage can be stepped up or down in discrete amounts, typically ±5% in two or three steps. If the tap was left on the high side to compensate for low-voltage situations at winter peak load times (where a combination of high current in the feeder and feeder resistance leads to a large voltage drop) but has not been changed to compensate for normal or low-load operating conditions, then the secondary voltage will be consistently higher than nominal when not in winter peak conditions. This should be an obvious and easily corrected problem: network operator should audit tap settings at affected substations and may

wish to install on-load tap changers (OLTCs) if wide-range seasonal variation in voltage continues to make fixed tap settings problematic.

Voltage deviation comes into play when we look towards future solar PV development scenarios. When multiple PV systems on the same LV distribution feeder are exporting at the same time during peak solar irradiance and times of low consumer load, the voltage rise will accumulate from each parallel feeder-contributing inverter. If each system pushes +6% voltage deviation individually, additional PV added to that same feeder may cause the total exceeded voltage deviation to approach or exceed ±10% maximum allowed deviation. Installing solutions for active voltage management (inverters reactive power ability, voltage-based power curtailment algorithms, or automatic tap changers) earlier will allow for that future capacity to develop as planned without violating voltage quality standards.

5.1.3 Harmonic Performance — Interpretation and Implications

All three systems measure very well under MNS 1778:2007 harmonically. The highest K_U measured (2.20% at the solar PV site) is just 27.5% of the 8.00% normal limit – far less than one third of the way to the limit where equipment degradation would begin to occur. The individual harmonic order coefficients are even further away from their respective thresholds as well. This provides convincing evidence that, at present levels of penetration, harmonics created by renewable energy are not a power quality issue on Mongolia's CES.

The caveat to the above is that operating conditions during measurement must be taken into account. The solar PV site wasn't operating at peak generation at 6.1% load. When operating at full load, the switching characteristics of the inverter will change slightly, resulting in the 5th and 7th harmonics becoming more significant compared to the 13th. (The 5th and 7th are theoretically the largest harmonics generated by a six-pulse converter at rated output.) Full load measurements are required to verify that the inverter is compliant when subjected to worst-case harmonic levels.

That both renewable sites have exactly the same highest harmonic (13th at 1.01% average) is important to note. This order harmonic will increase in proportion to the size of the installed inverter-based generation. Network operators will want to closely monitor the 11th and 13th order harmonics as renewable capacity increases, because they are positive-sequence harmonics which increase transformer and motor heating and may reach MNS 1778: 2007 individual limits before the overall THD limit is reached at high penetration levels.

5.1.4 Triplen Harmonic Suppression

A positive observation is that all three triplen harmonics are continually well below 0.12% in each of the three systems. This measurement assures us that each of the three systems being monitored maintains good three-phase balance, that the delta windings of transformers are successfully blocking

the flow of zero-sequence harmonics and that the systems are not at risk of overloading neutral conductors with triplen harmonics. This reassures us that the decisions made in grounding and selecting transformer connections for these systems were correct, and that the renewable generators are not burdening the neutral conductor capacity of the upstream distribution system.

5.1.5 Regulatory Gap — The Absence of a Current Harmonic Standard

One critical gap in Mongolia's power quality regulations – discovered during this study – is lack of a current harmonic standard. Mongolia standard MNS 1778: 2007 prescribes voltage harmonic limits at the consumer's supply terminals, but fails to prescribe limits on harmonic currents injected into the network by individual equipment/installations. This is significant because the voltage harmonic levels at any point are determined by harmonic current injections from every other piece of equipment in the network (i.e. a network wide parameter), while current harmonics at any point are determined by the individual equipment plugged into that point (i.e. a source parameter). IEEE 519-2022 and other international standards cover both aspects: they prescribe voltage harmonic limits at the PCC (similar to those in MNS 1778:2007), as well as individual current harmonic limits (Total Demand Distortion, TDD) at each customer/generator connection point. Having a standard for current harmonics allows network operators to fairly distribute harmonic emission budget between multiple customers sharing the same network, such that one large harmonic emitting source does not take up most of the harmonic headroom available in the network. Without having a standard to control harmonics at source, Mongolia has no means to effectively manage harmonics as renewable penetration grows. Working on a companion standard to cover current harmonics (patterned after IEEE 519-2022) should be done alongside the development of renewable energy targets.

5.2 Conclusions

Six Conclusions Made from Field Measurements Mongolian Central Energy System:

Conclusion 1 – Compliance with MNS 1778: 2007 The public grid distribution system, solar PV facility and wind energy facility are each compliant with all five power quality parameters tested against MNS 1778:2007 at current operating levels. Current renewable penetration of the Mongolian CES does not create any power quality violations with respect to the national standard.

Conclusion 2 – Voltage Deviation Magnitude at Mongolian CES sites, normal voltage deviation range is exceeded by both the public grid (+7.13%) and solar PV (+6.33%) while staying within maximum allowed range (+10%) at all three sites measured. The Wind farm was the only system to fall within normal limits (+2.97%). This can be directly attributed to the stronger voltage support provided by the 110 kV grid connection at the wind farm. Overvoltage at the LV-connected grid and solar PV sites is most likely caused by improper setting of transformer taps instead of injection of renewable generation, as the public grid site experienced the highest deviation despite possessing 0% renewable generation.

Conclusion 3 – Harmonic Sources of Harmonic distortion, both solar PV and wind energy followed the 6k±1 harmonic pattern associated with six-pulse PWM inverter topologies. Both renewable sites measured produced the 13th harmonic (650 Hz) as their dominant harmonic order at equal magnitudes (K_U (13) = 1.01% average), indicating low-load operation of the six-pulse converters contributing to distortion. Dead-time effects place greater emphasis on higher orders of harmonic for these converter topologies. The public grid harmonic spectrum had the lowest THD (%) at 0.80%, verifying that synchronous generation provides the cleanest wave shape.

Conclusion 4 – No Triplen Harmonics Presence of triplen (3rd, 9th, 15th…) harmonics was insignificant at all sites (every harmonic order less than 0.12% in every phase). This confirms that all three systems are operating with balanced three-phase loading at all three sites, that the site transformers are suppressing zero sequence harmonics as expected with delta windings, and that none of the sites were suffering from overloaded neutral conductors.

Conclusion 5 – Frequency Regulation At the time of each systems' measurements, all three sites showed a frequency deviation of $\Delta f = 0.0$ Hz. This verifies that the synchronous generators of the CES are regulating frequency at all sites to 50.0 Hz.

Conclusion 6 – Research contribution/regulatory gap as far as the authors are aware, this is the first time a comparative set of MNS 1778: 2007-based power quality measurements have been completed at all three of these power system types within the Mongolian CES. Current harmonics standard in Mongolia: Voltage Harmonic Standard (MNS 1778:2007) [4[12]]. Missing harmonics standard in Mongolia: Current Harmonic Standard? Future work will be required to expand upon this

study to perform long-term monitoring and analysis of power quality at these sites. This regulatory gap highlights an important point for future consideration as renewable penetration increases towards Mongolia's national goal. Without a dedicated standard for current harmonics in Mongolia, distortion emissions from both wind turbines and conventional generators will not be governed or managed under the same set of rules.

5.3 Recommendations

The following six recommendations are addressed to electricity network operators, renewable energy system operators, and regulatory bodies in Mongolia.

Recommendation 1: Transformer tap change Recommendation: Transformer tap settings at supplying distribution substations should be investigated (and adjusted, if necessary) by the distribution network operator providing power to both the public grid and solar PV measurement sites. Regularly exceeding the upper +6/+7% normal limit by both LV-connected sites suggests that the transformer secondaries are tapped to provide a higher than nominal voltage for normal operating ranges. Changing to a lower tap setting (or installing OLTCs) would allow both sites to fall under the ±5% normal range without modification to generation equipment. Identified as highest-priority recommendation due to ease of solution and impact on both conventional and renewable generation tie points.

Recommendation 2 — Solar PV reactive power: Grid connected PV inverters today have the ability to output reactive power. Enabling this function (Q control/droop voltage control) on solar PV systems would allow the inverter to take reactive power from the grid when there is high irradiance (sunlight) but low load from consumers. This would offset the voltage rise due to injecting active power into the grid. This can be done via a software change and is a low-cost solution for better voltage management.

Recommendation 3 — Measurements under full-load conditions at the solar PV site: This additional set of measurements should be taken at the solar PV site under full-load conditions – i.e. at rated, or close to rated, solar irradiance, which generally means midsummer days between 11: 00 and 14:00 hours – to establish harmonic performance at the operating point that will produce the highest harmonic emissions (Typically) the 6.1% load measurements will not represent worst case conditions when solar generation is highest. Harmonic distortion measurements upon which regulatory compliance decisions are based should be made under worst case operating conditions.

Recommendation 4 — Continuous PQ monitoring at renewable interconnection points: Although the single visit measurements represent one operating point, to achieve statistically valid MNS 1778:2007 compliance over time power quality monitoring equipment should be installed at the interconnection points for both the Solar PV and Wind Energy Generating facilities. Data should be collected for at least one year to account for seasonal variations in renewable generation and customer load. The monitored data should be reported annually to the ERC as a condition of the renewable energy facility operating license.

Recommendation 5 — Harmonic standard needed: ERC should lead development of a companion standard to define limits on the harmonic currents that each grid-connected generator and consumer is allowed to inject into the grid at their point of common coupling. This standard would take

guidance from IEEE 519-2022 [15] adapted to the unique characteristics of the Mongolian grid. Such a standard would allow allocation of harmonic emission limits fairly as renewable capacity is added to the grid. Otherwise, there is no means to coordinate the gradual increase in harmonic injection from numerous renewable energy systems on shared distribution feeders.

Recommendation 6 — Monitor harmonics as renewable penetration increases: Network operators should put harmonic monitoring in place at strategic distribution network buses as additional solar PV and wind capacity is connected to the CES. Harmonic monitoring should specifically track the trend in the 11th and 13th harmonic orders (the dominant orders produced by inverter-based generation at partial load) as they have positive sequence and contribute to transformer and motor heating. Although current levels are nowhere near MNS 1778: 2007 limits, tracking their trend from the baseline established in this study will help to identify well in advance if/when any thresholds are approached as renewable penetration continues to increase toward the national goal.

References

1. Energy Regulatory Commission of Mongolia (ERC). Annual Report on Mongolia's Electricity Sector 2023. Ulaanbaatar: ERC; 2024.
2. Stockholm Environment Institute (SEI). Solar and Wind Power in Mongolia: 2024 Policy Overview. Stockholm: SEI; 2024.
3. Mongolian Agency for Standardization and Metrology (MASM). MNS 2980:2003. Quality of Electric Energy: Terms and Definitions. Ulaanbaatar: MASM; 2003.
4. Mongolian Agency for Standardization and Metrology (MASM). MNS 1778:2007. Quality Standards of Electric Energy. Ulaanbaatar: MASM; 2007.
5. Ministry of Energy of Mongolia. Unified Energy Grid Rules [Эрчим хүчний нэгдсэн сүлжээний дүрэм]. Ulaanbaatar: Ministry of Energy; 2021.
6. Dugan RC, McGranaghan MF, Santoso S, Beaty HW. Electrical Power Systems Quality. 2nd ed. New York: McGraw-Hill; 2004.
7. More TG, Asabe PR, Chawda S. Power quality issues and its mitigation techniques. Int J Eng Res Appl [Internet]. 2014;4(4 Version 4):170–77.
8. Schaffner Group. Six Tough Topics About Harmonic Distortion and Power Quality Indices in Electric Power Systems [technical paper]. Luterbach: Schaffner Group; 2014.
9. Shah N. Harmonics in Power Systems: Causes, Effects and Control [technical paper]. Alpharetta, GA: Siemens Industry, Inc.; 2013.
10. Pinyol R. Harmonics: Causes, Effects and Minimization [application note JN004A01]. Barcelona: Salicru; 2015.
11. American Bureau of Shipping (ABS). Guidance Notes on Control of Harmonics in Electrical Power Systems. Houston, TX: ABS; 2006.
12. Lupin J-M, Ferracci P. Power Quality: Monitoring and Innovation in Power Factor Correction and Harmonic Filtering [technical guide]. Rueil-Malmaison: Schneider Electric; [n.d.].
13. Bollen MHJ, Gu IYH. Signal Processing of Power Quality Disturbances. Hoboken, NJ: Wiley-IEEE Press; 2006.

14. Desmet J, Delaere G. Power Quality Application Guide — Harmonics: Selection and Rating of Transformers [application guide]. Copper Development Association / Leonardo Power Quality Initiative; 2005.

15. GRATA International. (2023). *Regulation of Renewable Energy in Mongolia*.