Power Quality of a Battery Energy Storage System (BESS) with Nonlinear Load

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1 INTRODUCTION

Power quality is a broad area that describes how well the electrical power system is operating. Power quality impacts the reliability, stability and efficiency of power system. It generally considers any non-ideal operation that exists momentarily or continuously in the power system.

Power quality includes the quality of the voltage (dips, swells, interruptions, waveform shape and noise), the quality of the current (surge/inrush, waveform shape and noise), and how efficiently energy is flowing through the system. Ideally, the voltage and current waveforms should both be sinusoidal and in phase (aligned with each other), such that maximum useful power flow is achieved. Power factor describes how much of the voltage and current is producing useful (active) power with respect to the maximum it could be delivering. For linear loads that only have resistance, capacitance and inductance (no switching or power electronics), the voltage and current waveforms remain sinusoidal and only the phase/alignment of the waveforms changes. When the voltage and current waveforms are not in phase, the power factor drops below 1.

Nonlinear loads use semiconductor switches and actively switched power electronics to operate. Typical examples are phone chargers, computer power supplies, inverter driven motors and appliances like air conditioners, rooftop solar inverters, electric vehicle chargers, and battery energy storage systems! Nonlinear loads may distort the current and voltage waveforms, producing non-sinusoidal waveforms full of noisy switching components (causing interference) and harmonics. Distorted voltage and current waveforms reduce the amount of real/useful power that can flow for a given voltage and current rating, can cause addition heating and power loss in power system components (e.g. transformers), can affect the stability or voltage regulation of the power system, and can cause other devices to operate less efficiently, operate incorrectly and even prematurely age.

As the power system and consumer devices evolve, more and more nonlinear loads are being used on the low voltage part of the grid (where most customers are connected). Higher power nonlinear devices are becoming more common, including inverter controlled appliances, solar PV inverters, domestic energy storage and electric vehicle chargers. As this trend continues, the risk of power quality issues increases. A better understanding of power quality at the low voltage level is required to ensure all these devices can coexist without impacting each other or the grid, and can operate in a way that ensures the efficient flow of energy through the power system.
2 MICROGRID ISLAND WITH NONLINEAR LOAD

The Australian Energy Storage Knowledge Bank’s (AESKB) Mobile Test Platform is a portable microgrid system with embedded battery energy storage system. The system uses an inverter to control the flow of energy between the battery and the microgrid generation bus. To investigate the behaviour of the system with nonlinear loads, the Mobile Test Platform was deployed in Thebarton South Australia, per Figure 1.

![Diagram of Mobile Test Platform configuration in Thebarton South Australia](image)

For the islanded tests, the diesel generator and load bank were disconnected, leaving only the six wind tunnel fans. Each fan is controlled by a variable speed drive (VSD), with a total power rating under 800kW. For this test, the fans are only operated at a low speed, resulting in lower power consumption. Low power operation is also where the worst power quality and efficiency of a device typically appears.

Each variable speed drive is a nonlinear load, consisting of a three-phase rectifier that converts the power back to DC, followed by a three-phase inverter that converts the DC back to three phase AC. Each fan’s speed is controlled by the frequency of the three-phase voltage applied to the fan motor. Hence the VSD uses rapidly switched DC to produce an AC voltage at different frequencies.

To capture the detailed operation of the system, the Mobile Test Platform includes an embedded data logging system that performs advanced multi-channel power quality analysis, with the ability to record high bandwidth raw waveforms. For the islanded test with VSD loads, the analysis in this report focuses on the inverter AC measurements recorded at nodes E and F in Figure 1.
2.1 DISTORTION POWER

With the diesel generator and load disconnected, the inverter was started in islanding mode. The wind tunnel variable speed drives where turned on, then the wind tunnels fans run at low power for just under 10 minutes.

Figure 2: Power during islanded operation of the wind tunnel fans, aggregated over 3 second intervals (approx. 150 cycles per point).

Figure 2 shows the power aggregated over 3 seconds, where each point represents approximately 150 electrical cycles. The power analyser module that produces these measurements uses a method based on IEC 61000-4-30, where the incoming voltage and current waveforms are dynamically resampled to achieve a sample rate locked to the power system frequency (i.e. the number of sample points in one cycle is kept constant, and the sample rate varies with the power system frequency). The baseline analysis is performed at a rate of 5Hz (nominal), or 10 electrical cycles per reporting time/measurement. The 3 second aggregation has the effect of averaging the measurements over each 3 second period.

Viewing the 3 second aggregated data, the microgrid island appears to be functioning smoothly. However, this is not case. Using the underlying higher reporting rate data, a very different picture is seen.

Figure 3: Power during islanded operation of the wind tunnel fans, sampled at 5Hz (10 cycles per point).
Figure 4: Battery power during islanded operation of the wind tunnel fans, sampled at 5Hz (10 cycles per point).

Figure 3 shows the power, sampled at 5Hz, or every 10 electrical cycles. When recording at this faster rate, it is clear how the power delivered is not smooth or constant. Instead the power delivered is varying quite rapidly and erratically. Figure 3 includes a breakdown of the power components: apparent power $S$, active power $P$, reactive power $Q$ and distortion power $D$. In the plot, the apparent power is larger than the active power, with the difference mainly coming from the distortion power (the reactive power remains quite low).

The active and reactive powers are calculated by the data logging system using a method first devised by Budeanu in 1927. This method breaks the voltage and current into a set of frequencies, then calculates the active and reactive power at each frequency (up to a limit of 2500Hz, or the 50th harmonic in this case). The sum of each respective set of active and reactive powers is the total active power $P$ and reactive power $Q$.

In the ideal case of sinusoidal voltage and current waveforms, the power triangle can be used to show the relationship between active, reactive and apparent power. This is described using the equation $S = \sqrt{P^2 + Q^2}$. However, in the case of non-sinusoidal or distorted waveforms, this relationship breaks down and the terms do not add up. Budeanu’s solution was to reconcile this with a new term: distortion power $D = \sqrt{S^2 - P^2 - Q^2}$. Instead of forming a power triangle, these terms now form a power tetrahedron.

Although distortion power reconciles the relationship between $P$, $Q$ and $S$ for non-sinusoidal waveforms, the resulting reactive power no longer has much meaning as it does for the sinusoidal case. A reactive power of zero no longer means a power factor of 1, and consequently trying to reduce the reactive power to zero using capacitors or inductors may not be able to improve the power factor. Hence reactive power is no longer a useful parameter when trying to improve the power factor of a system.
Figure 6 shows the power factor ($PF = P / S$) and the fundamental power factor ($\cos \phi = PF_1 = P_1 / S_1$). $\cos \phi$ uses the fundamental active and apparent powers $P_1$ and $S_1$, which represent are calculated by extracting the 50Hz sinusoidal component in the waveforms. In Figure 6, $\cos \phi$ shows that most of the fundamental power is active/useful power. However, the overall power factor is much lower, resulting from the non-fundamental components of apparent power, which represent instantaneous energy flow at a frequency other than 50Hz. This is a problem for most devices, which can only use the power delivered at the fundamental frequency. For example, higher frequency power applied to a motor doesn't provide mechanical power, and instead is wasted as heat.

2.2 NON-SINUSOIDAL POWER ANALYSIS AND IEEE STANDARD 1459

To better describe a power system with non-sinusoidal operation, different techniques are required to provide more meaningful analysis. The IEEE standard 1459 provides some guidance. Despite the data logger’s real time analysis using an IEC 61000-4-30 method, there is enough information contained in the data set to perform additional IEEE 1459 non-sinusoidal analysis.

First the voltage and currents are broken into their fundamental and harmonic components. The harmonics components are everything that isn’t the fundamental. Because the inverter is being analysed as a complete three-phase system, the effective values are calculated. The effective values of voltage, current and apparent power were first introduced by Buchholz in 1922 and Goodhue in 1933, and can better handle the case of unbalanced and non-sinusoidal systems.
Figure 7: Effective voltage components during islanded operation of the wind tunnel fans. $V_e$ is the effective voltage of all three phases, $V_{e1}$ is the effective fundamental voltage, and $V_{eh}$ is the effective nonfundamental voltage.

Figure 8: Closer view of the effective voltage and effective fundamental voltage.

Figure 9: Effective current components during islanded operation of the wind tunnel fans. $I_e$ is the effective current of all three phases, $I_{e1}$ is the effective fundamental current, and $I_{eh}$ is the effective nonfundamental current.

Figures 7 and 8 show that the fundamental effective voltage is close to the effective voltage, with a low nonfundamental voltage component indicating a small harmonic component. Figure 9 shows the effective current components, with a much larger nonfundamental component, indicating the presence of many more harmonics compared to the voltage.
Figure 10: Power components during islanded operation of the wind tunnel fans. $P$ is the total active power, $P_1$ is the fundamental active power, and $P_H$ is the nonfundamental active power.

The active power can also be broken down into fundamental and nonfundamental components. In Figure 10 this shows that almost all active power is fundamental active power, with very little harmonic power flowing. Harmonic power is active power (net energy transfer) that happens at a frequency other than the fundamental. Despite being actual energy (not energy that flows back and forth), most power devices cannot make use of it and it is wasted as heat.

Figure 11: Nonactive power during islanded operation of the wind tunnel fans, derived from the effective apparent power and the active power.

The power triangle relationship can also be used for the IEEE 1459 method, but in this case the result is the nonactive power $N$ ($N = \sqrt{S_e^2 - P^2}$). This represents all the fundamental and nonfundamental, nonactive components. In the special case of only pure sinusoidal waveforms, the value of $N$ is equal to the traditional reactive power $Q$. The plot of $N$ in Figure 11 should be contrasted with the plot of $Q$ in Figure 3.
Figure 12: Apparent power components during islanded operation of the wind tunnel fans. $S_e$ is the effective apparent power, $S_{e1}$ is the effective fundamental apparent power, and $S_{eN}$ is the effective nonactive apparent power.

The effective apparent power can also be decomposed into fundamental and nonfundamental components. The nonfundamental apparent power $S_{eN}$ can further be decomposed into three components:

1. Effective current distortion power $D_{el}$, produced by current harmonics and the fundamental voltage component.
2. Effective voltage distortion power $D_{eV}$, produced by voltage harmonics and the fundamental current component.
3. Effective harmonic apparent power $S_{eH}$, produced by voltage harmonics and the current harmonics.

Figure 13: Nonfundamental apparent power components during islanded operation of the wind tunnel fans. $D_{el}$ is the effective current distortion power, $D_{eV}$ is the effective voltage distortion power, and $S_{eH}$ is the effective harmonic apparent power.

Figure 13 shows these three components, each produced from different combinations of the effective fundamental and nonfundamental voltage and current. This immediately provides insight into the source of the lower power factor and high nonactive apparent power, showing the nonfundamental apparent power is dominated by current distortion power produced by the current harmonics of the variable speed drives. In comparison, there is a much smaller amount of voltage distortion power, and even lower harmonic apparent power.
The effective harmonic apparent power can be used with active harmonic power to find the effective harmonic distortion power ($D_{eh} = \sqrt{S_{eh}^2 - P_{H}^2}$). In this case, the active harmonic power was very low, resulting in the effective harmonic apparent power being dominated by harmonic distortion power.

![Figure 14: Effective harmonic distortion power $D_{eh}$, effective harmonic apparent power $S_{eh}$, and harmonic active power $P_{H}$ during islanded operation of the wind tunnel fans.](image)

IEEE 1459 uses the same definition of power factor and $\cos \phi$ fundamental power factor, producing the same plot as shown in Figure 6. In addition to power factor, the harmonic pollution factor is also defined, being equal to the effective nonactive apparent power divided by the effective fundamental apparent power ($S_{eN}/S_{e1}$). This value should be ideally as low as possible.

![Figure 15: Harmonic pollution factor during islanded operation of the wind tunnel fans.](image)

The fundamental power factor $\cos \phi$ is useful for looking at the how efficiently power is flowing in each phase at the fundamental frequency. In a three-phase system the instantaneous power must also flow in the correct phase order. The Instantaneous power in each phase pulsates at twice the system frequency, and each phase pulsates at evenly spaced times and in the correct phase sequence (phase A, B, C, then repeating back to phase A). In ideal conditions, the total power flow of all phases adds up to a constant. If only some of the power flows in the correct phase order, then a load may not be able to use all the power, despite the power factor of individual being phases is high.
The technique of symmetrical components can decompose the three-phase system into three sequence components. The positive sequence component represents how much of a signal has the correct phase order/sequence. The other two components are the negative sequence (reverse phase order) and the zero sequence (power pulsating at the same time with no phase order). Using the fundamental positive sequence active power component $P_1^+$ and the fundamental positive sequence power component $S_1^+$, the fundamental positive sequence power factor can be evaluated: $\text{PF}_1^+ = \frac{P_1^+}{S_1^+}$. This is similar to $\cos \phi$ but further isolates the fundamental quantities to the power producing positive sequence component. Figure 16 shows $\text{PF}_1^+$ compared to $\cos \phi$.

![Power Factor](image)

*Figure 16: Fundamental positive sequence power factor during islanded operation of the wind tunnel fans.*

![Load Unbalance](image)

*Figure 17: Load unbalance $S_{ul}^+$, plotted alongside the effective fundamental apparent power $S_{ef}$ and fundamental positive sequence apparent power $S_1^+$, during islanded operation of the wind tunnel fans.*

Load unbalance represents the portion of fundamental apparent power that is not a part of the fundamental positive sequence. This represents apparent power flow resulting in the three-phase system not being balanced (the phases are not operating in an identical fashion). Figure 17 shows the load unbalance in red. For the case of the variable speed drives with fan loads, there is some unbalance, particularly as the fans increase in speed.

By dividing the load unbalance by the fundamental positive sequence apparent power, the load unbalance factor can be produced.
For more context, the load unbalance factor can be compared to the IEC 61000-4-30 method of unbalance, which compares the negative and zero sequence components to the positive sequence. In a balanced system, both the negative and zero sequence components of a signal are zero. In the wind tunnel test, there were no zero sequence components in the voltage and current, leaving only positive and negative sequences. The $u_2$ unbalance calculated from these values is shown below in Figure 19. This shows that the voltage is balanced, but the current has a large amount of unbalance.

Figure 18: Load unbalance factor during islanded operation of the wind tunnel fans.

Figure 19: $u_2$ Unbalance for voltage and current, during islanded operation of the wind tunnel fans.
Figure 20: Fundamental positive sequence active power $P_{1+}$ and effective apparent power $S_e$ during islanded operation of the wind tunnel fans.

Figure 20 shows a summary of the power in the microgrid island with non-linear VSD load. The fundamental positive sequence active power $P_{1+}$ represents the total useful, real power flowing from the inverter to the variable speed drives at the 50Hz power system fundamental frequency and in the correct phase sequence. This represents the usable active power for a typical three phase load. For contrast, the effective apparent power $S_e$ shows the total apparent power of the three phase system, and represents the actual loading on the power system, in this case the islanded microgrid’s inverter.
3 Harmonic Components and Total Harmonic Distortion

When dealing with non-ideal and distorted signals, the total harmonic distortion (THD) is a useful measurement for describing how distorted the waveform is. THD is calculated as a ratio of nonfundamental voltage (or current) to fundamental voltage (or current): \( THD_V = \frac{V_H}{V_1} \) and \( THD_I = \frac{I_H}{I_1} \). Current and voltage both use the same formulas for THD. There are two methods for calculating THD, arising from the two methods of calculating the nonfundamental term:

1. Sum method, used by IEC 61000-4-7, \( THD_V = \frac{V_H}{V_1} = \sqrt{\sum_{h=2}^{\text{max}} V_h^2} \). 
   a. Note: this method is also included in IEEE standard 1459, but the summation also includes the DC term \( V_0 \).

2. Difference method, used by IEEE standard 1459, \( THD_V = \frac{V_H}{V_1} = \sqrt{\frac{V_2^2 - V_1^2}{V_1^2}} \).

The sum method simply compares the sum of all harmonics (but excluding the fundamental) to the fundamental. The difference method takes the total RMS value minus the fundamental and compares it to the fundamental. Both methods then express the result as a percentage (by scaling by 100). There are two main differences between these approaches:

- The sum method only includes harmonic components (multiples of the 50Hz system frequency), and does not include components in between these frequencies (no interharmonic components).
- The sum method only includes harmonic components up to a maximum harmonic, typically the 50th (which is 2500Hz for a 50Hz power system).

In contrast, the difference method captures everything that isn’t the fundamental, including interharmonics and components above the 50th harmonic. It’s also simpler to calculate because it doesn’t require the waveform to be deconstructed into frequency components.

![Figure 21: Voltage THD (difference method), during islanded operation of the wind tunnel fans.](image-url)
Figures 21 and 22 show the THD for voltage and current respectively, calculated using the difference method. The voltage THD is sitting at about 12.5%, but the current THD is over 75%. There is a lot of current distortion, and the current waveform is more distorted than the voltage waveform.

Figures 23 and 24 show comparisons between the sum and difference method, for voltage and current respectively. The voltage THD values are very different, with the sum method showing a much lower THD below 5%, compared to 12.5% for the difference method. This discrepancy is caused by nonharmonic components in the voltage waveform that are not captured by the sum method. This is to be expected, considering the inverter produces a lot of switching noise at a frequency above the 50th harmonic, and at frequencies not synchronised to the power system frequency (hence not registering as harmonics but interharmonics).

NOTE: although the voltage waveform appears to have high distortion, this is only the case at the inverter terminals. The isolation transform filters the voltage waveform, and the grid only sees a clean voltage with very low distortion.
Figure 24: Comparison of the THD sum and difference methods for the same waveform (Phase A current), during islanded operation of the wind tunnel fans.

Figure 24 shows that both THD methods produce a similar result. This suggests that most of the distortion is from harmonics of the fundamental power system frequency (multiples of 50Hz). The difference method has a wider spread of values and more noise, indicating that it is also detecting interharmonic and noise components.

Figure 25 shows all voltage harmonics, from the 0\textsuperscript{th} (DC) to the 50\textsuperscript{th} (2500Hz). These are calculated as subgroups, using the method in IEC 61000-4-7. This method breaks the signal into 501 frequency components, each separated by 5Hz and each 5Hz in width. The harmonic subgroup is calculated from 3 frequency bins (15Hz total width), centred on each harmonic. The subgroup allows detection of harmonics that aren’t sitting exactly on a multiple of the power system frequency, preventing these components from being accidently excluded.

Figure 26 shows the voltage interharmonics, which represent anything that isn’t a harmonic and consequently not captured by the harmonics subgroups. Using the method in IEC 61000-4-7, the interharmonics are calculated from all the frequency bins between the harmonic subgroups. In this case, 7 bins are used with a width of 35Hz, centred between harmonic subgroups. The 0\textsuperscript{th} interharmonic subgroup represents components between 7.5Hz to 42.5Hz, the 1\textsuperscript{st} represents components between 57.5Hz and 92.5Hz, all the way up to the 49\textsuperscript{th} interharmonic which represents components between 2457.5Hz and 2492.5Hz.

Recording harmonic and interharmonic data consumes a lot of space. In this case, recording both requires 101 channels of data per input channel. Three voltages and three currents require a total of 606 channels to capture this information. This is impractical for long term data logging, hence measures like THD are preferred, where the harmonic information can be condensed into 1 or 2 channels per waveform channel. For this test of the microgrid island with variable speed drive loads, the embedded data logger was recording harmonics aggregated over 3 second intervals (not at 5Hz).
Figure 25: All voltage harmonic subgroups, during islanded operation of the wind tunnel fans.

Figure 26: All voltage interharmonic subgroups, during islanded operation of the wind tunnel fans.

The voltage harmonics in Figure 25 show the fundamental being the largest component, with all other harmonics being very small. Hence the sum method of THD produces a low result. Figure 26 also shows minimal interharmonics, with all having a magnitude of ~1V or less. In this case the difference between Sum and difference

Figure 27: All current harmonic subgroups, during islanded operation of the wind tunnel fans.
The current harmonics in Figure 27 show a large fundamental and large 5th and 7th harmonic components. All other harmonics are small. Figure 28 shows that a large number of interharmonics are present, with a magnitude below 10% of the fundamental. The largest two interharmonics are the first two components, representing current with a frequency just below and just above the 50Hz microgrid frequency. These interharmonics are expected, considering the variable speed drives are produce a variable frequency that is not synchronised to the microgrid’s 50Hz frequency, and operates well below 50Hz when the fans run at low speed. The presences of interharmonics explains the small differences between the THD sum and difference methods, but because the interharmonics are small compared to the harmonics, both THD methods achieve a similar result.
4 **Voltage Waveforms and RMS Measurement**

The embedded data logging system includes three methods of root-mean-squared (RMS) measurement, used to determine the magnitude of the voltage and current waveforms. Two are performed in the time domain: RMS (TD) and Fundamental RMS (TD).

The RMS (TD) measurement is the conventional RMS measurement (square root of the average of all squared waveform data points) and is performed over each waveform block of 10 electrical cycles (approx. 200ms length).

The fundamental RMS measurement first decomposes the waveform into two fundamental components: one in phase with the reference voltage (the inverter’s phase A is the reference), and the other 90 degrees out of phase. This is the fundamental phasor. The RMS of the phasor’s instantaneous magnitude is then measured, over the waveform block of 10 cycles.

The third method (labelled “RMS” in the figures below) is the RMS of all frequency components used for harmonic analysis. This RMS is performed from the 0th (DC or 0Hz) bin up to the 500th bin (2500Hz or 50th harmonic).

Figure 29 shows the three RMS values for the inverter’s phase A current waveform. The RMS (TD) and RMS values are effectively the same, and the fundamental RMS (TD) measurement is lower. This result is expected because of the presence of large current harmonics that are captured by both the RMS and RMS (TD) measurements.

![Figure 29: Comparison of current RMS measurements, during islanded operation of the wind tunnel fans.](image)

Figure 30 shows the three RMS values for the inverter’s phase A voltage waveform. Unlike the current measurement, the RMS (TD) and RMS values are different, but the RMS and fundamental RMS (TD) measurements are similar. This result is caused by the RMS measurement having a limited bandwidth of 2500Hz. As shown in Figures 25 and 26, there are no significant voltage harmonic or interharmonic components other than the fundamental. The fundamental RMS (TD) and fundamental RMS measurements only see the fundamental voltage, hence they both return a similar value. The discrepancy between RMS (TD) and RMS can be explained by the presence of voltage components beyond 2500Hz.
The embedded data logger can record high bandwidth waveforms, directly from the voltage and current transducers. For the inverter, these waveforms have a 500kHz sample rate, and use high bandwidth transducer of 500kHz for voltage and 200kHz for current. This allows for high frequency components to be captured beyond the typical 2.5kHz upper limit of conventional analysis.

The voltage waveform for the islanded microgrid was analysed, with the variable speed drives powered off. These waveforms have the same set of three RMS values as shown at the very end of Figure 30.

Figure 31 shows the noisy and distorted voltage waveform of the inverter, over a 100ms period. Despite the large amount of noise, the fundamental shape (a sinewave) is visible. The inverter produces a sinewave by very quickly switching the battery DC voltage (~800V) between a positive and negative value, using pulse width modulation (PWM). The inverter includes a filter to smooth out the voltage into a sinewave, however some noise still gets through, as seen in Figure 31.

NOTE: this high frequency noise is filtered out by the isolation transformer, hence the voltage seen by the grid and load is very close to a sinewave. The examples below look specifically at the inverter output terminals, and the quality of the voltage waveform when there is no further filtering beyond the inverter’s internal sinewave filters.
Figures 32 and 33 take a closer look at the voltage waveform, and clearly show the inverter’s switching transients. The high-speed waveform recorder has a high enough bandwidth to capture these transients, including the ringing/oscillations after each switching event. These transients and associated ringing is common to power electronic devices, and dependent on the inverter’s power module design and internal filtering.

More information about the inverter’s voltage can be found in the frequency domain. Figure 34 displays the full inverter voltage spectrum from 0Hz to 250kHz, with a 0.5Hz resolution (size of each frequency bin measured). The spectrum is produced from the fast Fourier transform of 1 million waveform data points, spanning a 2 second period. The amplitude is displayed using a logarithmic scale, and each frequency component magnitude is an RMS value (for example, the 50Hz frequency bin has an amplitude matching the fundamental RMS value).
The largest component is the 50Hz fundamental frequency. The next largest components are from a very broad line spectrum of inverter switching components. Figure 35 shows the inverter spectrum between 0 and 10kHz. The 4kHz PWM switching frequency can clearly be seen, along with harmonics of the switching frequency appearing at 8kHz and beyond. There are no inverter switching components below 3.5kHz.

Figure 35: Inverter voltage spectrum (RMS), from 0Hz to 10kHz (up to the 200th harmonic).
Figure 36 shows the inverter spectrum between 0 and 500Hz, which corresponds to a region of the 0th to 10th harmonic. The spectrum shows the presence of a 5th harmonic a 7th harmonic, and interharmonic components below the 7th harmonic (the 6th interharmonic region). Although the 7th harmonic appears to be larger than 1V, this is actually an interharmonic component at 348Hz. The 7th harmonic at 350Hz has a 0.3V magnitude. However, when using 10 cycle analysis (per IEC 61000-4-7), this 348Hz component would be included in the harmonic bin (which has a width of 5Hz). The other interharmonic at 336Hz would be included in the 6th interharmonic bin.

Because of how sparsely populated the spectrum is below 2.5kHz (when excluding the inverter switching noise), it is not efficient to record all of the spectral content (or record the waveform at very high rate) for any length of time. The techniques for harmonic and interharmonic analysis in IEC 61000-4-7 provide a more efficient way of capturing this data, rely on the fact that most distortion components will be harmonics of the fundamental. Recording harmonics still consume a large amount of storage space, hence measures like total harmonic distortion (THD) provide a good compromise between effectively measuring waveform distortion and the volume of data produced to do so.

![Figure 37: Inverter voltage waveforms, showing both the original high bandwidth waveform and a filtered waveform to obtain the fundamental.](image)

To investigate the cause of the RMS discrepancies in Figure 30 (where RMS (TD) larger than RMS), detailed analysis was performed using the high bandwidth voltage waveform. Figure 37 shows the fundamental voltage, performed by filtering the high bandwidth waveform to exclude any components beyond 100Hz (the second harmonic). This is another method for extracting the fundamental component, although is typically done with very sharp filter that keeps the 50Hz component and rejects the 100Hz component. Such a filter is very difficult to design and use in a real time measuring device, often being too computationally intensive to function in real time.
Figure 38: Inverter RMS voltage $V$, fundamental RMS voltage $V_1$, and nonfundamental RMS voltage $V_H$, all produced using a sliding RMS method of 10 cycle width.

Figure 38 reproduces the RMS voltage, fundamental RMS voltage (using the filtered waveform), and the nonfundamental RMS voltage. The RMS and fundamental RMS were produced using a sliding window RMS calculation, with a window width of 10 cycles. This method produces an RMS measurement every 2µs, but each method is produced from 200ms of data around that point. The nonfundamental voltage is produced using the IEEE 1459 method (see Section 2.2). Figure 39 shows the corresponding values produced in real time by the data logging system (except $V_H$, which was added during offline analysis).

Figure 38 has a much larger value of nonfundamental voltage $V_H$ of 73V when compared to the end of Figure 39, which shows only 27V. The fundamental RMS voltage is similar at 212.8V. The RMS voltage in Figure 38 is 225V, higher than the 214.5V shown at the end of Figure 39.

These differences are caused by the limited bandwidth of the power quality analyser module used by the data logging system. All waveforms are decimated (filtered then sample rate reduced) as part of the resampling process that synchronises the new sample rate to the power system frequency. For the data in this report, the nominal sample rate used for real time analysis was 9600Hz, which can only capture frequency components below 4800Hz. Some of the PWM switching noise is captured by the power quality analyser module, however the broad spectral components (8kHz onward, see Figure 34) are not captured. Hence the RMS and nonfundamental RMS values of the waveforms are much higher.

Figure 39: RMS, fundamental RMS measured by the data logging system, and nonfundamental RMS calculated from these values, during islanded operation of the wind tunnel fans.
Using the nonfundamental RMS measurement of the high bandwidth voltage waveform, the true total harmonic distortion can be calculated. Figure 40 shows this measurement, with a value just over 34%. In contrast, the corresponding real time analysis THD values at the end of Figure 23 show the THD sum method producing a value less than 1% THD, and the THD difference method producing a value of 12.6%.

These results highlight that when power electronic devices like inverters are used, high frequency switching noise and non-sinusoidal waveforms should be assumed. The specific implementation of standard measurements like RMS and THD is critical to providing correct and valid results. This is critical for when comparing these measurements and using them to characterise the underlying behaviour of the power system.
5 CONCLUSION

Three phase power systems are complex, and their power quality can be difficult to understand. The operation of a power system is more difficult to analyse and understand when the system operates in a non-ideal or abnormal way. There are many analysis tools that can be used to better understand a power system’s operation, particularly in abnormal or non-ideal conditions. This report touches on a few of the common and useful techniques that have been deployed in practical power system measurement.

This report has looked at the practical example of an islanded battery energy storage system powering a set of variable speed drives. This test showed that the system was functional and could operate continuously, however the power quality was less than ideal. The system experienced rapidly fluctuating power, non-ideal power factor, current harmonics, distortion and unbalance. This test provides a pilot example of what a future microgrid may look like, where the generation and load devices are all non-linear with actively switched power electronics.

Power factor and total harmonic distortion are simple and useful measurements that can summarise the operation and power quality of a system. However, the implementation of these measurements is critical for obtaining meaningful values that describe the power system. The results have shown that the conventional concept of reactive power becomes meaningless once the power system operates with non-sinusoidal waveforms. Instead, other power quality techniques were demonstrated that can analyse the system in these non-ideal states. The impact of high frequency inverter switching noise was investigated, and it was shown that the measurement bandwidth of the system can heavily influence the calculation of RMS and total harmonic distortion measurements.

The field of power theory and power quality is constantly evolving, with new research and techniques being developed. With the increased prevalence of non-linear loads, power electronic devices and battery energy storage systems, there is a stronger need to understand the impact these devices have on each other and the grid. A better understanding of power quality can help optimise this new technology to achieve higher power quality, minimal interference, and more efficient energy delivery.