PORTABLE EMERGENCY BACKUP GENERATORS

BE CAREFUL WHAT YOU PLUG INTO THEM

MARCH 2022
AN INDEPENDENT REPORT
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INDEPENDENT REPORT
RESIDENTIAL HOME
ASSESSING VOLTAGE-CURRENT-POWER FACTOR-TOTAL HARMONIC DISTORTION BETWEEN POWER UTILITY MAIN AND PORTABLE GENERATOR (BACKUP POWER SOURCE DURING UTILITY POWER OUTAGE)
(WITH/WITHOUT LOAD; WITH/WITHOUT POWER CONDITIONER)

SUMMARY

Caution is advised when residential homeowners use portable generators as backup power supply during a utility power outage since the power produced by such portable generators could be 'dirty' and adversely affect *sensitive electronic equipment*[1] such as computers, modems, routers and phone chargers.

Ideally, electric power provided to operate sensitive electronic equipment should be 'clean' sinusoidal overlapping (i.e., in phase) voltage and current waveforms with only one fundamental frequency (typically in the U.S., 60 Hz frequency). 'Dirty' electric power is introduced when harmonic distortion is introduced into the circuit (the voltage and current waveforms are out of phase, not over lapping and are affected by harmonic frequencies which causes the ideal sinusoidal fundamental frequency waveform to become multiple harmonic frequencies and the ideal sinusoidal overlapping waveforms to be distorted and nonuniform waviness). This distortion can cause damaging impacts on sensitive electronic equipment as well as the out of phase waveform between the current and voltage resulting in a lower Power Factor or less efficient use of electricity (paying for power not usefully used and wasted).

A measure of the 'dirtiness' of electric power is Total Harmonic Distortion (discussed in Appendix B). It has been the authors experience that most residential electronic and electrical equipment manufacturers do not report to consumers in their marketing literature, Total Harmonic Distortion specification[2]. Further, the author did not identify a *standard* Total Harmonic Distortion specification for sensitive electronic equipment. There are 'guidelines' (in addition to mandatory State utility regulations) suggested by various organizations which indicate 'safe' Total Harmonic Distortion limits for sensitive electronic equipment ideally should be less than 5% and ideally less than 3% for any one harmonic frequency.

Since the author will power his residential home sensitive electronic equipment with a portable (non-inverter[3]) generator during emergency power outages, the author made test measurements (voltage, current, Total Harmonic Distortion, Power Factor) with the aid of an oscilloscope, his residential utility power and portable generator power output, with and without a load (a 1875 Watt hair dryer and 45 Watt oscillating fan) in addition to testing the portable generator equipped with installation of a residential clean power conditioning system[4] (designed to improve the cleanliness (condition) of dirty

[1] There is not a standard definition of *sensitive electronic equipment*, but guidance is provided in Appendix C.

[2] Since most electricity used to power sensitive electronic equipment is provided by a utility company, State utility regulators require utilities to provide low Total Hamonic Distortion (less than ~5%) power to its customers so sensitive electronic equipment manufacturers do not concern themselves with citing Total Harmonic Distortion specifications in their sales advertisements. However the introduction of emergency portable power generators results in power quality possibly not being of the same cleanliness as a utility so caveat emptor – buyer be ware!

[3] Inverter portable generators in contrast to non-inverter generators, are designed to produce 'clean' power at Total Harmonic Distortion values below 5%, so safe to use to power sensitive electronic equipment. Since the price difference is similar between inverter and non-inverter generators, it would suggest the better consumer selection is always an inverter generator.

[4] Discussed in Appendix A are an array of options that could be used to assist in cleaning up portable generator power so that it becomes less risky that sensitive electronic equipment will be harmed. The author's design includes installation of a transfer switch which will isolate from the utility

generator power to improved levels of cleanliness or lower Total Harmonic Distortion and improved Power Factor and safer to power sensitive electronic equipment), for the purpose of assessing how clean the portable generator power is in regard to using it to power sensitive electronic equipment.

Measurement and test results are summarized in the below table.

	UTILITY MAINS (WITHOUT POWER CONDITIONER)			PORTABLE GENERATOR (gasoline fuel) (WITHOUT POWER CONDITIONER)			PORTABLE GENERATOR (gasoline fuel) (WITH POWER CONDITIONER)		
	No Load	LOAD (Dryer[1])	LOAD (Fan[2])	No Load	LOAD (Dryer)	LOAD (Fan)	No Load	LOAD (Dryer)	LOAD (Fan)
Voltage, Volts, AC									
Min	122.1	114.8	122.6	120.7	117.6	120.9	118.7	117.5	118.9
Avg (RMS)	122.1	114.9	122.6	121	117.8	121.1	119	118.4	119.3
Max	122.1	114.9	122.7	121.3	118.1	121.6	119.4	118.7	119.8
Peak	169.5	159	157.7	183	171.5	185	185	182	186.6
Std Dev.	99.6 µV	201 µV	194 µV	5.2 µV		1.0 mV	2.4 mV	2 mV	1 mV
Current, Amps, AC									
Min	-	13.03	.37	-	13.2	0.39	-	12.9	0.36
Avg (RMS)	-	13.02	.37	-	13.2	0.39	-	12.96	0.36
Max	-	13.02	.376	-	13.3	0.39	-	12.98	0.36
Std. Dev.	-	0.004	.002	-	1.5mV	127 µV	-	1.6 mV	90 µV
Total Harmonic Distortion, % (Channel)	A	B	B	A	B	B	A	B	B
Min	2.71%	5.1%	11.49%	11.9%	10.5%	13.4%	16.1%	15.45%	10.85%
Avg	2.73%	5.13%	11.53%	19.4%	10.6%	14.3%	16.2%	15.6%	10.9%
Max	2.74%	5.16%	11.57%	29.0%	10.7%	15.6%	16.24%	15.8%	11.1%
Std. Dev.	0.009%	0.013%	0.028%	5.7%	0.06%	0.67%	0.08%	0.12%	0.06%
Phase Angle[a], Voltage/Current	-	-	-	-	-		-	-	-
Peak-to-Peak Voltage-Current Phase Time Difference, ms (t_d)	-	0.31-0.92	2.48	-	0.18	2.3	-	<0.1	1.55-1.8
Cycle Time, ms (t_p)	16.76	16.65	16.72	16.21	16.44	16.21	16.22	16.48	16.22
Frequency, Hz (ω)	59.7	60.1	59.8	61.9	61.0	61.6	61.5	60.5	61.5
Phase Angle[a], Degrees	-	6.7° – 19.9°	53.4°	-	4°	51.1°	-	2.2°	34.4°-40°
Phase Angle, Radians	-	0.11 – 0.35	0.93	-	0.069	0.89	-	0.04	0.6-0.7
Displacement Factor[b]	-	0.99-0.94	0.60	-	0.99	0.63	-	0.99	0.83-0.76
Distortion Factor[c]	0.99	0.99	0.99	0.98	0.99	0.98	0.98	0.98	0.99
Power Factor[d], %	-	98% - 93%	54%	-	98%	62%	-	97%	82.%-75%
Average Power, Watts (DC average of the math channel[e])	-	1493	29.4	-	1556	29.2	-	1520	27.4
Power Factor[d], %	-	99.9%	65.0%	-	100%	61.8%	-	98.8%	63.8%

Hair Dryer BabyBliss PRO Model# BP6685; 125 V AC 60Hz 15.2 AMP 1900 Watt

[2] Oscillating Fan Suntea Model# SFC-2016; 120 V AC 60Hz 0.35 AMP 42 Watt

a Phase Angle (degrees) = [(peak-to-peak voltage-current phase time difference, t_d)/(one cycle time, t_p)] * 360°

Example: t_d = 2.48 ms; t_p = 16.72 ms; (2.48/16.72)*360° = 53.4°.

b Displacement Factor = Cosine Phase Angle (radians)

Example: Phase angle = 53.4° = 0.932 radians; Displacement Factor = Cosine (0.932) = 0.596

c Distortion Factor = Square Root [$1/(1+ THD^2)$]

Example: THD = 0.2 (20%); Distortion Factor = Square Root [$(1/(1 + 0.2^2)$] = 0.98

d Power Factor = Displacement Factor x Distortion Factor

Example: 0.596 x 0.98 = 0.584 (58.4%)

e Average Power is the PicoScope math channel of A*B (voltage times current = power) and the Average DC of that channel being the average working power actually consumed.

power main certain circuits in the residence during a utility power outage emergency event, when a portable generator is in use to power such circuits. The transfer switch and portable generator power is attached to a PowerworRx Residential Clean Power System designed to improve (condition) the power quality and cleanliness of portable generator power supplied to the switched circuits. (Note the PowerwoRx system is not tied to the utility mains service).

f Power Factor, based on Average Power (PR, real power)/RMS (PA, apparent power) measurements (%) = Average Power (DC Average – Oscilloscope integrates voltage x current over one power cycle) / (RMS voltage*RMS current)*100

Example: RMS AC voltage (V) = 121.5 V; RMS AC current (I) = 0.37 Amps; Apparent Power = V * I = 121.5 * 0.37 = 44.95 Watts;

Real Power = DC Average Power from oscilloscope reading = 29.4 Watts; Power Factor = 29.4 (Real Power)/44.95 (Apparent Power) = 65.4%

The author's tested utility main power and unconditioned portable generator observations indicated:

- **Utility Main**
  - **No load Total Harmonic Distortion less than 3%.**
  - **Power Factor for two test loads:**
    - **Oscillating Fan: 59.6%-65% (62.3% avg)**
    - **Hair Dryer: 94%-99% (>99% avg)**
  - **Wave form 'wobble': Essentially none**
- **Unconditioned Portable Generator**
  - **No load Total Harmonic Distortion 19.4% avg.**
  - **Power Factor**
    - **Oscillating Fan: 62.3% avg.**
    - **Hair Dryer: 99.5% avg.**
  - **Wave form 'wobble': Yes**

The author installed a PowerwoRx CPS-E3-N3, Residential Clean Power System, to test its effects on conditioning (making cleaner) the power generated by the test portable generator.

(Power conditioners also provide other functions such as increased protection of electrical circuits from power surges such as from lightening strikes).

- **Conditioned Portable Generator**
  - **No load Total Harmonic Distortion 16.2% avg.**
    - **16%-20% improvement[5]**
  - **Power Factor**
    - **Oscillating Fan: 82.5%-76.6% range (manual phase angle measurement) - 63.8% (oscilloscope integration);**
      - **0% to 24% improvement[6]**
    - **Hair Dryer: 99.5% avg.**
    - **Since Power Factor is already close to 100% without a conditioner, accuracy of test equipment and test procedure was unable to confirm a difference in Power Factor.[7]**
  - **Wave form 'wobble': Very little**
    - **Much reduced wobble in the voltage, current and power wave forms.**

[5] 19.4%-16.2% = 3.2%; 3.2%/19.4%=16%; 3.2%/16.2%=20%

[6] 63.8%-62.3%=1.5%; 1.5%/63.8%~0.02% or 0%; 82.5%-62.3%=20.2%; 20.2%/82.5%=24%

[7] Some internet references cite that power conditioners do not provide the benefits claimed (i.e., they do not produce higher Power Factor and therefore do not result in reduced electric bill) but in regard to the independent tests performed by the author, his Power Factor, contrary to such references, indicated improvement (increased).

OVERALL OBSERVATIONS – NON-INVERTER PORTABLE GENERATOR

- ✓ **Was the Total Harmonic Distortion improved with a power conditioner –**
  YES
- ✓ **Was the Power Factor improved with a power conditioner –**
  YES
- ✓ **Was the wobbliness of voltage-current-power wave forms improved with a power conditioner –**
  YES

Consequently, a correctly sized (the right start-up and run wattage) non-inverter portable generator, used during an emergency incident to provide electric power, associated with an appropriate power conditioner (which may include a PowerwoRx , Residential Clean Power System), is unlikely to harm sensitive electronic equipment, such as computers, modems, routers and chargers, when powered by such generator.

CONCLUSION

The author is comfortable that the use of his portable generator to power certain electrical circuits in his home during emergency power outages along with installation of the PowerwoRx CPS-E3-N3, Residential Clean Power System, 120/240V, Single Phase, Outdoor NEMA 3 Encl. system, will result in improved conditioned and clean (lower Total Harmonic Distortion, improved Power Factor, less wobbliness in voltage-current-power wave forms) that operation of his sensitive electronic equipment (such as computers, modem, router and chargers) with such power sourced from the conditioned portable generator should not be harmed.

I, Larry D. Killion, P.E., a registered professional engineer in the State of Texas, hereby certify that the information, measurement, and test results reported are to the best of his knowledge, accurate and fairly and truthfully represent the results of the author's independent and unaffiliated and unsponsored, analysis and investigation.

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INTRODUCTION

Many homeowners will rely on a standby portable power generator[8] as emergency backup to power certain electronic equipment when their utility power is down (typically because of storms). These small generators (say up to 10000-Watt startup capacity) are typically used to power critical electrical equipment (such as lights, refrigerator, some kitchen appliances such as microwave ovens, garage door opener, small floor heaters, fans, chargers, etc.) but typically not large enough to power large power demands such as air conditioners, central electric heaters, electric hot water heaters or electric clothes dryers.

Most homeowners during temporary power outages will require as a minimum, portable generator power to operate sensitive electronic equipment (such as computers, modems, routers, phone chargers, etc.) and other 'essential' equipment such as lights, refrigerator, some kitchen appliances, gas heater blowers, etc. Generally the homeowner is willing to not have powered during temporary power outages, large power consumers (not uncommon using 240 AC voltage) such as air conditioners, electric clothes dryers, electric central heaters, dish washer and washing machine. Sensitive electronic equipment is generally sensitive to the quality or 'cleanliness' of the electrical power supplied to operate the equipment. If the supplied power is too 'dirty', it can cause operating problems with the equipment and could even damage sensitive electric circuits. This report describes what is meant by 'dirty' and 'clean' power and how it is measured and controlled.

It is not uncommon for homeowners to overlook and not take into account the quality of electricity produced by portable generators and the likelihood that sensitive electronic equipment might be damaged by such power quality.

Generally, many portable generators produce 'dirty' power that could adversely affect sensitive electronic equipment (except for certain generators described as ***inverter*** generators[9] which are designed to produce clean or low Total Harmonic Distortion power which converts – inverts - alternating voltage first to direct voltage and then invert it back to cleaner alternating voltage. This inversion process improves (reduces) Total Harmonic Distortion resulting in cleaner power).

There are various options a homeowner could consider which could make more clean the power generated by portable generators, making such power safer to power sensitive electronic equipment. These options have various degrees of effectiveness discussed in Appendix A.

This report was prepared as a reference for relevant technical information and real test measurements of the cleanliness and dirtiness of unconditioned electrical power supplied by (i) a utility and (ii) a non-inverter portable generator, with and without a load (hair dryer/oscillating fan) used in an electrical circuit, as well as (iii) the effect of using a commercially available residential clean power conditioning system, designed to improve the cleanliness (condition) dirty power generated

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[8] Some homeowners will install whole house backup generators that will supply power to all home power requirements as a substitute for the power utility power. While a convenient thing to have, it is often a challenge to justify economically whole house generator power backup when such units are rarely used and are costly to own (can cost in the 10's of thousands), operate and maintain. Sometimes, critical emergency power needs are priority circumstances, other than just cost and economics, which justify installing a whole house generator, such as a home being located in remote rural areas with limited access to timely power restoration during and after an emergency or critical requirements to ensure continuous operation of life saving medical equipment powered by electricity or other circumstances that are more important than economic cost. In large metropolitan cities, such as Houston, Texas (the authors location), power outage events are generally corrected rather quickly (a few days or week or so) and in those circumstances in the 'extreme' case – and putting convenience aside regardless of cost as a motivating factor - a homeowner could travel to a location where power is available and pay for accommodation, the cost of which is far less than owning a whole home emergency backup power generator.

[9] The author desired to operate a tri-fuel portable generator, one capable of being powered by natural gas (as well as gasoline and LPG), a fuel source generally more reliable during an emergency, when the availability of LPG or gasoline could be in short supply. The author was unable to locate a tri-fuel inverter generator (one capable of using natural gas) and hence has used a non-inverter portable generator (having natural gas fueled capabilities).

by a non-inverter portable generator and the resultant cleaner energy (lower Total Harmonic Distortion and higher Power Efficiency less wobbliness in the voltage-current-power wave forms) being safer to power sensitive electronic equipment.

The following Appendices discusses relevant technical details.

Appendix A – Various Ways to Make A Portable Generator Safe For Sensitive Electronic Equipment

Appendix B – Discussion of Total Harmonic Distortion (a measure of how dirty electrical power is and how it may adversely affect sensitive electronic equipment)

Appendix C – Definition of *Sensitive Electronic Equipment*

Appendix D – What is Power Factor (Power Quality) (another measure of how dirty or clean is electrical power is and how efficient power is being used – you don't want to pay for what you don't use)

Appendix E - How To Measure Power Factor With An Oscilloscope

Appendix F – Test Procedure for Voltage, Current, Total Harmonic Distortion, Power Factor (using an oscilloscope)

Appendix G – Test Results and Discussion

<u>APPENDIX A</u>
<u>VARIOUS WAYS TO MAKE A PORTABLE GENERATOR SAFE FOR SENSITIVE ELECTRONIC EQUIPMENT</u>

The PowerZone reference (https://portablepowerzone.com/make-generator-safe-for-electronics/) summarized below, is an excellent resource to assess…

Various Ways to Make a Portable Generator Safe for Electronics
In the United States, portable generators (typically used at construction sites or for home power backup when the utility power is out, such as during bad weather), produce AC – alternating current - power of 120/240 volts at 60Hz (frequency, cycles per second). The power generation process depends on a combustion engine (fueled by gasoline, LPG or natural gas) whose speed and power production varies based on different factors.

The electrical power supplied by the portable generator isn't always consistent and clean (referred to as 'dirty' power), unlike utility power companies that are subject to government regulations that require 'clean' power or low fluctuation power supplied to their customers. This dirty power fluctuation is referred to as *Total Harmonic Distortion (THD)*, which is explained in Appendix B.

Sensitive electronics such as computers, modems, routers, phones, TVs, chargers and various other appliances can easily be damaged when the power they use fluctuates (adversely affected by dirty power, referred to as *harmonic distortion*). AC (alternating current) voltage (measured in volts) and current (measured in amps) is normally produced in a sinusoidal (harmonic) waveform pattern oscillating between on average (or RMS – root mean square value) +120/240 volts to – 120/240 volts (the peak – highest point - of the sinusoidal wave form, when the average voltage is 120 volts RMS, could be in excess of 160 volts).

The harmonic fluctuations or distortions (dirty power) in voltage and current, in power generated by portable generators can create momentary power surges and drops which wear out electronics and can even fry their circuitries.

The solution to avoiding excessive wear on sensitive electronic equipment is finding ways to shield electronics from these dirty power fluctuations. The solution is not always easy since harmonic distortion can be created and sourced both (1) externally (introduced by the power source such as the utility company or sourced from a portable generator and supplied into the electric supply mains) or (2) self-inflected internally generated by the consumer electric equipment creating the distortion within the internal circuit. Thus Total Harmonic Distortion is the sum of both external and internal sourced harmonic fluctuations. In some cases, you may need to employ more than one solution to clean up dirty power for the best experience.

Ways to protect electronics

1. Use a surge arrester
A surge arrester is a device which protects individual pieces of equipment or the whole house from large power surges from different sources. The surges can be from lightning, mains power or a generator. Whole house surge arresters may not be able to absorb the whole power of a surge but can manage as much as 90% of it which is typically enough to prevent damage to electronics. The rest of the power surge not stopped by a surge arrester can be handled by smaller surge protectors in devices and in the power circuit. However, if Total Hamonic Distortion is present in stable waveform, a surge arrester may not detect a 'surge' and the arrester not protecting against such 'stable' Total Harmonic Distortion.

2. Use a surge protector

Individual surge protectors, protect electronics from power surges which occur from harmonic distortions (dirty power or power surges) of a portable generator or power from the grid. Surge protectors detect ‘excess’ voltage in the power input then redirect it to a grounding wire.

With each time it absorbs and sends some joules to the grounding wire, surge protectors become less and less effective at protecting electronics, so they may need to be replaced periodically to give the best protection. However, similar to a serge arrester, if Total Hamonic Distortion is present in stable waveform, a surge arrester may not detect a ‘surge’ and the surge protector not protecting against such ‘stable’ Total Harmonic Distortion.

3. Use an Uninterruptible Power Supply (UPS)

A UPS is a device that stores power in a battery then supplies it to electronics when the utility or wall power goes out. The UPS power supplied is sometimes just a few minutes to allow for the proper shutdown of affected electronic equipment.

You can get larger UPS devices for the whole home, or you can get smaller ones that only serve one or a few devices. When looking for a UPS, consider the following aspects:

Find one with a generator mode.
This helps steady (or ‘condition’) the power from portable generators besides storing some for the devices when the generator dies down abruptly.

Go for dedicated UPSs for your devices.

While it’s wise to get a UPS that covers the whole house, it’s even wiser to get one for each device. This is because some devices in the household don’t need that much power to shut off.

Choose double-conversion UPSs.
These are like adding an inverter to a portable generator but with the extra benefit of a battery. They work the same way as an inverter by converting power from AC to DC then back to AC. The resulting power is thus cleaner than the input. Besides providing power for the electronics when the input goes out, it also stabilizes out the power input making it safer for electronics.

4. Use an inverter generator

Portable inverter generators automatically produce clean, low harmonic distortion power. Since the cost differential between an inverter generator and a non-inverter generator is small (inverters are a little more costly), an inverter generator should be the preferred choice.

As of February 2022, inverter generators in the U.S. are fueled only by LPG or gasoline (dual fuel inverter generators) and not natural gas. If natural gas is a preferred fuel, then the non-inverted natural gas fueled generator dirty power will need to be cleaned up by one of the options cited in this report.

A power inverter turns the AC power generated by the generator to DC then back to AC. The converted AC power produced is stable and thus cleaner power (low Total Harmonic Distortion) for use by electronics.

5. Use a power line or clean power conditioner

Power line conditioners (for both utility power and power supplied by portable backup generators) are devices that suppress the noise in electrical power making it stable and clean in brownouts and when dirty power is from portable generators.

Power line conditioners eliminate or filters out many different types of noises, surges and harmonic distortion, from input power including electro-magnetic interferences (EMI), radio frequency interferences (RFI), over-voltages, power surges and others.

As such, a power line conditioner has many benefits and could be the only device you need to make a portable generator safe for electronics in the home and workplace.

6. Use Automatic Voltage Regulators (AVR)

Automatic Voltage Regulators are devices added to the portable generator to smooth out the load and RPM fluctuations with the result of generating more consistent cleaner power than a standard generator alternator would. They do this without converting the power to DC. Some generators come with these devices making them produce clean energy without necessarily being inverter generators.

FAQS

What kind of portable generator is safe for electronics?

Generators with inverters and Automatic Voltage Regulators are the safest for electronics, provided gasoline and LPG fuel choices are readily available.

Will a generator harm electronics?

Not always. Inverter generators and those with Automatic Voltage Regulators are less likely to harm electronics. Those without devices may also not harm your electronics but the risk is higher.

Can a portable generator damage appliances?

Yes. If it’s not fitted with an inverter or Automatic Voltage Regulator, it generates harmonic distortion in the power which could damage sensitive electronics.

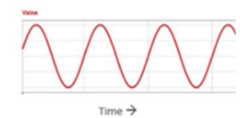
Do portable generators produce dirty power?

Generators without inverters or Automatic Voltage Regulators produce dirty power (generally, Total Harmonic Distortion is greater than 5%) that’s unstable and can be dangerous to electronic equipment.

<u>**APPENDIX B**</u>

<u>**TOTAL HARMONIC DISTORTION (A MEASURE OF DIRTINESS OR CLEANLINESS OF ELECTRICAL POWER)**</u>

Total Harmonic Distortion



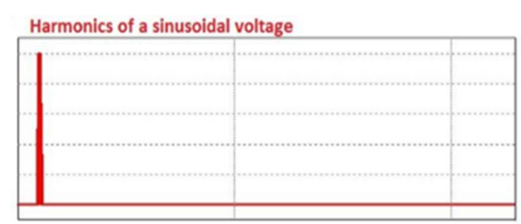
Alternating Current (AC) electricity (power) supplied to homes, factories and offices (either from the utility company power mains or from portable back-up generators) is normally delivered in sine waveform (see illustration to the right of a sine waveform, vertical or y axis is voltage and horizontal or x axis is time) at a frequency of 50 (typically in Europe) or 60 (typically in the USA) Hertz (Hz – cycles per second, often noted as ω), depending on the region where you are located. The supplied frequency (say 60 Hz) is called the 'fundamental' frequency.

Power generation companies are generally obliged to deliver to their customers "clean" sinusoidal supply voltages within certain limits set by State regulatory bodies and *ideally* voltage delivered only at the fundamental frequency (which never happens). If the electricity used by a customer (the so called 'load', such as turning on a hair dryer, using a microwave oven, running a refrigeration, operating air conditioning and heating units, powering computers, lights, etc.) consumed or used by the consumer is linear (meaning the electricity consumed is generally steady and constant over time when used – such as the refrigerator constantly running) - and does not fluctuate – (such as turning a light switch repeatedly on and off over a short period of time). The current (measured in amps) waveform is also sinusoidal.

V**oltage** (measured in volts, either alternating current voltage [AC] – such as power to one's home from a utility company or portable generator - or direct current voltage [DC] – such as power from a battery) is the electricity *potential* or how 'strong' (its 'pressure') it is (similar to water stored in a storage tank supported off the ground and the height of the stored water off the ground - similar to battery size - indicates how much water pressure - or electrical pressure or potential - will be available – the taller the water storage tank, the more water pressure there is due to the 'potential' energy stored in the water elevated off the ground – and when a water valve is opened and water allowed to flow out of the storage tank by gravity, the potential energy of the stored water is converted to kinetic energy or moving water which is supplied to the water mains and our homes and offices).

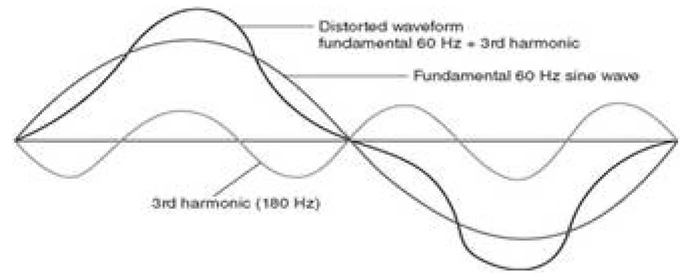
Current is how much electricity is flowing in the power lines and the rate of flow of electrons (measured in coulombs) or speed or current (measured in amps or coulombs per second) is affected by (i) the voltage or energy potential or pressure – how strong the energy source is, and (ii) how much resistance (for linear electric consumption) or impedance (similar to resistance but affects that slowdown the flow of current such as from non-linear equipment like a capacitor affecting the non-linear flow of electricity), where such resistance or impedance restricts the flow of current or flow of electrons (current or electron flow is similar to how much water is flowing in a pipe from the water storage tank – the higher the storage tank and the more open a water supply valve is opened and the bigger the size or diameter of the delivery pipe – both reducing the restriction or resistance of water flow, the more water that can flow).

Many modern devices that use electricity (home and office electronic equipment for example) do not consume linear loads from the AC supply. In-stead such equipment takes fluctuating or erratic "bites" out of the electricity supply waveform, so the current (amps) drawn or used from the power supply includes *harmonics of the 50 or 60 Hz fundamental supply frequency,* explained below.



Perfectly 'clean' (non-dirty) electricity ideal or perfect sine waveform has only one peak voltage at its fundamental frequency. The graph illustrates such ideal perfect sine waveform where the horizontal or x axis measures frequency (and in this case a 60 cycle per second fundamental frequency) and the vertical axis the power of the voltage measured in dB (decibels). The decibel (**dB**) is a logarithmic unit used to measure sound level. It is also widely used in electronics, signals and communication. The dB is a logarithmic way of describing a ratio. The ratio may be power, sound pressure, voltage or intensity or several other things. The higher the dB the stronger or higher the voltage.

Harmonics are currents or voltages with frequencies that are integer (whole number like, 2, 3, 4, etc.) multiples of the fundamental power frequency. If the fundamental power frequency is 60 Hz, then the second harmonic is 120 Hz (2 x 60 = 120) , the third is 180 Hz (3 x 60 = 180) and so on. Harmonic frequencies are a distortion of the ideal, perfect, normal single fundamental frequency electrical current sinusoidal waveform. Thus when harmonic frequencies are introduced into the sinusoidal waveform, the electricity becomes non-ideal or so called 'dirty' electricity.



The graph to the right shows a fundamental ideal frequency waveform (which could be voltage or current) of 60 Hz electrical system. This example shows the third harmonic waveform is also a pure sine waveform but with 180 Hz frequency (meaning there are three cycles to every one cycle of the fundamental frequency). However, the total power waveform (adding the fundamental frequency waveform to the third harmonic frequency waveform) is now *distorted*, no longer a smooth regularly shaped waveform, with the presence of the 3rd harmonic. The ratio of the sum of all harmonic power (here, up to 3rd harmonic) to the fundamental wave will be the third harmonic distortion. If the frequency of voltage, current and power in a circuit is not 'constant' but varies, this is called distortion.

A voltage or current that is purely sinusoidal has no harmonic distortion (frequency is "constant" and at the fundamental frequency) because it is a signal consisting of a single frequency. A voltage or current that is periodic but not purely sinusoidal will have higher frequency components in it contributing to the harmonic distortion of the signal. In general, the less that a periodic (cycling) signal looks like a sine waveform, the stronger the harmonic components are and the more harmonic distortion it will have.

So, a purely sinusoidal signal has no distortion while a non-sinusoidal wave form such as a square wave, which is periodic but does not look sinusoidal at all, will have lots of harmonic distortion. In the real world, sinusoidal voltages and currents are not perfectly sinusoidal; some amount of harmonic distortion will always be present.

Total Harmonic Distortion or THD is an indicative measurement of power quality in electrical systems. When there is presence of harmonics in electrical power system, it will create a disturbance in electrical supply. Both voltage and current frequency can have harmonic components to create a distortion. THD refers to the total amount of distortion (or disturbances) created by these harmonics. THD is important in several types of systems, including power systems, where a low THD means higher power factor – a good thing (explained in Appendix D), lower peak currents, and higher efficiency.

Distortion can originate from two sources:

1. Distortion can be introduced from the power source (the utility company or portable backup generator) whose voltage and current are not very 'clean' (thus the requirement by utility regulators that power companies provide certain level of clean electricity or low Total Harmonic Distortion),
2. Distortion can be 'created' from the equipment used by the consumer, because of the variable, non-linear consumption of 'bite' size electric use, which back-feeds harmonic distortions into the power circuit of the user and possibly even entering the power mains.
    a. Consequently, this internal created "unavoidable" source of THD should not be aggravated by also adding "dirty" high Total Harmonic Distortion power coming in from the external portable backup generators which can be much higher than electronic component THD contribution – hence clean up the portable generator THD before it enters the circuit.

Switch mode power supplies (SMPS), variable speed motors and drives, lighting controls (such as fluorescent lights), personal computers, TVs, electromagnetic emissions and core losses in motors and battery chargers, are examples of nonlinear loads that an electric consumer creates. SMPS contribute a large part of the non-linear electrical load on most electrical distribution systems. For example, all computer systems use SMPS that convert utility or portable generator AC voltage to regulated low-voltage DC for internal electronics. These non-linear power supplies draw current in short, high-amplitude pulses (‘bites’) that create distortion in the electrical current and voltage wave shape that is back fed into the electric system – harmonic distortion, measured as total harmonic distortion (THD).

The distortion travels back into the power source and can affect other equipment connected to the same source.

Most power systems can accommodate a certain level of harmonic currents (and voltages), but experience problems when harmonics become a significant component of the overall load. As ***higher frequency harmonic currents*** flow through the power system, they can cause problems and damage, such as:

- Overheating of electrical distribution equipment, cables, transformers, etc.
- High voltages and circulating currents surges caused by harmonic resonance
- Equipment malfunctions due to excessive voltage distortion
- Increased internal energy losses in connected equipment (such as overheating), leading to component failure and shortened life span
- False tripping of circuit breakers
- Metering errors
- Fires in wiring and distribution systems
- Damage to sensitive electronic equipment such as computers, modems, routers, TVs.
- Damage to appliances such as tabletop ovens, refrigerators, etc.

THD definition

According to the Institute of Electronic and Electrical Engineers (IEEE), the definition of THD or Total Harmonic Distortion is:

The ratio of the root mean square of the harmonic content, considering harmonic components up to the 50th order and specifically excluding inter-harmonics, expressed as a percent of the fundamental. Harmonic components of order greater than 50 may be included when necessary.

THD is the cumulative degree of distortion within an electrical power compared to the ideal power. The fundamental voltage frequency waveform of a 60 Hz looks like a pure sine waveform. As earlier discussed, the presence of a second harmonic also look like a pure sine waveform, but the number of cycles will be doubled. Hence the frequency of 2nd harmonic wave will be 120 Hz. Similarly, third harmonic frequency of a 60 Hz voltage nothing but 180 Hz.

Calculating Total Harmonic Distortion

$$THD = \frac{\sqrt{H_1^2 + H_2^2 + H_3^2 + H_4^2 + H_5^2}}{F}$$

$$THD_F = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots}}{V_1}$$

As the THD definition says, it is a ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency. Whereas, for a 60 Hz electrical power system, fundamental frequency is 60 Hz. Further, harmonics will have frequencies in integer multiples of the fundamental frequency. F (or V_1) denotes the fundamental frequency, whereas H_n (V_n) are the voltage harmonics with H_1 (V_1) denoting the second harmonic and so on. Consequently, in an ***ideal system***, the only frequency is the fundamental frequency in the voltage or current waveform and no other harmonic frequencies. Thus, the THD for that system is $\frac{\sqrt{0}}{00}$ = 0%.

Consequently, the higher the THD percentage means there is much more harmonic frequencies compared to the fundamental frequency.

However, there is a caveat. Recall that higher harmonic frequencies tend to have more adverse impacts on electrical systems. Thus take the case of two systems in which the THD have each been measured to be 25%. In the first system, the non-fundamental harmonic frequencies are low, say the 2nd (120 cycles) and 3rd (180 cycles) harmonics. In the second, the non-fundamental harmonic frequencies are high, say the 20th (1200 cycles) and 40th (2400 cycles) harmonics. Arguably the second system 25% THD can be much more damaging to an electrical system because its THD is comprised of much higher harmonic frequencies.

Table 1—Voltage distortion limits

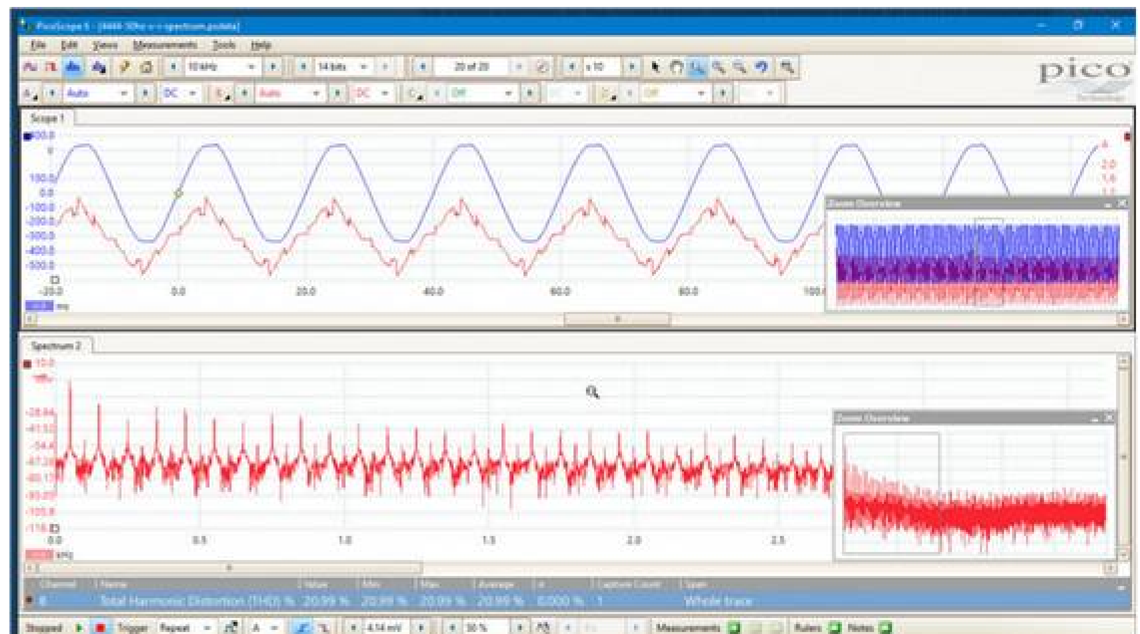
Bus voltage *V* at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
V ≤ 1.0 kV	5.0	8.0
1 kV < *V* ≤ 69 kV	3.0	5.0
69 kV < *V* ≤ 161 kV	1.5	2.5
161 kV < *V*	1.0	1.5[a]

[a]High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected.

THD control guidelines

THD is one of the key factors affecting power quality from utility companies. Hence it is very essential to manage harmonic distortions both for current and voltage within a specific limit.

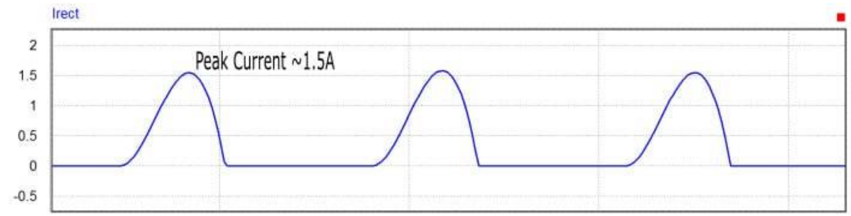
Table-1 displays the voltage harmonic distortion or voltage THD limits set as per IEEE guidelines. Total harmonic distortion voltage limits are inversely proportional to the system voltage. For power systems under 1 kV voltage can have THD Total Harmonic Distortion up to 8%. But for individual harmonic limit at the same voltage is 5%. And it decreases with increase with power system voltage.



An oscilloscope, such as PicoScope, can be used to measure electrical waveforms as well as determine Total Harmonic Distortion.

In the example on the right, the blue trace is mains voltage, red is current drawn. Spectrum plot (lower) shows total harmonic distortion. The oscilloscope allows the waveforms to be viewed in the time domain and the spectrum allows the harmonics to be displayed in the frequency domain and THD to be automatically measured.

Harmonic distortion is a disruption in the amplitude and / or frequency of a sine wave. Total Harmonic Distortion is the percentage representing the number of times the sine wave becomes distorted. By taking the first wave (fundamental harmonic – say 60 Hz or 60 sine wave cycles per second) in the series as being the constant, each subsequent wave (harmonics or integer multiples of the fundamental, the 2nd Harmonic is 2 x 60 or 120 Hz or cycles per second) is measured, comparing it to the first. Each time a wave is distorted (it does not match the first wave), the THD percentage is increased. The term “clean power” is often used when referring to an electric supply. Clean power basically means low THD, ideally 5% or less based on IEEE guidelines. Ideally, the voltage and frequency should remain uniform, but this is never possible. Even the cleanest power, using sophisticated electronic power management systems, will only reach THD levels of less than 1% and never zero. Harmonics are associated with non-linear loads which draw non-sinusoidal currents from essentially sinusoidal voltage source (i.e., load current doesn't look like applied voltage). Sources of such harmonics include: non-incandescent lighting, computers, un-interruptible power supplies, telecommunications equipment, copy machines, battery chargers, any device with a solid-state AC to DC power converter (such as computer chargers) and sold state variable speed drives. Harmonics are present as both network currents and network voltages. Non-linear currents generate non-linear voltages as they flow through the electrical network.



THD is highest at maximum load or power demand on a circuit.

Improving Power Factor and Total Harmonic Distortion…the Science…

The concept of Total Harmonic Distortion is a little bit more complicated than that of energy efficiency. THD is determined by summing all of the harmonic components of a signal (in this case, current) and comparing this sum to the fundamental frequency.

In other words, THD is created by all of the frequencies in a signal that are multiples of the fundamental frequency but are *not* the fundamental frequency.

A general way to think about THD is as follows: a perfect sine wave has no harmonic components, and the less that a periodic signal looks like a perfect sine wave, the more harmonic components it will have. THD standards for current are important because those *higher-frequency current components* have various undesirable effects on electrical systems, including increased total currents, increased core losses in motors, and electromagnetic interference with other electronic equipment.

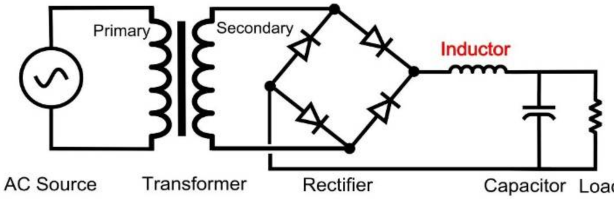
PF (Power Factor) (Further explained in Appendix D)

Power Factor (PF) is the amount of ***real power*** delivered to and ***actually used*** in a system to ***produce useful work*** divided by the amount of ***apparent power*** delivered to a system (maximum Power Factor is 1 (or 100% of the power delivered is used in useful work) and the closer to 1 the better): PF = P/S where PF is the power factor, P is the real power, and S is the apparent power.

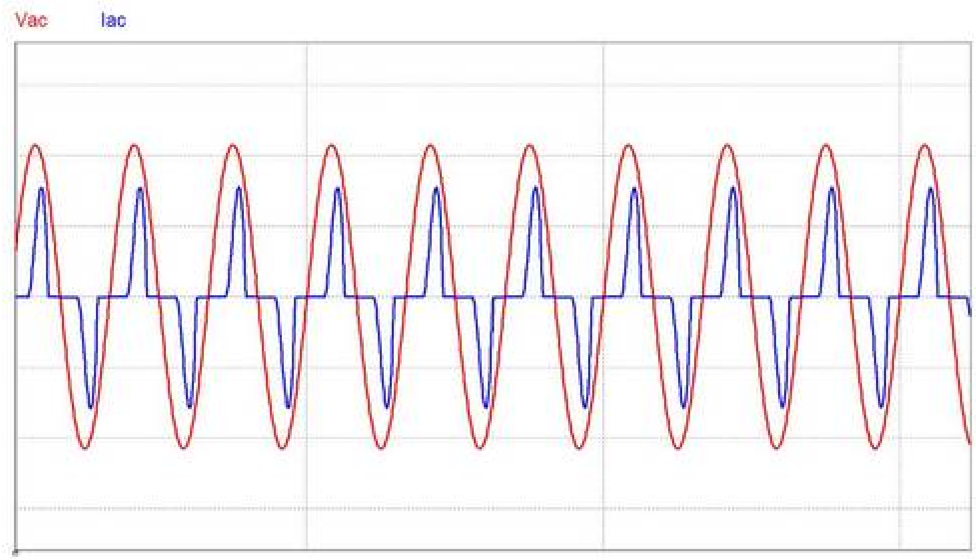
The remainder of the power not used in productive work (S – P) is called ***reactive power***, which oscillates back and forth in the system from source to load without getting used up. If two systems require the same amount of real power, the current delivered to the system with more reactive power must be higher than the current delivered to the system with less reactive power. In other words, power factor standards are important because a low-power-factor system will require a higher peak current to deliver the same amount of real power.

The two key aspects of the system that affect the power factor are the harmonic distortion (this is called the distortion factor) and the phase relationship between the AC voltage and current (the cosine of this phase difference is called the displacement factor or Power Factor). The more sinusoidal the current is, the closer to unity the distortion factor will be (a good thing). The smaller the phase difference between the voltage and current is, the closer to unity the displacement factor will be (also a good thing).

Smoothing Current with an Inductor



To reduce the current harmonics and increase the power factor, the current must be made smoother, such that it more closely matches the shape of the AC voltage. That is, we'll need to make the current sinusoidal and in phase with the AC voltage.



A simple way to make the current smoother is to add an inductor at the output of the rectifier. This inductor will act as a filter that can smooth out sharp changes in current. A power supply circuit with an added inductor filter is shown in the diagram.

The inductor current on the DC side for this new circuit is shown in the figure. The current is still delivered in bursts (blue), but now the peak current is lower, and the bursts are much less abrupt. This means that the AC side will not have to provide such large, intense spikes of current. This partial smoothing of the current helps to improve the power quality of the system.

Measurements of the current (blue) and voltage (red) on the AC side are shown in the figure; these waveforms give more evidence that the power quality is improving. The current is still out of phase with the voltage, but it's looking more sinusoidal.

Measurements of both the power factor and THD do indeed show significant improvement: in this example the power factor is around 0.7 and the THD is around 20%.

However, these improvements are still not enough to meet the power factor or THD requirements of IEC 61000-3-2 or Energy Star 80 Plus. Something more radical than a passive current filter will need to be added to the circuit to meet those specs.

The type of circuit that will be able to meet the PF and THD specifications will be something that forces the AC current to follow the AC voltage, thus causing the power factor to be very close to one and keeping the THD very close to zero. This circuit will require sensors to monitor the voltage and current, as well as a feedback system to force the current to follow the voltage.

A switching circuit of some kind will be required, and one of the most common types of circuits that can implement this improvement is called a "boost power factor correction" (or "boost PFC") circuit. As the name suggests, this circuit is based on a boost converter and can significantly improve the PF and THD.

APPENDIX C

HOW IS *SENSITIVE ELECTRONIC EQUIPMENT* DEFINED

Sensitive Electronic Equipment

It has been the experience of the author, that there is not a generally acceptable universal definition of '*sensitive electronic equipment*'.

For example, Article 647 – Sensitive Electronic Equipment, of the National Electric Code, which governs installation and wiring of sensitive electronic equipment in the commercial and industrial sectors (but not residential), does not define sensitive electronic equipment (such as in Article 100, the definitions section). Even so, 647 affects sensitive electronic equipment systems 'defined' to operate at 120 volts line-to-line and 60 volts to ground, which is a form of definition by defining certain operating criteria.

The Institute of Electronic and Electrical Engineers, 1100-1992 guidance, while not a compulsory standard (a volunteer guidance), cites Recommended Practice for Powering and Grounding *Sensitive Electronic Equipment* used in commercial and industrial applications (but not residential). The **IEEE 519-2014** standard defines the voltage and current harmonics distortion criteria for the design of electrical systems. ***Goals*** (not mandatory criteria) for designing electrical systems that contain both linear and non-linear loads are established in this standard.

A search in various internet search engines, indicates publishers of electronic related information, generally describe sensitive electronic equipment to include:

- Communication equipment (for example such equipment used in hospitals or airports) that is essential that can affect human life.
- Televisions, computers, modems, routers and other similar equipment that generally convert alternating current/voltage to direct current/voltage, so called 'non-linear' electronic equipment, whose integrated circuitry is sensitive to variations and surges in power that is required to operate such systems.

Thus, Total Harmonic Distortion (THD) is a disruption in the amplitude and / or frequency of a sine waveform. Total Harmonic Distortion is the percentage representing the number of times the sine waveform becomes distorted (compared to a single waveform at the fundamental frequency). By taking the first waveform (the fundamental frequency) in the series as being the constant, each subsequent wave is measured, comparing it to the first. Each time a wave is distorted (it does not match the first wave), the THD percentage is increased. The term "clean power" is often used when referring to an electric supply. Clean power basically means low THD, typically 5% or less. Ideally, the voltage and frequency should remain constant, but this is never possible. Even the cleanest power, using sophisticated electronic power management systems, can reach THD levels of less than 1% but never zero.

THD does not affect all electric equipment equally. Resistance heaters are hardly affected. Electric motors will be less efficient and generate extra heat when THD increases; but will still function normally. Electronic equipment, like computers and TVs, are the most sensitive. High THD levels can damage electronic components over time. When THD greatly exceeds 5%, some electronic equipment may not function properly, possibly not at all. High THD may also cause lights to flicker, especially LED lights.

The author's review of technical literature associated with many different computer and mobile phone manufacturers (especially the name brand models) indicates such technical specifications do not mention or address Total Harmonic Distortion, particularly if there are any preferred specifications regarding THD.

The author's chat, email and written contact with technical support staff of many of the name brand computer and mobile phone manufacturers, resulted in none of the technical staff help lines contacted, providing any guidance on Total Harmonic Distortion specifications or preferences for relevant electronic equipment.

The author's research indicated that power utility companies are regulated by State power commissions and obligated by regulation to provide customers with Total Harmonic Distortion limits.

The author's research regarding portable backup generators used in homes and other facilities when utility service is interrupted (such as by bad weather) indicated such generator marketing literature generally does not mention or discuss Total Harmonic Distortion and to what extent the generator THD affects equipment powered by such generators. The author after some effort of research did identify some generator manufacturers discussing THD in special reports not commonly found in general advertising literature and in the case of sensitive electronic equipment (generally not defined) powered by a portable generator, such generator should be an inverter generator (designed to produce low THD power) or attachment of power cleaning equipment or accessories to a non-inverter generator, designed to reduce THD.

Consequently, in the absence of electronic equipment manufacturers (computers, modems, routers, mobile phone chargers, etc.) reporting THD guidance, the author has relied on general literature guidance regarding THD best practice:

- Computers and allied equipment, such as programmable controllers, frequently require AC sources that should ideally target **no more than 5% harmonic voltage distortion factor [THD]**, with the largest single harmonic being ideally **no more than 3% of the fundamental voltage**. Higher levels of harmonics result in erratic, sometimes subtle, malfunctions of the equipment that can, in some cases, have serious consequences (such as overheated and burned-out electronic circuitry). However, the higher the frequency of the harmonic, the greater the propensity to potentially cause damage. So if two identical THD measurements are 25%, the one with the lower component of low frequency harmonics (say less than 600 Hz, where any one of the harmonics is less than 3% of the fundamental) will be less damaging than the one whose harmonic components are much higher (say greater than 1500 Hz, especially if one or more of the higher frequency harmonics is greater than 3% of the fundamental).
- Low quality power is acceptable for intermittent use for power tools and most appliances. THD less than 10%
- Higher quality power is required as your requirements for more needs go up. THD 6% to 9%
- Highest quality 'clean power' is needed for your more sensitive electronics such as LCD screens, TV's, and other microprocessor appliances (THD ideally $< 5\%$, and ideally $< 3\%$)
- The above observations are tempered with the following comments
    - Higher THD can be tolerated if the waveforms are conditioned and less wobbly, resulting in more stable power
    - The frequency of the non-fundamental harmonics are important, high frequency harmonics (say above 1200 Hz) are more likely to be damaging than low frequency harmonics (say below 600 Hz), thus the frequency range content of the distortion is important.
    - Power Conditioners can reduce power consumption (improve Power Factor) by reducing the quantity of current (amps) used. This reduction in current can cause the mathematical determination of Total Harmonic Distortion to increase, since THD is determined by the fundamental current I_{rms} being in the denominator of the THD equation, a lower denominator, increases the calculation result (dividing a smaller number into the numerator).
    - Consequently, while there are guidelines, there is no one size fits all.

APPENDIX D
WHAT IS POWER FACTOR? ; POWER QUALITY

Power factor is an expression of energy efficiency. It is usually expressed as a percentage (0 – 100%) —and the lower the percentage, the less efficient power usage.

Power factor (PF) is the ratio of working or useful power, measured in kilowatts (kW), divided by apparent or demand power, measured in kilovolt amperes (kVA). Apparent power, also known as demand power (both useful and wasted energy use), is the measure of the total amount of power supplied to run machinery and equipment during a certain period and the power supplied by the utility or portable generator. It is found by multiplying (RMS[10] Volts x RMS Amperage = kVA – the voltage and current used to power a machine). The result is expressed as kVA units.

PF expresses the ratio **of true power** used in a circuit to the **apparent power** delivered to the circuit. A 96% power factor demonstrates more efficiency than a 75% power factor.

How to make sense of power factor….using beer as an analogy…

Beer (non-foam – the liquid portion) is active power (kW)—the Useful or True Power, or the liquid beer, is the energy that is doing work. This is the part you want.

Foam is reactive power (kVAR)—the foam is wasted power or lost power. It's the energy being produced that isn't doing any useful work, such as the production of heat or vibration.

The Mug is apparent power (kVA)—the mug is the demand power, or the power being delivered by the utility (or portable generator). The utility provides both Liquid Beer and Foam and that is what the user is paying for…and is thus paying for the foam that is not being used for useful work.

If a circuit were 100% efficient, demand (the **Mug**) would be equal to the power available (or Useful Power = Apparent Power, or no foam, all liquid beer). When demand is greater than the power available from the utility company, a strain is placed on the utility system. If demand requirements are irregular, the utility must have more reserve capacity available than if load

[10] RMS = Root Mean Square, see https://www.electrical4u.com/rms-or-root-mean-square-value-of-ac-signal/ for a discussion of what RMS means and how it is calculated. Generally, it is a weighted average of a voltage or current waveform whose instantaneous values are constantly changing.

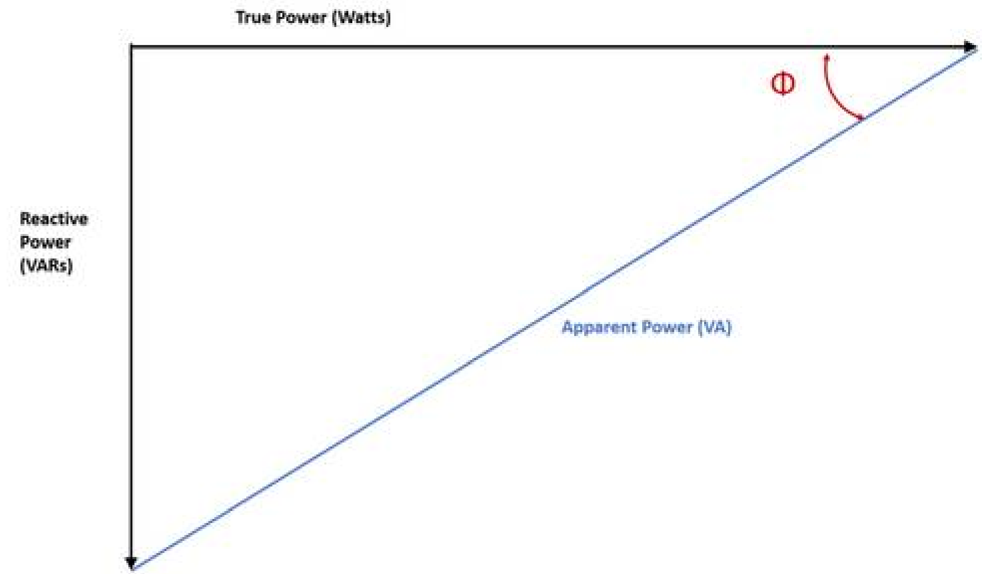
requirements remain constant. A customer pays extra for the utility to build-in extra power capacity (which is not used most of the time) in the utility system.

Peak demand is when demand is at its highest (sort of like everyone turning on at the same time their air conditioners on a hot summers day). The challenge for utilities is delivering power to handle every customer's peaks. Using extra power at the very moment it is in highest demand can disrupt overall supply unless there are enough reserves. Therefore, utilities charge extra for peak demand, in part because the utility has to invest in equipment capable of providing energy during peak periods, but most of the time the extra energy is not required, the equipment not used and sitting idle…yet the utility had to make the investment (capital, operating and up-keep costs).

Utilities apply surcharges to companies with a lower (inefficient – or wasteful use) power factor – in other words an extra charge for the consumer wasting energy supplied to it. The costs of lower power efficiency can be steep—akin to driving a gas-guzzling car. The lower the power factor, the less efficient the circuit, and the higher the overall operating cost. The higher the operating cost, the higher the likelihood that utilities will penalize a customer for overutilization. In most AC circuits there is never a power factor equal to one (1) because there is always some impedance (interference or wasted energy) on the power lines.

Measuring power factor with a power factor analyzer.

One way to determine power factor, is to use a power quality analyzer or power analyzer that measures both working power (kW) and apparent power (kVA), and to calculate the ratio of kW/kVA.



The power factor formula:

PF = (True power)/(Apparent power)

OR

PF = W/VA

Where watts (W) measure useful power, while VA measures supplied power. The ratio of the two is essentially useful power to supplied power, or as this diagram demonstrates, power factor compares the real or true power (useful or working power or power available to perform work) being consumed, to the apparent power, or demand power (sum of useful and wasted power) of the load.   And consequently, the ratio of True (Useful or Working) Power (Watts) and Apparent (Demand) Power (VA) is the same as the Cosine of the (phase) angle, Φ, between the two, cosine Φ = True Power/Apparent Power. (For example, assume Φ = 20º = 0.349 radians; cosine 30º = 0.94 x 100 = 94% Power Factor.

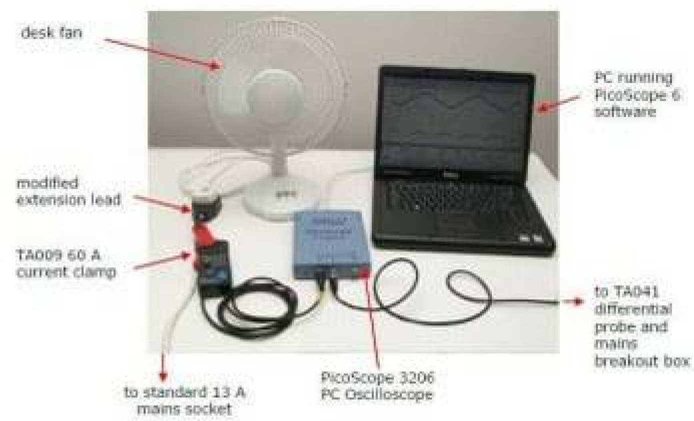
Poor power factor means that a power consumer is power inefficient. This matters to power consumers because it can result in:

- Heat damage to insulation and other circuit components

- Reduction in the amount of available useful power
- A required increase in conductor and equipment sizes
- Extra costs, paying for power that is wasted and not used

Power factor increases the overall cost of a power distribution system because the lower power factor requires a higher current to supply the loads.

USING OSCILLOSCOPE FOR MAINS POWER ANALYSIS - MEASURING POWER FACTOR (Determining actual and apparent power)



An oscilloscope such as a PicoScope (a commercially available oscilloscope using a laptop computer for its output screen) can be used to measure power and even calculate power factor. Here's how.

The setup

For illustration purposes, measuring power factor of a mains-powered desk fan. This appliance was chosen because it contains a small AC motor, and is therefore likely to have an interesting current waveform and a low power factor.

The measuring equipment is as follows:

- Desk fan, rated at 25 W, 220 V to 240 V
- PicoScope 3206 PC Oscilloscope (or any two- or four-channel PC Oscilloscope in the PicoScope range).
- Laptop PC to run the PicoScope software
- Pico TA009 60 A current clamp
- Pico TA041 700 V differential probe
- Modified 13 A extension lead. This has the 'exposed' insulated live conductor separated from the neutral and earth conductors and formed into a loop which allows the current clamp to be clamped on the live conductor (to measure current by measuring the magnetic flux field generated by the moving current). The cable is protected by heat shrink sleeving so that the entire assembly is safely double-insulated.
- Mains breakout box. This allows the shrouded 4 mm plugs on the differential probe's input leads to be safely connected to the mains.

Setting up the input channels

The fan is plugged into the modified extension lead, which is then plugged into the mains. Then switch on the current clamp, press the 'ZERO' button and hooked it onto the live conductor loop in the extension lead. The BNC lead from the current clamp is connected to channel A on the PicoScope oscilloscope. The PicoScope is connected to the laptop and set it to trigger on channel A, and selected the '60 A current clamp (20 A mode)' custom probe from the channel A setup menu. With the fan switched on, noisy, distorted sine wave is observed on the PicoScope display.

Next switch on the voltage differential probe, set it to its ‘x100’ range and connected it to channel B of the PicoScope oscilloscope. With a ‘x100’ custom probe selected for channel B, a clean sinusoidal 240 V waveform was displayed.

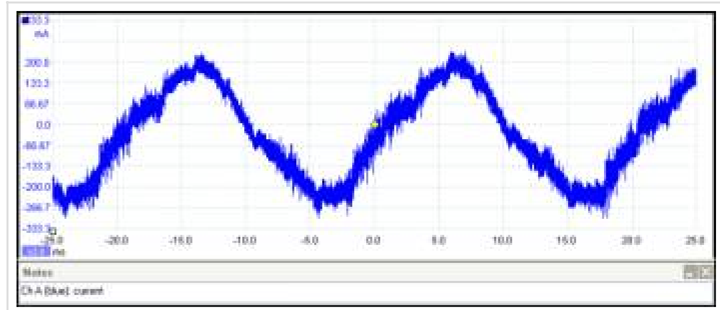


Figure 1: Channel A, Noisy, distorted current sine wave

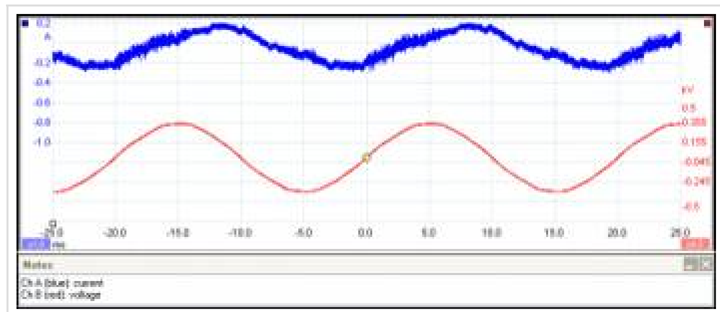


Figure 2: Channel B, Clean sinusoidal 240 V waveform

Measurements and calculations

With the current and voltage traces displayed in the correct units, next turn to the math channel feature in PicoScope. This creates a new channel (C), similar in appearance to an input channel but formed by a mathematical function of one or more inputs. In this illustration it is desired to calculate instantaneous power. By clicking the math channel button (Σ) to open the Math Channel dialog, find the ‘A*B’ function listed and switched it on by ticking the check box. (The most common functions are listed, but if the one desired is not there, type in your own equation.) This gave a third channel showing the instantaneous power plotted against time. By default, PicoScope displays a ‘?’ as the unit symbol on the vertical axis of every new math channel, which is changed to ‘W’, for watt, the SI unit of power. Also change the colour of the trace to green for better contrast. The green trace (bottom) shows how the instantaneous power varies over each mains cycle, depending on both the rotation of the fan motor and the phase of the current.

The next step is to add some automatic measurements. With PicoScope, this is a simple matter of clicking the ‘Add Measurement’ button ( ) and selecting the source channel and measurement type. Three measurements are added: a DC Average (of the A*B Math Channel) of the math channel (and therefore the average power), and RMS values for the current and voltage input channels.

The measurements table shows an average power of about 19 W, which is expected from this fan on its low–power setting. There is a small error in the calculations since power has been averaged over a period of 50 ms, which is not an integer multiple of the 20 ms cycle time. Accuracy can be improved by setting up two rulers 20 ms or 40 ms apart on the scope view and restricting the measurement to the interval between them

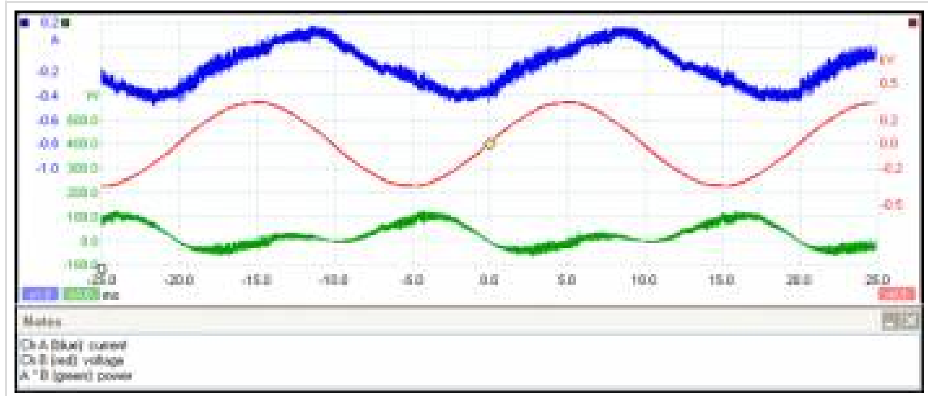


Figure 3: instantaneous power varies over each mains cycle

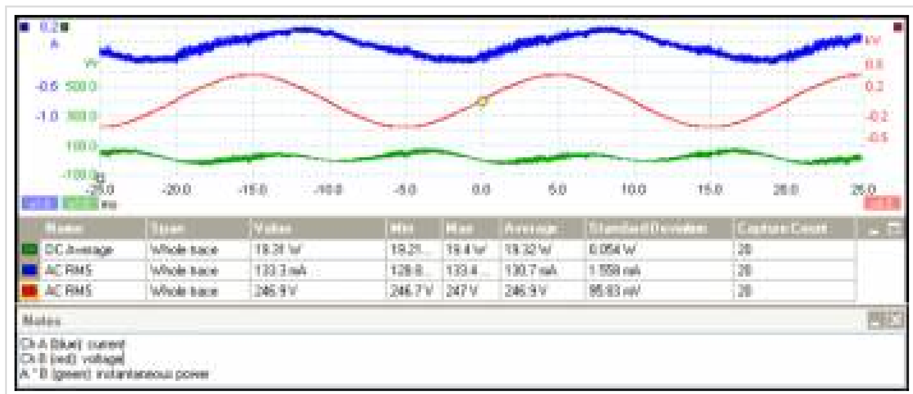


Figure 4: Measurements table shows an average power of about 19 W

Calculating the power factor

The second and third rows in the table show the RMS current and RMS voltage. Sufficient information is available to calculate the power factor (pf), which is defined as follows:

pf = PR / PA

where PR is real power and PA is apparent power, both averaged over one cycle of the mains waveform.

PR = 19.32 W

PA, the apparent power, is calculated and defined as the product of RMS current and RMS voltage, which are in the second and third rows of the table:

PA = 0.1307 A x 246.9 V ≈ 32.27 W

So the power factor is:

pf ≈ 19.32 W / 32.27 W ≈ 0.60

Power factors are always in the range 0 to 1, with 0 indicating a purely inductive or capacitive load and 1 a purely resistive one, so 0.60 (60%) is about what is expected for a small AC motor.

As a check, the cosine of the phase angle between the current and voltage is also the power factor. In this example, the frequency of the voltage is 20 ms or 50 Hz (cycles per second). The difference in the peaks of the current and voltage is about 3 ms. Thus the phase angle is (3/20)* 360 or 54º and in radians ~ 0.94. The Power Factor is cosine of 0.94 = 0.588 or 58.8%, which is very close to the 60% determined with the measured real and apparent power.

Conclusion

An oscilloscope, such as a PicoScope, can be used to view mains power waveforms using only basic equipment such as that available from Pico Technology or found in most electrical laboratories. With the measurement and calculation features built in to the program, it is fairly efficient to calculate real and apparent power, and power factor.

ADDENDUM – CORRECTING POWER FACTOR CALCULATIONS WITH DISTORTION FACTOR

The full definition of power factor must include the phase relationship between the voltage and current (displacement factor) as well as the harmonic distortion (distortion factor). For a complete understanding of the power factor and the means to correct it, the distortion factor must also be included in any power factor calculations.

To understand this distortion factor correction, the below article (March 15, 2017) by David Williams, electrical engineer and an instructor for the Electronic Engineering Technology program at Okanagan College in Kelowna, BC, Canada, was published on line in the All About Circuits, entitled, *Understanding Total Harmonic Distortion (THD) in Power Systems,* https://www.allaboutcircuits.com/technical-articles/understanding-thd-total-harmonic-distortion-in-power-systems/.

Total harmonic distortion (THD) is an important aspect in power systems and it should be kept as low as possible. Lower THD in power systems means higher power factor, lower peak currents, and higher efficiency. Low THD is such an important feature in power systems that international standards such as IEC 61000-3-2 set limits on the harmonic currents of various classes of power equipment.

Introductions to AC circuit analysis typically focus on power factor as being determined by the phase relationship between the voltage and current in a circuit while generally ignoring the effect of Total Harmonic Distortion on power factor. Specifically: Power Factor=$\cos(\theta_v - \theta_i)$ eqn. 1

Where θ_v is the phase of the voltage and θ_i is the phase of the current.

This is not the full definition of power factor and this equation, which is called the ***displacement factor***, is only true if both the voltage and the current are completely sinusoidal.

Most folks new to AC circuits are introduced to the proper definition of power factor, but after this introduction they typically focus only on the displacement factor and not the effect of THD. The full definition of power factor is: Power Factor=$P_{avg}/[(V_{rms})(I_{rms})]$ eqn. 2

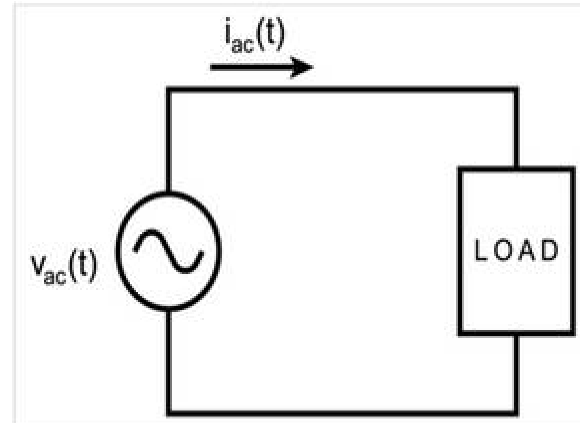


Figure 1. AC voltage source with load

Power Factor is applicable to circuits with the general form of Figure 1 where there is an AC voltage source that provides an AC current for some kind of load. It is the nature of the load that determines the nature of the current and therefore the power factor.

Power Factor without THD

If the voltage and current are purely sinusoidal, then the RMS voltage and current can be determined directly from the peak voltage and current: $V_{rms}=V_{pk}/\sqrt{2}$ and $I_{rms}=I_{pk}/\sqrt{2}$

If the load is purely resistive, then the average power and apparent power would be equal and the power factor would be 1. If the load also has capacitive and/or inductive elements then the phase difference between the voltage and current could be measured to determine power factor from the equation 1. Figures 2 to 4 show three types of loads along with the relationship between the phases of the voltage and current as well as the relative power factors. Remember, these power factors can be calculated directly from equation 1 because the voltage and current are purely sinusoidal.

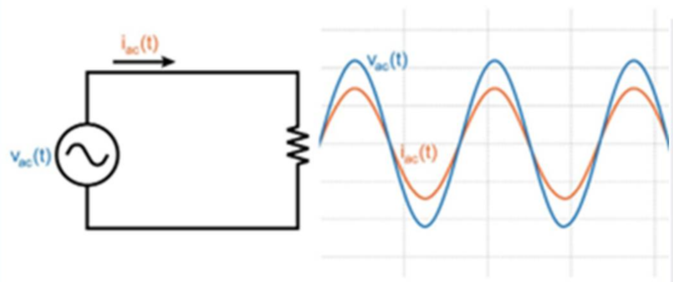


Figure 2. Resistive load with waveforms (Power Factor = 1. Voltage and current are in phase)

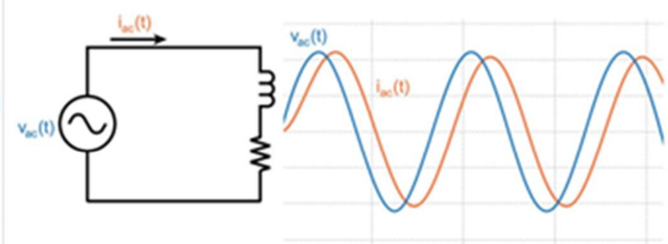


Figure 3. Resistive and inductive load with waveforms (Power Factor < 1 and voltage leads current)

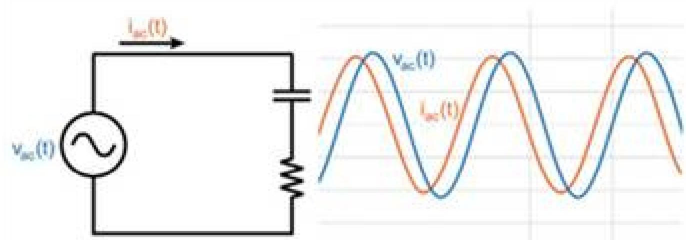


Figure 4. Resistive and capacitive load with waveforms (Power Factor < 1 and current leads voltage)

Improving the power factor in systems like those in Figures 3 and 4 requires placing a component with the opposite amount of reactance into the system to counteract the reactance already in the system.

THD in Power Factor

Most electrical systems do not have loads with only resistors, inductors and capacitors. Most loads also include power conversion of some kind (such as AC/DC – especially computer and sensitive electronic systems, DC/AC, or DC/DC converters) or some other kind of non-linear load (e.g. fluorescent lighting). These power converters and other non-linear loads change the nature of the current so that it is no longer sinusoidal. Switching power supplies, in which the power element rapidly transitions between a fully-on and a fully-off state, can be especially non-linear. Tricks such as filtering or adding control systems to force current flow to follow a reference signal are often used to reduce the effect of the switching. Even "linear" AC/DC converters significantly change the nature of the current so that it is no longer sinusoidal. Current in these types of converters is "bursty", and this article describes exactly why that is the case.

Since the current in these non-linear systems is still periodic (just not sinusoidal), this change in the nature of the current can be described in terms of the harmonic distortion of the current. Each one of the harmonics in the current has an RMS value, so calculation of the RMS current of the whole signal (as you would need to do when calculating power factor) involves summing the RMS value of each harmonic.

$$I_{rms} = \sqrt{\left[I^2_{dc} + \sum_{k=1}^{\infty} I^2_{k\_rms} \right]} \qquad \text{eqn. 3}$$

If you assume that you have a good voltage source that provides a sinusoidal voltage, then there is no voltage at frequencies other than the fundamental so real power will only be provided at the fundamental frequency: $P_{avg} = V_{1\_rms} \times I_{1\_rms} \times (\text{DisplacementFactor})$ eqn. 4

On the other hand, apparent power which is equal to $V_{rms}I_{rms}$ will include all of the current harmonics, so the term in the denominator of Equation 2 will be higher than what you would expect if you are only using the current at the fundamental frequency. Taking eqn. 3 and 4 and plugging them into eqn. 2 gives:

$$\text{PowerFactor} = \frac{[V_{1\_rms} \times I_{1\_rms} \times (\text{DisplacementFactor})]}{[V_{1\_rms} \times \sqrt{[I^2_{dc} + \sum_{k=1}^{\infty} I^2_{k\_rms}]}}$$

$$= \frac{I_{1\_rms}}{\sqrt{\left[I^2_{dc} + \sum_{k=1}^{\infty} I^2_{k\_rms} \right]}} \times \text{Displacement Factor} \qquad \text{eqn. 5}$$

Distortion Factor and THD

As mentioned before, the displacement factor is due to the phase difference between voltage and current ($\cos(\theta_v - \theta_i)$). The other term shown in eqn. 5 is called the distortion factor and is due to the harmonic distortion of the current.

$$\text{Distortion Factor} = \frac{I_{1\_rms}}{\sqrt{\left[I^2_{dc} + \sum_{k=1}^{\infty} I^2_{k\_rms} \right]}} = I_{1\_rms} / I_{rms}$$

Clearly, distortion factor is due to the harmonic distortion of the current, but we need to consider how distortion factor is related to the measurement of THD, where

$$\text{THD} = \frac{\sqrt{\left[\sum_{k\neq 1} I^2_{k\_rms}\right]}}{I_{1\_rms}}$$

[SPECIAL COMMENTARY BY L KILLION: AS SHOWN BY THE ABOVE ALTERNATE EQUATION FOR DETERMINING TOTAL HARMONIC DISTORTION, IF THE FUNDAMENTAL CURRENT, $I_{1\ rms}$ IS REDUCED (BETTER POWER FACTOR), WHICH COULD HAPPEN WHEN A POWER CONDITIONER IS INTRODUCED INTO THE CIRCUIT, THEN THD CAN INCREASE (DEPENDING ON WHAT HAPPENS TO THE SQAURE ROOT OF THE SUM OF THE SQUARES OF THE NON-FUNDAMENTAL HARMONIC CURRENTS) BECAUSE THE DENOMINATOR OF THIS EQUATION WOULD DECREASE CAUSING THD TO INCREASE (DIVIDING A SMALLER NUMBER INTO THE DENOMINATOR RESULTS IN INCREASE IN THE RESULT). THUS, EVEN THOUGH A POWER CONDITIONER CAN REDUCE THE WOBBLINESS OR DISTORTION IN THE CURRENT AND VOLTAGE WAVEFORMS (A GOOD THING) AND IMPROVE (INCREASE) POWER FACTOR (A GOOD THING), IN PART BY REDUCING THE CURRENT REQURED FOR REAL AND APPARENT POWER, AN ADDITIONAL KNOCK-ON EFFECT IS AN INDICATIVE INCREASE IN THE TOTAL HARMONIC DISTORTION MEASUREMENT, WHICH SEEMS COUNTER-INTUITIVE, SINCE A LOWER THD IS GENERALLY THE DESIRED OBJECTIVE. DEPENDING ON WHETHER THE DISTORTION IS CONTRIBUTED FROM HIGH FREQUENCY HARMONICS OR NOT, THIS INDICATIVE INCREASE IN TOTAL HARMONIC DISTORTION DETERMINATION MAY (IF THE DISTORTION IS MAINLY FROM HIGHER FREQUENCY HARMONICS – LESS DESIRABLE EFFECT) OR MAY NOT (IF THE DISTORTION IF MAINLY FROM LOWER FREQUENCY HARMONICS – THE PREFERRED EFFECT) HAVE AN ADVERSE OR MINOR IMPACT, IF ANY, ON SENSITIVE ELECTRONIC EQUIPMENT.]

With a little bit of arithmetic, distortion factor can be determined in terms of THD:

$$\text{Distortion Factor} = \sqrt{\ [1 / [1 + \text{THD}^2\ ]\ ]}$$

so power factor can be calculated in terms of displacement factor and THD:

$$\text{Power Factor} = \text{Displacement Factor} \times \text{Distortion Factor}$$

$$\text{Power Factor} = \cos(\theta_v - \theta_i) \times \sqrt{\ [1 / [1 + \text{THD}^2\ ]\ ]}$$

THD and Power Factor in Example Power/Power Electronic Systems

Let’s take a look at two example systems; both have harmonics in the current, but one of the systems tries to minimize the effect of the harmonics on THD. The examination below specifically looks at the effects of the harmonics on power factor.

Example 1: AC/DC Converter

This first example is a simple AC/DC converter as shown in Figure 5:

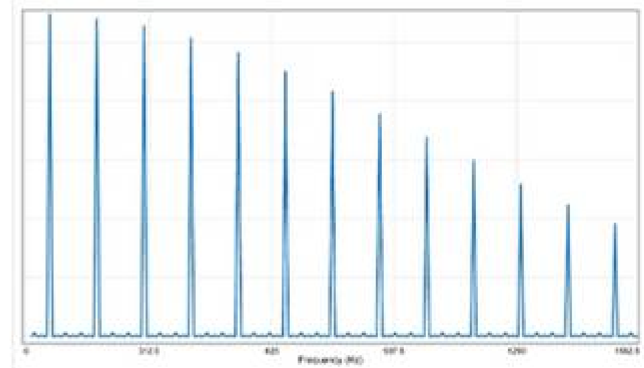


Figure 7. Harmonics of current flowing into a linear power supply

This circuit produces the voltage and current waveforms that appear in Figure 6.

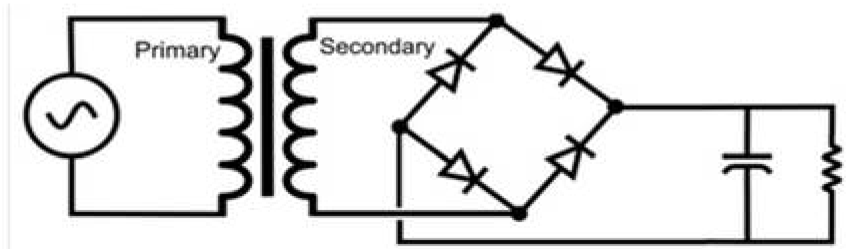


Figure 5. A simple AC/DC Converter

Because of the obvious distortion in the current, you would expect the harmonic current content to be high, and this can be seen in the FFT of the current in Figure 7:

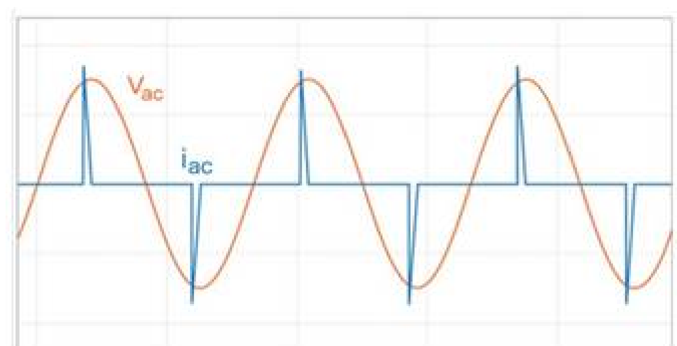


Figure 6. Voltage and current waveforms for a linear power supply

Clearly there is a lot of distortion in the current. Imagine a large scale power system with hundreds or thousands of AC/DC converters connected and the contribution to the harmonic distortion of all of those converters.

Let's actually quantify the power quality and perform the measurements and calculation for determining the power factor.

To determine the power factor requires two separate measurements. The first is the THD of the current in Figure 6, and it is measured as 2.8 (that means 280%). The second is the phase shift between the fundamental of the current and the voltage and it is about 10 degrees, 0.175 radians). This means power factor is

$$\text{PowerFactor} = \cos(10^o) \times \sqrt{[\ 1 / [1 + (2.8)^2\ ]\ ]} = (0.985)(0.336) = 0.331\ (33.1\%)$$

which is a very low power factor, and the biggest contributor to this low power factor is the harmonic distortion of the current.

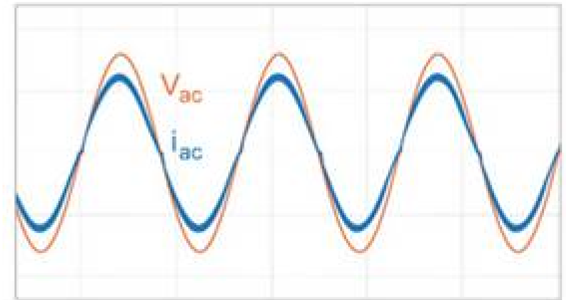


Figure 9. Voltage and current into boost PFC circuit

Example 2: AC/DC Converter with Power Factor Correction

The second example has circuitry is shown in Figure 8 that tries to make the current track the voltage as closely as possible. The purpose of this tracking is to improve the power factor, and while this power factor correction is certainly not perfect, it is a big improvement over the first example.

This circuit produces voltage (v_{ac}) and current (i_{ac}) waveforms that look like this:

The current is obviously distorted, but not by much; the power factor correction significantly reduces the distortion.

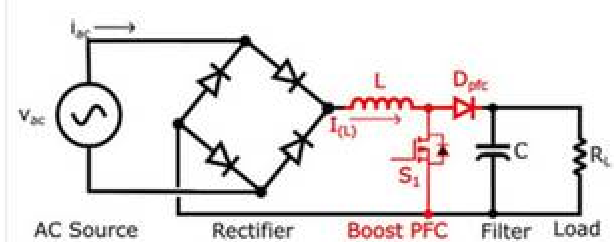


Figure 8. Boost Power Factor Correction Circuit

This next figure, Figure 10, gives an indication of how much the current harmonics have been reduced when compared to the harmonics in Figure 7.

Current harmonics are low and so is the phase difference between voltage and current (about 3º). The combination of the two components, current harmonics (as measured by THD) and phase difference between voltage and current as per equation 5, gives us the power factor. The THD measured in the current signal shown in Figure 9 is 0.2 (or 20%), and the phase shift is 3º, resulting in a power factor of

$$\text{PowerFactor} = \cos(3^\circ) \times \sqrt{[\,1 / [1+(0.2)^2\,]\,]} = (0.999)(0.98) = 0.979\ (97.9\%)$$

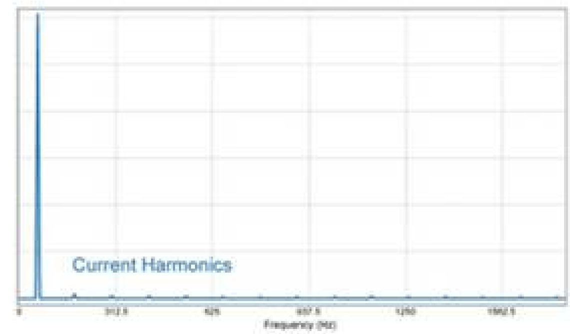
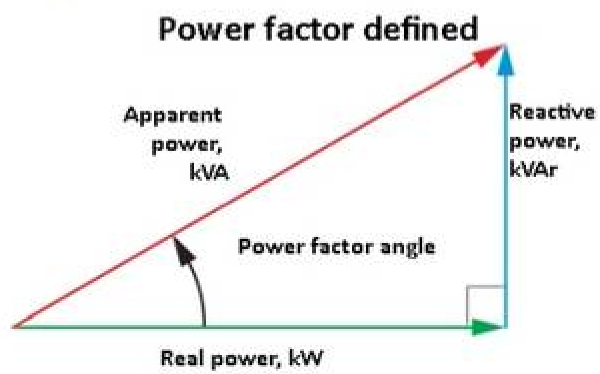


Figure 10. Harmonics of current into boost PFC circuit

This is a high power factor, but if only displacement factor was (incorrectly) used in this calculation, power factor would have been determined to be 0.999 (99.9%).

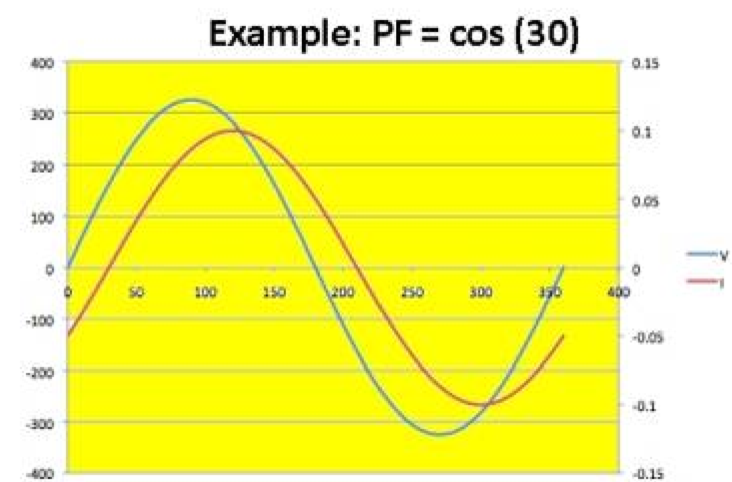
APPENDIX E
HOW TO MEASURE PHASE ANGLE (DISPLACEMENT FACTOR) WITH AN OSCILLOSCOPE, SEPTEMBER 21, 2016 BY DAVID HERRES (EDITED)

By definition, Displacement Factor (sometimes cited as power factor, which is not totally correct since Power Factor is Displacement Factor times Distortion Factor – see Appendix D for full explanagion, but both terms in this section used interchangeably) is a dimensionless quantity ranging from 0 to 1. It is the ratio between real power dissipated in the load (see diagram) and apparent power, which oscillates in the circuit but does not dissipate in the load and consequently does not perform useful work (i.e., wasted power).



The value of the Displacement Factor depends upon the nature of the load. In a purely resistive load such as an incandescent light bulb or electric heater, the factor is close to 1, ***most*** of the power goes into useful work. (There is always some inductance in any conductive body.)

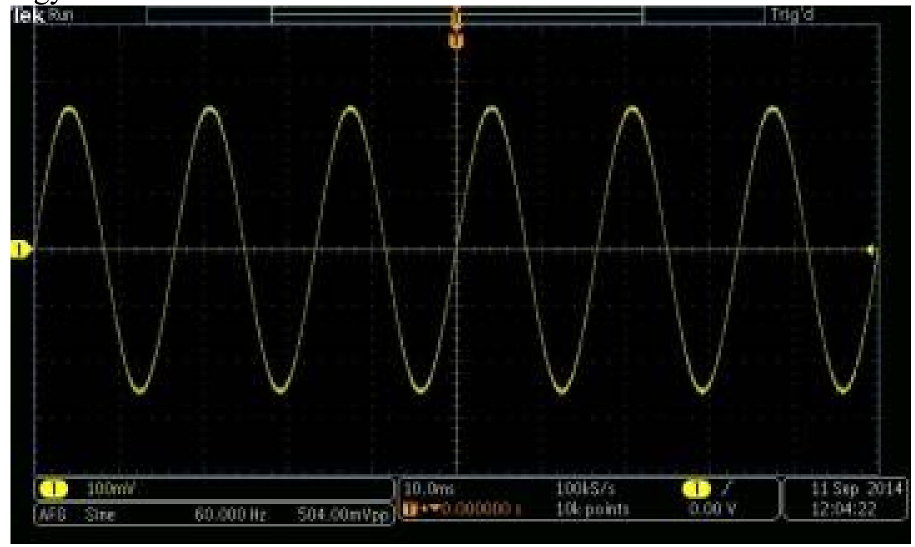
Reactive loads, either inductive or capacitive, lower the factor, necessitating use of larger conductors and devices though the reactive component performs no useful work. Also, there is wasted power (such as heat or vibration). When the factor is less than one, the cost usually gets passed on to the customer in the form of a power factor penalty added to the utility bill.



Most premises loads, especially in industrial or large commercial facilities, have a significant inductive component. Motors, transformers, and other magnetics — as well as fluorescent light ballasts and nonlinear electrical equipment (such as electronic equipment especially those that convert AC to DC such as computers) — contribute to this imbalance.

Displacement Factor, caused by a net inductive (or possibly capacitive) loading, arises from the fact that the applied voltage and measured current waveforms are out of phase (not ideally coincident or overlap with each other). Their peaks occur at different points in time, as shown in the diagram along the Y-axis of an oscilloscope when it is operating in the time domain (X axis is time). The amount of current in a reactive load relates not to the amplitude of the applied voltage, but to the *rate of change* of that amplitude. Examine the graph of a sine wave and you will see that the slope (rate of change) is close to vertical as it crosses the X-axis and near horizontal at its peaks. When the amplitude of the applied voltage is high, the rate of change is low (gradual slope), and when the amplitude is low, the rate of change is high (steep slope).

In an inductive load, the current waveform lags (trails) the voltage waveform. Energy needed to build the magnetic field where it is stored requires a definite amount of time to do so, and another time interval elapses as the energy is returned to the electrical circuit. If the load is capacitive, the current waveform is said to lead (ahead of) the voltage waveform, where electrical energy is stored in the dielectric medium in the form of an electrostatic charge.



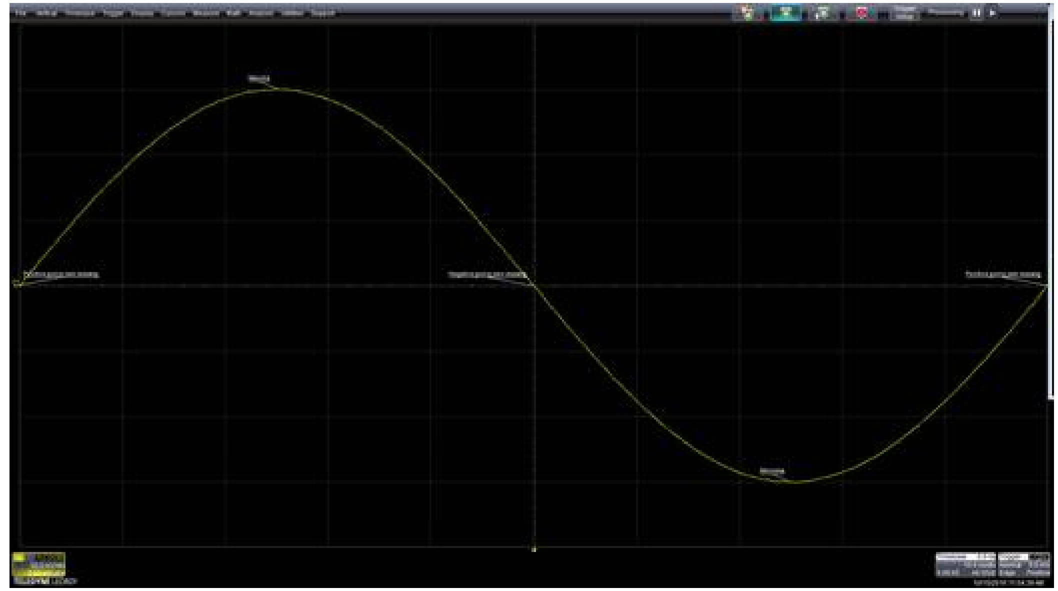
The amount of time separation between the voltage waveform and the current waveform — in other words the degree to which they are out of phase — is expressed as power factor. The oscilloscope is a common instrument for visualizing and measuring power factor in a real-world electrical system and also to ascertain the contribution of an individual motor or other device.

The diagram illustrates a simple sine wave display.

Considering the situation where the voltage and current waveform is sinusoidal. An oscilloscope with conventional probing is a simple voltmeter but one that displays a graphic representation of the voltage (Y axis) plotted with respect to time (time domain in the X axis). An oscilloscope having at least two analog input channels (two probes attached, one for voltage and one for current) is capable of also displaying the current waveform of that signal, plotted against the same amplitude (Y) and time (X) axes. The two aspects of the signal may be shown superimposed or in split-screen format.

A simple current probe in series.
Voltmeter probe leads are attached so the oscilloscope is in ***parallel*** (clamp on) with the power source or load. In contrast, a current ammeter reading, uses probe leads connected in ***series*** (test wire is cut and the meter inserted in the circuit) with the power source or load. Using a conventional ammeter (usually a milliammeter) requires cutting into one of the circuit wires or device leads and the ammeter inserted between the cuts and later re-soldering or re-terminating the cut leads. Moreover, because all the current, in accordance with Kirchhoff's Current Law, passes through the meter, this method is not feasible for large loads.

A clamp-on ammeter in use.
To avoid the problems mentioned above when taking current readings with a multimeter connected in series and cutting the measured circuit, there is an alternative to the ordinary series ammeter. It is the clamp-on ammeter (which correlates flowing current in a wire with the induced magnetic field around that wire, and measuring the intensity of the magnetic field as relating to current flow – electromagnetic principles if you will). This clamp on meter, has jaws which open so a (magnetic field) conductor can be inserted. Thus there is no wire cutting or stripping involved. And the conductor needn't be perfectly centered in the probe; it can pass through at an angle.



Also it doesn't have to be motionless, so vibration present in leads to a running electrical device such as a motor won't compromise accuracy.

The jaws contain a coil to detect the magnetic field surrounding a body conducting electricity (recall moving electrons or current or electricity creates a magnetic field. If there is no current or moving electrons then there is no magnetic field). There is no direct electrical connection between the meter and the power source, so there is no danger of overvoltage unless it is so extreme that arcing takes place. Beyond a certain level, the core becomes saturated and no further transfer of energy takes place.

As an oscilloscope accessory, clamp on current probes are available and it is essential for many types of work, including ***power factor measurements***. The oscilloscope current probe resembles the electrician's clamp-on ammeter, except it is somewhat smaller. Some models have jaws that are not insulated, so bare wire without a sleeve should not be inserted.

To measure motor power factor using an oscilloscope, first ascertain that voltage limits of the oscilloscope will not be exceeded. Then, configure one channel to measure voltage, using a conventional 10:1 attenuation probe, and configure another channel to measure current, using the current clamp on probe. Display both signals simultaneously on the oscilloscope.

Using cursors, manually measure the phase angle between the two waveforms. The following equation relates power factor (Displacement Factor) and phase angle
The power factor PF (Displacement Factor) is equal to the cosine of the phase angle: $PF = \cos(\varphi)$ Where PF is power factor (Displacement Factor, Φ is phase angle. In the above example where the phase angle is 30 degrees or 0.523 radians, its cosine is 0.866 or Power Factor (Displacement Factor) is 86.6% (0.866 x 100).

Care must be taken when using an oscilloscope to measure line voltages and current. Any connection of the ground return lead to a hot line that is referenced to but floats above ground potential can be disastrous for the instrument.

DETERMINING PHASE ANGLE AND POWER FACTOR WITH AN OSCILLOSCOPE

The phase of a periodic electrical waveform describes a specific position at a point in time. The below diagram cites some significant phase points: maximum amplitude, minimum amplitude, and both positive and negative going zero crossings. The phase of a waveform is periodic and a complete cycle of the waveform is defined as having 360º or 2π radians of phase.

The significant phase points on a periodic sine wave shown in the diagram are the peaks and zero crossings.

Phase difference, or phase angle, is the difference in phase between two phase points, usually on two different waveforms with the ***same frequency***. A waveform with a leading phase has a specific phase point occurring earlier in time than the same phase point on its partner. That's the case of when a signal passes through, say, a capacitor: the output current will lead the output voltage by 90º. Conversely, a waveform with lagging phase has phase points occurring later in time than the other paired waveform. Two signals are said to be in opposition if they are 180º out of phase. Signals that differ in phase by ±90º are in phase quadrature.

Phase difference using delay time measurement

Phase difference can be measured on an oscilloscope by finding the time delay between two waveforms and their period plotted in the time domain (the X axis is time and the Y axis, voltage and amps). You can accomplish that using the oscilloscope's cursors as shown in the diagram where relative cursors measure the time difference between the maxima of the two sine waves (in this example, 10 MHz). Cursor time readouts in the lower right corner of the screen indicate a delay of 10 ns. The period can also be measured using the cursors. The phase difference, in degrees, can be determined using the equation:

Phase Angle (Φ) in degrees = $t_d / t_p \times 360 = 10\text{ ns}/100\text{ ns} \times 360^\circ = 36^\circ$
Where: t_d is the delay between waveforms (10 ns in this example) and t_p is the period of the waveforms (100 ns in this example being the time for the wave to complete one cycle).

Phase parameters

This technique is a remnant of analog oscilloscope measurements. It works on digital oscilloscopes (DSOs), but the measurement accuracy is very dependent on the manual placement of the cursors. **DSOs simplify phase measurements by offering direct phase measurement** (and avoid the less accurate manual cursor measurement method) , based on measuring the delay and period of the source waveforms. You can select the measurement thresholds and slopes for each waveform. The phase measurement applies an interpolator to assure accurate location of the measured phase points. The advantage of using the oscilloscope's built-in measurement capability is that it removes cursor placement as an error source. Phase can be read out in units of degrees, radians, or percentage of period. The diagram provides an example of a phase measurement.

Using the phase measurement parameter (if there is one): The parameter P1 (lower left) shows the phase parameter with statistics.

The phase measurement is performed using parameter P1 in the lower left corner of the screen image. This oscilloscope makes "all instance" measurements meaning that the phase is measured for every cycle on the screen for each acquisition. The large number of phase measurements available supports measurement statistics. Measurement statistics show the most recent measurement, the mean value of all the measurements, maximum and minimum values encountered, the standard deviation, and the number of measurements included in the statistics. The key statistical readouts are the mean value and the standard deviation. The mean is the average value of all the measurements made. The standard deviation is a measure of the uncertainty in the measurement. In this example the mean value is 36º. The standard deviation is 0.747º. Most of the uncertainty in this measurement is a function of the vertical noise on the waveform. The mean value reduces noise by averaging the measured values. Noise can further be reduced by decreasing the bandwidth of the oscilloscope front end.

APPENDIX F
TESTING PROCEDURE

Equipment used by the author to assess Total Harmonic Distortion (THD), voltage (volts), current (amps) and Power Factor (%) for equipment powered by utility mains power and portable power backup generator, includes:

- Lenovo W520 Laptop Computer (used to display PicoScope oscilloscope readings), See Figure 3 below.
- PicoScope 2207 PC Oscilloscope, See Figure 2 below.
- Pico PP264 (TA018) Current Clamp (60A AD/DC) with BNC (clamp on current measuring probe that can be plugged into the oscilloscope)
    - A Craftsman No. 161014658 40A/400A clamp on digital clamp on amp-meter was used to double check oscilloscope current measurements (and in all tests such check showed consistent current measurements).
- Pico TA041 25 MHz +/- 700 V Differential (high voltage – too 1000V) Probe (high voltage measuring probe that can be plugged into the oscilloscope)
- Triple Tap 3 Outlet Extension Cord (with a section of the primary exterior insulating wrap removed to expose insulated isolated power supply wires on which the current clamp on meter is attached to the current carrying wires (white or black). Plug the Extension Cord into either the utility mains wall socket or portable generator outlet plug and then plug a load, hair dryer and oscillating fan in this case, then take voltage and current measures from the Extension Cord to which the hair dryer/fan is plugged)
- Male To Male Extension Cord (used to plug into the Triple Tap 3 Outlet Extension Cord which allows access to electrical leads on which the voltage probe can be attached for measuring voltage). ([**SAFETY CAUTION IS INVOKED SINCE THE ELECTRICAL LEADS ARE EXPOSED AND CONTACT MUST BE AVOIDED TO PREVENT A SHOCK**]).
- Reliance Model# A310, Pro/Tran 2 Manual Transfer Switch (for isolating certain selected residential home circuits (9) from the utility power main when those circuits are to be powered by a portable generator. Prevents back-feed of generator power into the utility main when selected circuits are powered by the portable generator and not powered by the utility main)
- PowerwoRx CPS-E3-N3, Residential Clean Power System, 120/240V, Single Phase, Outdoor NEMA 3 Encl. (for assisting in cleaning or conditioning, the portable generator power to a cleaner Total Harmonic Distortion level (ideally < 5% - an improved Power Factor, and primarily installed to help protect sensitive electronic equipment, such as computers, modems, routers, etc., when powering such sensitive electronic equipment with the backup generator)
- Champion 100416 8000W/10000W Electric Start Tri-Fuel Gasoline Propane Natural Gas Portable Generator See Figure 1 below (for use in powering the nine (9) selected, 120 V AC, single phase residential circuits during emergency power outage, such circuits to also power sensitive electronic equipment such as computers, modems and routers. The project design does not power any 240 V devices, such as air conditioning or electric central heaters, electric clothes dryer or electric water heater. The design was not based on whole house power back up requirement – which the project developer assessed as not being practical or economic for his particular needs (particularly since the residential home is location in a large Metropolitan city – Houston, Texas - in which power outage restorage events, generally caused by inclement weather, generally occurs fairly quickly, thus a portable power generator used only for a short duration – measured in days)
- (Hair Dryer BabyBliss PRO Model# BP6685; 125 V AC 60Hz 15.2 AMP 1900 Watt) (used as an electrical load when conducting current, Total Harmonic Distortion and Power Factor measurements). Dryer was operated at high heat, high volume settings.
- (Oscillating Fan Suntea Model# SFC-2016; 120 V AC 60Hz 0.35 AMP 42 Watt) (used as an electrical load when conducting current, Total Harmonic Distortion and Power Factor measurements). Fan was operated at its highest settings and oscillating.

Figure 1, Champion 100416 8000W/10000W Electric Start Tri-Fuel Portable Generator

Figure 2, PicoScope 2207 PC Oscilloscope

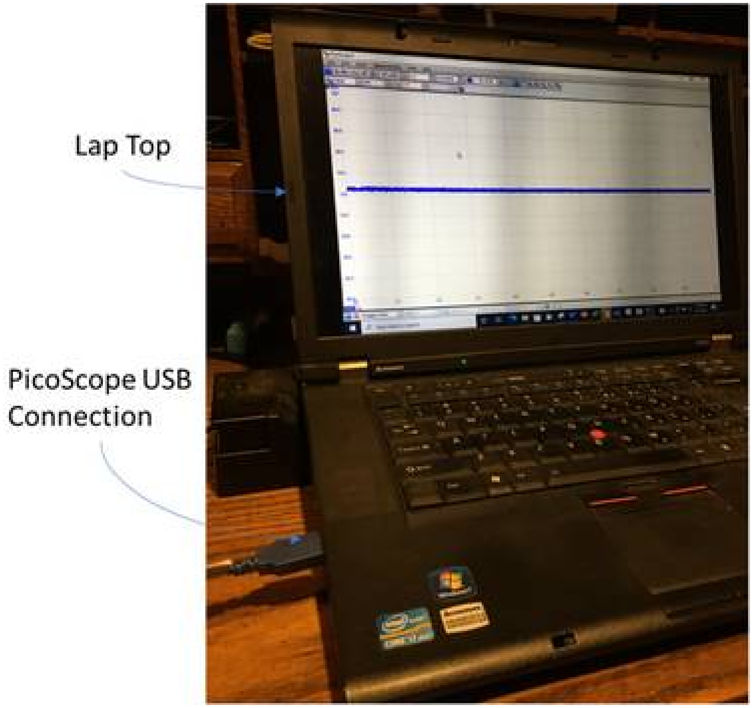


Figure 3, Lenovo W520 Laptop Computer

The below Figure 4, illustrates the test measurement set up.

- The PicoScope USB plug is attached to the Lenovo Lap Top computer and the PicoScop software activated.
- The BNC plug of the high voltage plug is attached to Channel A of the PicoScope and the probe attached to exposed prongs of a plug which is plugged into the 3 prong extension cord (measures voltage).
- The BNC plug of the clamp-on current probe is attached to Channel B of the PicoScope and the probe clamped onto the exposed white wire of the 3 prong extension cord (measured current). The supplemental clamp on digital ampmeter is also clamped on the same wire and amp readings compared.
- The hair dryer/fan loads are plugged into the 3 prong extension cord.
- The 3 prong extension cord is plugged into a convenient utility mains wall outlet or generator outlet

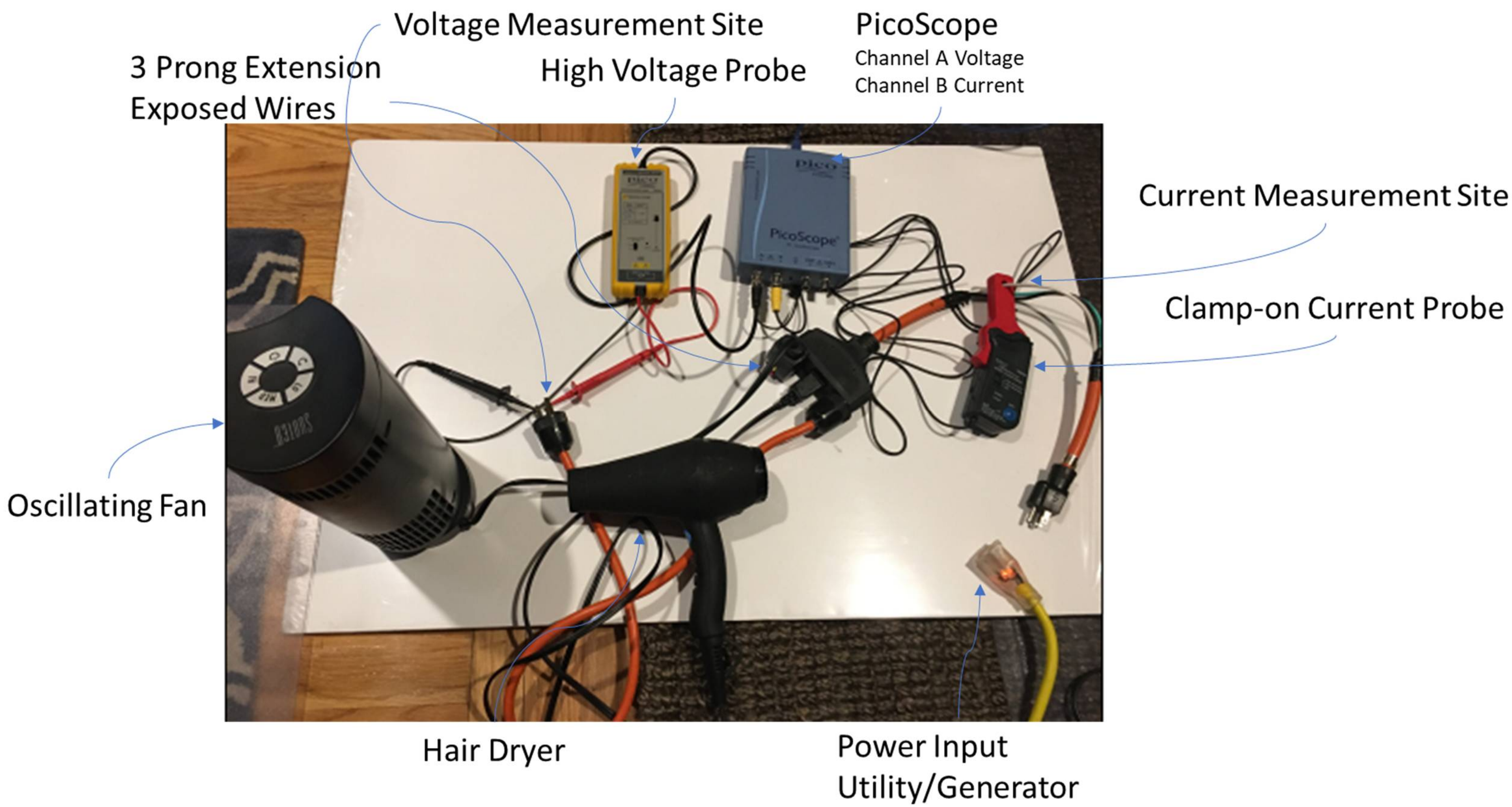


Figure 4, Test Measurement Set Up

MEASUREMENT AND TESTING PROCEDURES

The procedure for measuring or calculating Total Harmonic Distortion, current, voltage and Power Factor for the utility main power and portable generator are discussed below.

1. **Utility Mains Test**
   a. No load circuit (utility power available – i.e., no power outage and portable generator is not required)
      i. Plug the Outlet Extension Cord into a convenient wall socket (rated at 15- or 20-amp circuit breaker controlled) not using a load
      ii. Attach voltage probe to Male to Male extension prongs plugged into the 3 prong extension containing exposed power wires, attach probe to oscilloscope and attach oscilloscope to lap top computer

iii. Plug the Male to Male extension cord into the Outlet Extension Cord (being careful not to touch the exposed leads)
iv. Measure lines voltage and Total Harmonic Distortion – Channel A Voltage (record oscilloscope measurement graphical sine waveform of each measurement shown on the laptop).

b. Load circuit
   i. Plug the Outlet Extension Cord into a convenient wall socket (rated at 15- or 20-amp circuit breaker controlled) not using a load
   ii. Attach voltage probe to Male to Male extension prongs plugged into the 3 prong extension containing exposed power wires, attach probe to oscilloscope and attach oscilloscope to lap top computer
   iii. Plug the Male to Male extension cord into the Outlet Extension Cord (being careful not to touch the exposed leads)
   iv. Attach clamp on current probe to exposed Outlet Extension Cord wires (white), attach probe to oscilloscope and attach oscilloscope to lap top computer
   v. Plug hair dryer or Fan into Outlet Extension Cord and turn on hair dryer or Fan, as applicable.
   vi. Measure lines voltage, RMS current and RMS voltage, actual power, cursor measurement of phase timing between voltage and current sine waves, and Total Harmonic Distortion – Channel B current (record oscilloscope measurement graphical sine waveform of each measurement shown on the laptop).
      1. Voltage and current graphical readings and noted phase difference in their waveform will be used to determine the Power Factor (explained in Appendix D and E).

2. Portable Generator (gasoline fuel powered) Test

a. No load circuit without PowerwoRx Residential Clean Power System
   i. Plug the Outlet Extension Cord into a convenient generator socket (rated at 15- or 20-amp circuit breaker controlled)
   ii. Attach voltage probe to Male to Male extension prongs plugged into the 3 prong extension containing exposed power wires, attach probe to oscilloscope and attach oscilloscope to lap top computer
   iii. Plug the Male to Male extension cord into the Outlet Extension Cord (being careful not to touch the exposed leads)
   iv. Measure portable generator voltage and Total Harmonic Distortion – Channel A voltage (record oscilloscope measurement graphical sine waveform of each measurement shown on the laptop).

b. Load circuit without PowerwoRx Residential Clean Power System
   i. Plug the Outlet Extension Cord into a convenient generator socket (rated at 15- or 20-amp circuit breaker controlled)
   ii. Attach voltage probe to Male to Male extension prongs plugged into the 3 prong extension containing exposed power wires, attach probe to oscilloscope and attach oscilloscope to lap top computer
   iii. Plug the Male to Male extension cord into the Outlet Extension Cord (being careful not to touch the exposed leads)
   iv. Attach clamp on current probe to the exposed Outlet Extension Cord wires (white), attach probe to oscilloscope and attach oscilloscope to lap top computer
   v. Plug hair dryer or Fan into Outlet Extension Cord and turn on hair dryer or Fan, as applicable.
   vi. Measure lines voltage, RMS current and RMS voltage, actual power, cursor measurement of phase timing between voltage and current sine waves, and Total Harmonic Distortion – Channel B current (record oscilloscope measurement graphical sine waveform of each measurement shown on the laptop).

1. Voltage and current graphical readings and noted phase difference in their waveform will be used to determine the Power Factor (explained in Appendix D and E).

c. No load circuit with PowerwoRx Residential Clean Power System

i. Confirm PowerwoRx Residential Clean Power System is connected to the circuit
ii. Plug the Outlet Extension Cord into a convenient generator socket (rated at 15- or 20-amp circuit breaker controlled)
iii. Attach voltage probe to Male to Male extension prongs plugged into the 3 prong extension containing exposed power wires, attach probe to oscilloscope and attach oscilloscope to lap top computer
iv. Plug the Male to Male extension cord into the Outlet Extension Cord (being careful not to touch the exposed leads)
v. Measure portable generator voltage and Total Harmonic Distortion – Channel A voltage (record oscilloscope measurement graphical sine waveform of each measurement shown on the laptop).

d. Load circuit with PowerwoRx Residential Clean Power System

i. Confirm PowerwoRx Residential Clean Power System is connected to the circuit
ii. Plug the Outlet Extension Cord into a convenient generator socket (rated at 15- or 20-amp circuit breaker controlled)
iii. Attach voltage probe to Male to Male extension prongs plugged into the 3 prong extension containing exposed power wires, attach probe to oscilloscope and attach oscilloscope to lap top computer
iv. Plug the Male to Male extension cord into the Outlet Extension Cord (being careful not to touch the exposed leads)
v. Attach clamp on current probe to the exposed Outlet Extension Cord wires (white), attach probe to oscilloscope and attach oscilloscope to lap top computer
vi. Plug hair dryer or Fan into Outlet Extension Cord and turn on hair dryer or Fan, as applicable.
vii. Measure lines voltage, RMS current and RMS voltage, actual power, cursor measurement of phase timing between voltage and current sine waves, and Total Harmonic Distortion – Channel B current (record oscilloscope measurement graphical sine waveform of each measurement shown on the laptop).

1. Voltage and current graphical readings and noted phase difference in their waveform will be used to determine the Power Factor (explained in Appendix D and E).

APPENDIX G
TEST RESULTS

Measurement results are illustrated in the below summary table, graphical illustrations and discussion.

Summary Table of Measurement Results

	UTILITY MAINS **(WITHOUT POWER CONDITIONER)**			PORTABLE GENERATOR (gasoline fuel) **(WITHOUT POWER CONDITIONER)**			PORTABLE GENERATOR (gasoline fuel) **(WITH POWER CONDITIONER)**		
	No Load	LOAD (Dryer[11])	LOAD (Fan[12])	No Load	LOAD (Dryer)	LOAD (Fan)	No Load	LOAD (Dryer)	LOAD (Fan)
Voltage, Volts, AC									
Min	122.1	114.8	122.6	120.7	117.6	120.9	118.7	117.5	118.9
Avg (RMS)	122.1	114.9	122.6	121	117.8	121.1	119	118.4	119.3
Max	122.1	114.9	122.7	121.3	118.1	121.6	119.4	118.7	119.8
Peak	169.5	159	157.7	183	171.5	185	185	182	186.6
Std Dev.	99.6 µV	201 µV	194 µV	5.2 µV		1.0 mV	2.4 mV	2 mV	1 mV
Current, Amps, AC									
Min	-	13.03	.37	-	13.2	0.39	-	12.9	0.36
Avg (RMS)	-	13.02	.37	-	13.2	0.39	-	12.96	0.36
Max	-	13.02	.376	-	13.3	0.39	-	12.98	0.36
Std. Dev.	-	0.004	.002	-	1.5mV	127 µV	-	1.6 mV	90 µV
Total Harmonic Distortion, % (Channel)	A	B	B	A	B	B	A	B	B
Min	2.71%	5.1%	11.49%	11.9%	10.5%	13.4%	16.1%	15.45%	10.85%
Avg	2.73%	5.13%	11.53%	19.4%	10.6%	14.3%	16.2%	15.6%	10.9%
Max	2.74%	5.16%	11.57%	29.0%	10.7%	15.6%	16.24%	15.8%	11.1%
Std. Dev.	0.009%	0.013%	0.028%	5.7%	0.06%	0.67%	0.08%	0.12%	0.06%
Phase Angle[a], Voltage/Current	-	-	-	-	-		-	-	-
Peak-to-Peak Voltage- Current	-	0.31-0.92	2.48	-	0.18	2.3	-	<0.1	1.55-1.8

[11] Hair Dryer BabyBliss PRO Model# BP6685; 125 V AC 60Hz 15.2 AMP 1900 Watt

[12] Oscillating Fan Suntea Model# SFC-2016; 120 V AC 60Hz 0.35 AMP 42 Watt

Phase Time Difference, ms (t_d)									
Cycle Time, ms (t_p)	16.76	16.65	16.72	16.21	16.44	16.21	16.22	16.48	16.22
Frequency, Hz (ω)	59.7	60.1	59.8	61.9	61.0	61.6	61.5	60.5	61.5
Phase Angle[a], Degrees	-	6.7° – 19.9°	53.4°	-	4°	51.1°	-	2.2°	34.4°-40°
Phase Angle, Radians	-	0.11 – 0.35	0.93	-	0.069	0.89	-	0.04	0.6-0.7
Displacement Factor[b]	-	0.99-0.94	0.60	-	0.99	0.63	-	0.99	0.83-0.76
Distortion Factor[c]	0.99	0.99	0.99	0.98	0.99	0.98	0.98	0.98	0.99
Power Factor[d], %	-	98% - 93%	54%	-	98%	62%	-	97%	82.%-75%
Average Power, Watts (DC average of the math channel[e])	-	1493	29.4	-	1556	29.2	-	1520	27.4
Power Factor[f], %	-	99.9%	65.0%	-	100%	61.8%	-	98.8%	63.8%

a Phase Angle (degrees) = [(peak-to-peak voltage-current phase time difference, t_d)/(one cycle time, t_p)] * 360°

Example: t_d = 2.48 ms; t_p = 16.72 ms; (2.48/16.72)*360° = 53.4°.

b Displacement Factor = Cosine Phase Angle (radians)

Example: Phase angle = 53.4° = 0.932 radians; Displacement Factor = Cosine (0.932) = 0.596

c Distortion Factor = Square Root [1/(1+ THD^2)]

Example: THD = 0.2 (20%); Distortion Factor = Square Root [(1/(1 + 0.2^2)] = 0.98

d Power Factor = Displacement Factor x Distortion Factor

Example: 0.596 x 0.98 = 0.584 (58.4%)

e Average Power is the PicoScope math channel of A*B (voltage times current = power) and the Average DC of that channel being the average working power actually consumed.

f Power Factor, based on Average Power (PR, real power)/RMS (PA, apparent power) measurements (%) = Average Power (DC Average – Oscilloscope integrates voltage x current over one power cycle) / (RMS voltage*RMS current)*100

Example: RMS AC voltage (V) = 121.5 V; RMS AC current (I) = 0.37 Amps; Apparent Power = V * I = 121.5 * 0.37 = 44.95 Watts; Real Power = DC Average Power from oscilloscope reading = 29.4 Watts; Power Factor = 29.4 (Real Power)/44.95 (Apparent Power) = 65.4%

Graphical Illustrations (from Oscilloscope readings)

Test Probes and Other Test Condition Settings

Interpreting the measurement reported from the PicoScop Oscilloscope viewing screen requires taking into account any measurement probe settings and making appropriate conversions to determine absolute measurement results.

Channel A is voltage probe and Channel B is current clamp on probe.

PicoScope Voltage Probe

- The voltage probe has two scale settings: +/- 70 volts @ a 1/10 scale and +/- 700 volts @ a 1/100 scale. The later scale was used in all measurements since line voltage is expected to be ~120 volt AC.
- The PicoScope Oscilloscope screen scale is was set at a range of +/- 2 volts (blue scale) since the probe converts high voltage to lower voltage scale compatible with the scope. A magenta coloured scale was set up to report actual AC voltage (which can be read directly off the graph – the A Channel is multiplied by 100).
- The measurement table at the bottom of the oscilloscope graphs, reports voltage for Channel A based on the +/- 2 volt setting which is multiplied by 100 (the probe factor) to determine actual voltage. For example a reading for A channel (voltage channel) of 1.221 Volt when multipled by 100 = 122.1 Volt AC. The peak voltage of the sine curve for voltage can be determined by moving the cursor of the PC over the top of the curve and pushing the right mouse button where a table is displayed showing the data for that particular point. The peak voltage is reported on a scale of +/- 2 volt which is multiplied by 100 to determine absolute peak voltage.
- In the case of no load, the current is zero. There will be a very small reading for current even without a load due to 'noise' in the oscilloscope circuitry.
- Frequency can be determined by measuring the distance for the voltage curve between peak to peak and read off the milli second of time which is the time for one cycle (say 16.76 ms). Inverting that number and multiplying by 1000 results in frequency in Hertz (Hz) or cycles per second. (1/16.76 ms)*(1000) = 59.7 Hz (close to the expected ideal frequency of 60).

PicoScope Current Clamp Probe

- The current probe has two scale settings: 20 A (100mV/Amp) and 60 A (10 mV/Amp). The oscilloscope reports amps as a milli Volt measurement which valued is converted to Amps by multiplying by the relevant scale factor (100 or 10).
- The Channel B (current probe) table at the bottom of the charts reports current in mV, which is multiplied by the appropriate factor (10 or 100) to determine Amps. For example, a setting of 100 mV/Amp for a 37.6 mV reading is equal to 0.376 Amps
- A Craftsman No. 160114658 clamp digital ampmeter (40A and 400 A scales) was used as a check against oscilloscope amp readings and in all tests, the Craftsman amp readings were very close to the PicoScope readings so confidence the oscilloscope amp measurements are valid.

Real Power

- Real power was measured direct by using the PicoScope math channels by multiplying Channel A (voltage) times Channel B (current) and using the DC Average tool (which integrates the voltage and current calculation over time). The units is Watts but depending on the probe settings, a multiplying factor may be required depending on the units of voltage and current. (Example: if Channel A (voltage) probe is set at a 1/100 scale and a reading of 1.2 V and

Channel B (current) probe is set at a scale of 10 mV/Amp, and a reading of 36.6 mV, the resultant power is 1.2 V x 36.6 mV (0.36 Amp), the power is 1.2 x 0.36 x 100 or 43.2 Watts. If Channel A voltage scale is 1/100 and current set 10 mV/Amp (and reported in volts) the power is indicated reading (say 1.495) is multipled by 1000 to determine watts or 1495 watts.

- Phase angle between voltage and current sine waves is determined by measuring the time difference between the peaks of the curves, converting to an angle in radians and then taking the cosine of that angle times 100 = power factor.

OBSERVATIONS DRAWN FROM THE TEST DATA

1) **Utility Power Without Power Conditioner (Oscilloscope Graphs 1 – 8)**
   a) **Graphs 1: No load, no wobble voltage sine waveform, V_{rms} = 122.1 volts; V_{peak} = 169.5 volts; 59.7 Hz frequency (clean power waveform as anticipated to be provided by a regulated utility)**
   b) **Graph 2: No load, Total Harmonic Distortion < 5% (2.7% avg) (visually majority of harmonic frequencies < ~1000 Hz) (clean power waveform as anticipated to be provided by a regulated utility). Theoretically, this THD is the power source background contribution fed into the circuit, with the other THD originating from equipment using the power, thus the sum of the background and load created THD contributing to the measured THD.**
   c) **Graph 3: Oscillating Fan Load (42 Watt nameplate), voltage, current and power waveform essentially no wobble, I_{rms} = 0.37 amp consistent with 0.35 amp nameplate rating.**
      i) **Power Factor ranged from 54% (manual phase angle measurement) to 65% (oscilloscope real and apparent power measurements); average of 59.5%; not uncommon for floor fans**
   d) **Graph 4: Oscillating Fan Load, Total Harmonic Distortion, 11.5% (avg) (visually majority of harmonic frequencies < 1200 Hz); oscillating fan motor tends take 'bites' from power supply to operate the fan, hence more harmonic interference from the fan: Theoretically 2.7% from the power source + 8.5% from the fan = 11.7% total.**
   e) **Graph 5-6: Hair Dryer (1900 Watt nameplate), voltage, current and power waveform essentially no wobble, I_{rms} = 13.03 amp consistent with 15.2 amp nameplate rating**
      i) **Graph 6: Closeup of phase angle manual measurement since it was so small (indicating high Power Factor, not uncommon for a resistive load such as a hair dryer using most of its energy to create heat).**
   f) **Graph 7: Hair Dryer Load, Total Harmonic Distortion, 5.13% (avg) (visually majority of harmonic frequencies < 1100 Hz) ; linear resistive dynamic load does not cause excessive spike demand bites from the power source which should lead to lower Total Harmonic Distortion. Theoretically 2.7% from the power source + 2.43% from the dryer = 5.13% total.**
2) **Portable Generator Power Without Power Conditioner (Oscilloscope Graphs 8 – 14)**
   a) **Graph 8: No load, wobble voltage sine waveform, V_{rms} = 121.2 volts; V_{peak} = 183.3 volts; 61.9 Hz frequency (erratic waveform as anticipated to be provided by a non-inverter generator)**
   b) **Graph 9: No load, Total Harmonic Distortion 19.4% (avg) (visually majority of harmonic frequencies < ~6000 Hz) (dirty power waveform as anticipated to be provided by a non-inverter generator). Theoretically, this THD is the power source background contribution fed into the circuit, with the other THD originating from equipment using the power, thus the sum of the background and load created THD contributing to the measured THD.**
   c) **Graph 10-11: Oscillating Fan Load (42 Watt nameplate), voltage, current and power waveform significant wobble, I_{rms} = 0.39 amp consistent with 0.35 amp nameplate rating.**

i) **Power Factor ~ 62%, comparable to utility power**

d) **Graph 12: Oscillating Fan Load, Total Harmonic Distortion, 14.3% (avg) (visually majority of harmonic frequencies < 4500 Hz); oscillating fan motor tends take 'bites' from power supply to operate the fan, hence more harmonic interference from the fan: Theoretically 19.4% from the power source – 5.1% from the fan = 14.3% total (which cannot happen so the harmonic distortion is less prevalent in this test case), but more distortion than the utility power of 11.53%.**

e) **Graph 13: Hair Dryer (1900 Watt nameplate), voltage, current and power waveform noticeable wobble (not as much as fan), I_{rms} = 13.25 amp consistent with 15.2 amp nameplate rating**

f) **Graph 14: Hair Dryer Load, Total Harmonic Distortion, 10.6% (avg) (visually majority of harmonic frequencies < 4000 Hz) ; linear resistive dynamic load does not cause excessive spike demand bites from the power source which should lead to lower Total Harmonic Distortion. Theoretically 19.4% from the power source – 8.8% from the fan = 10.6% total (which cannot happen so the harmonic distortion is less prevalent in this test case), but more distortion than the utility power of 5.13%.**

3) **<u>Portable Generator Power With Power Conditioner (Oscilloscope Graphs 15 – 20)</u>**

a) **Graph 15: No load, no wobble voltage sine waveform, V_{rms} = 119 volts; V_{peak} = 185 volts; 61.5 Hz frequency (smooth waveform as desired with a power conditioner associated with a non-inverter generator)**

b) **Graph 16: No load, Total Harmonic Distortion 16.2% (avg) (visually majority of harmonic frequencies < ~1100 Hz) (cleaner power waveform as anticipated to be provided by a non-inverter generator). Theoretically, this THD is the power source background contribution fed into the circuit, with the other THD originating from equipment using the power, thus the sum of the background and load created THD contributing to the measured THD. This THD, 16.2% with conditioner is 3.2% lower (better, ~20% improvement) than generator without the conditioner.**

c) **Graph 17: Oscillating Fan Load (42 Watt nameplate), voltage, current and power waveform significant wobble, I_{rms} = 0.36 amp consistent with 0.35 amp nameplate rating. Without the conditioner the power draw was 0.39 amps, so the lower amp draw (better power factor) ostensibly caused by the conditioner can result in a higher THD determination**

i) **Power Factor ranged from 82%-75% when phase angle formula was used (and phase angle had a long range due to long flat current peak and difficult to manually define peak amplitude from which to determine the phase) and 63.8% determined from the oscilloscope real and apparent power internal calculations. Two conclusions can be drawn: either the conditioner slightly improved the power factor (2%), or the power factor was marginally improved (between 11% to 19.2%).**

d) **Graph 18: Oscillating Fan Load, Total Harmonic Distortion, 10.9% (avg) (visually majority of harmonic frequencies < 1000 Hz); oscillating fan motor tends take 'bites' from power supply to operate the fan, hence more harmonic interference from the fan but the conditioner seems to have corrected some of this given the lower harmonic frequency distortion: Less distortion than the without the conditioner of 14.3%.**

e) **Graph 19: Hair Dryer (1900 Watt nameplate), voltage, current and power waveform very little wobble, I_{rms} = 12.96 amp consistent with 15.2 amp nameplate rating. Without the conditioner the power draw was 0.39 amps, so the lower amp draw (better power factor) ostensibly caused by the conditioner can result in a higher THD determination.**

f) **Graph 20: Hair Dryer Load, Total Harmonic Distortion, 15.6% (avg) (visually majority of harmonic frequencies < 2200 Hz) ; linear resistive dynamic load does not cause excessive spike demand bites from the power source which should lead to lower Total Harmonic Distortion. Theoretically 16.2% from the power source – 0.6% from the fan = 15.6% total. Higher distortion than the unconditioned THD of 10.6%. Part of this increase in THD can be attributed to the following: the power conditioner reduced the THD of the generator with no load (16.2% to 15.6%), the reduction in current used caused by the conditioner (12.96 amp vs 13.2 amp, can result in a higher THD).**

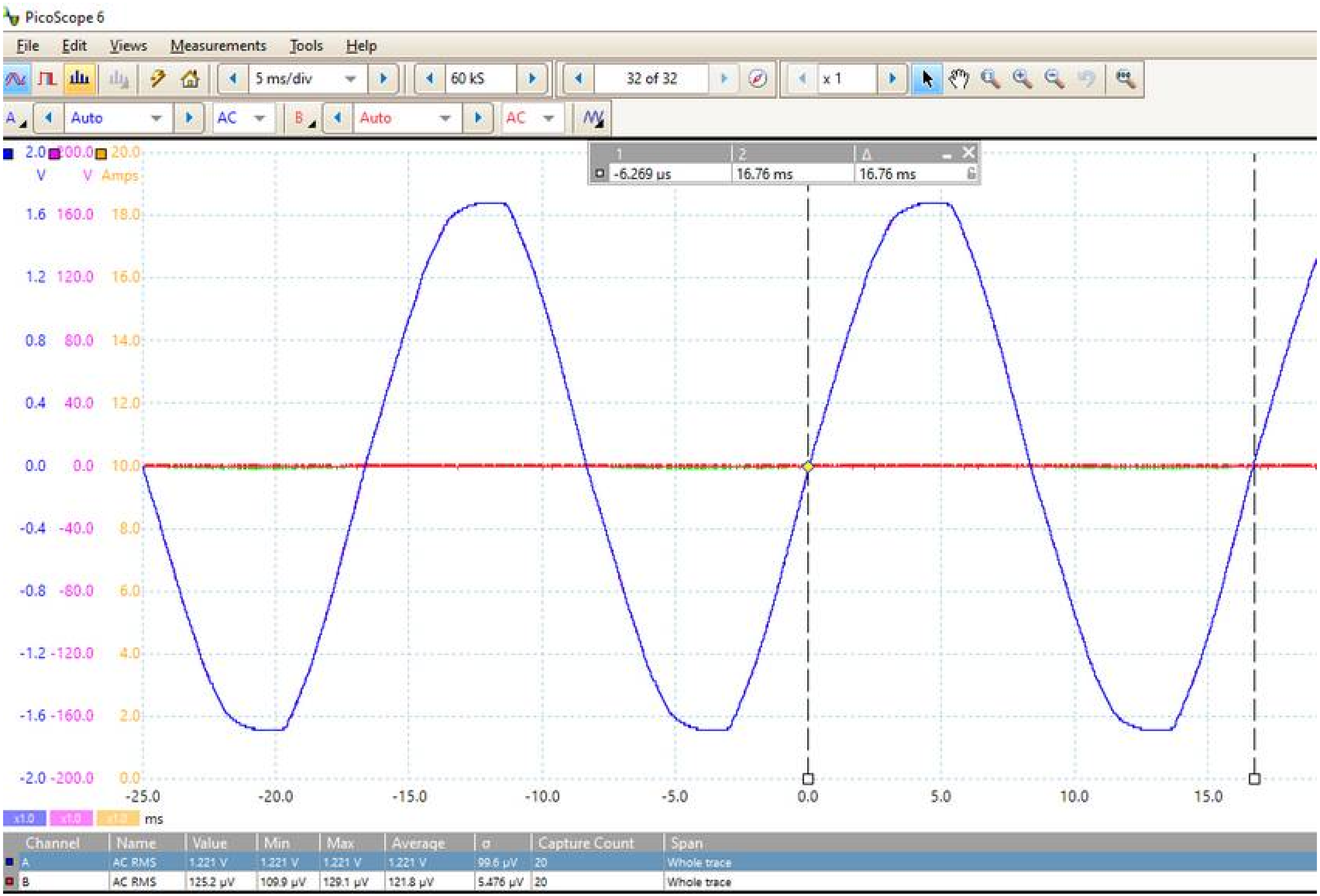
OVERALL OBSERVATIONS

- ✓ **Was the Total Harmonic Distortion improved with the power conditioner – YES**
- ✓ **Was the Power Factor improved with the power conditioner – YES**
- ✓ **Was the wobbliness of voltage-current-power wave forms improved with the power conditioner – YES**

Consequently, a correctly sized (the right start-up and run wattage) non-inverter portable generator, used during an emergency incident to provide electric power, associated with an appropriate power conditioner (which may include a PowerwoRx , Residential Clean Power System), is unlikely to harm sensitive electronic equipment, such as computers, modems, routers and chargers, when powered by such generator.

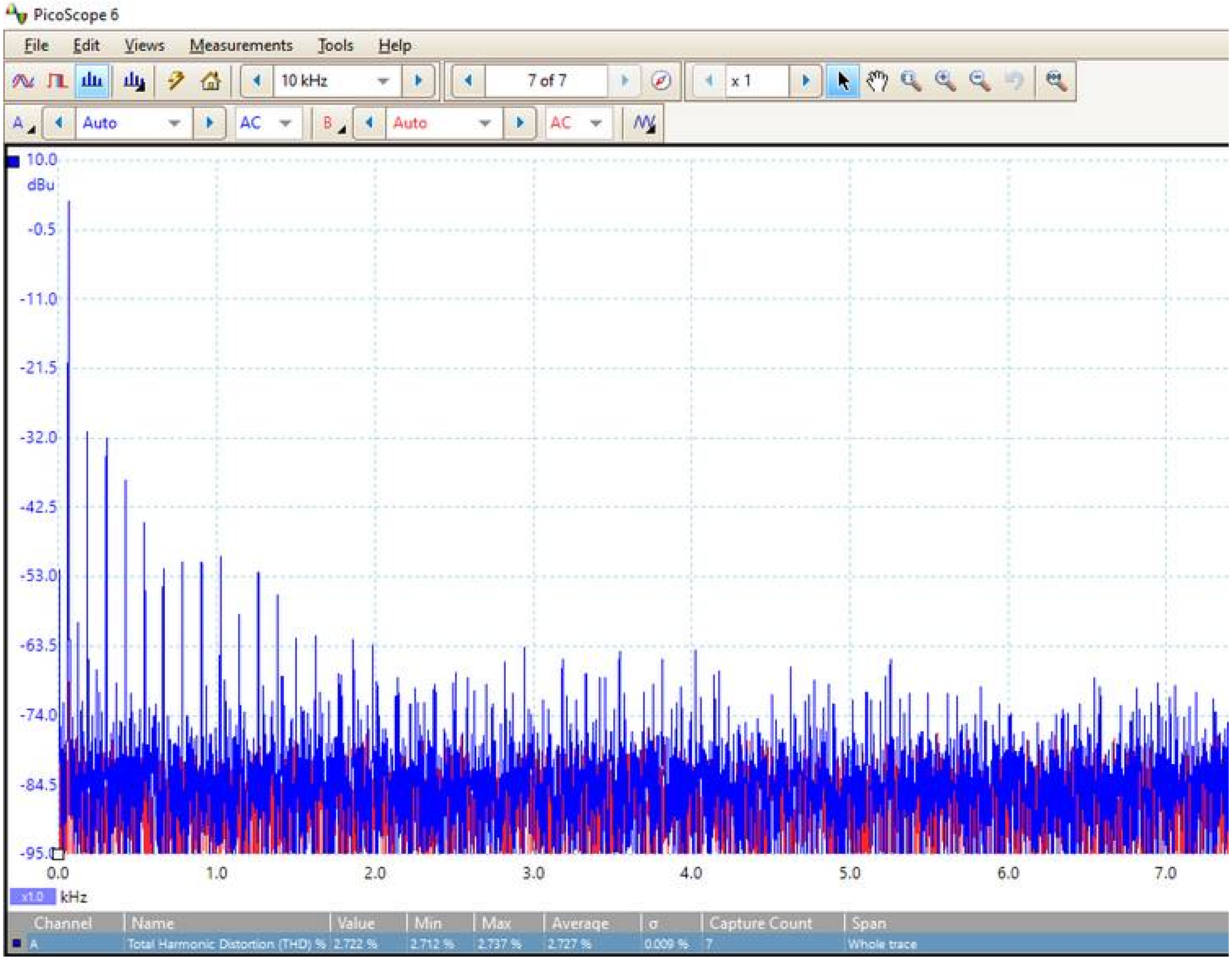
Graph 1: Utility Line – No Load (Utility RMS voltage and frequency consistent with expectations)

Volts: Peak = 169.5 Volts AC; RMS avg = 122.1 Volts AC; 0 Amps (no load); Frequency = 16.76 ms/cycle = 59.7 Hz (CPS)



Graph 2: Utility Line – No Load (Total Harmonic Distortion is below 5% for a utility and expected measurement)

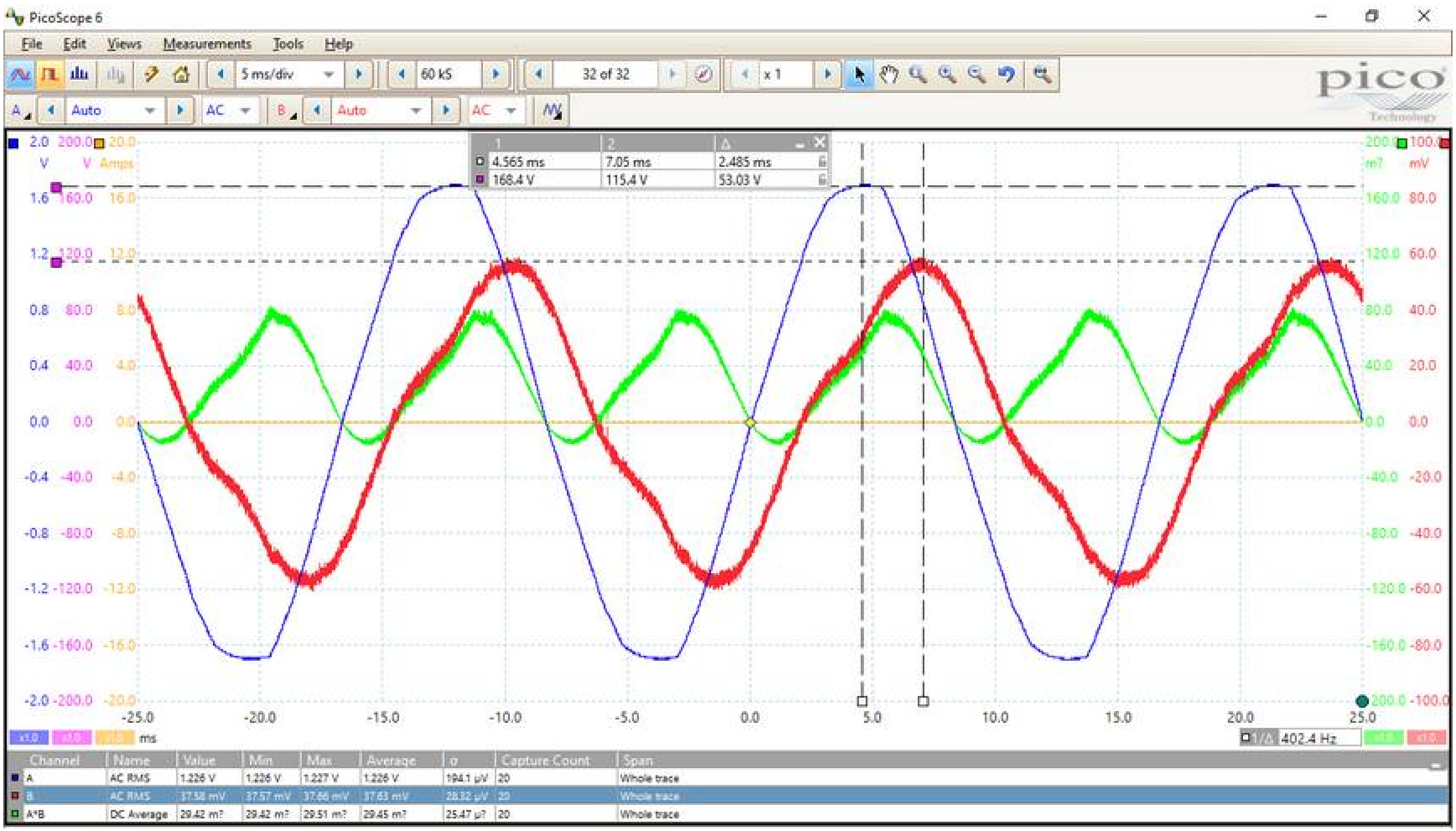
Total Harmonic Distortion (A Channel, voltage), %= Avg. 2.73% (Channel A voltage probe)



Graph 3: Utility Line - Oscillating Fan Load (Current and Power measurements consistent with Fan specifications)

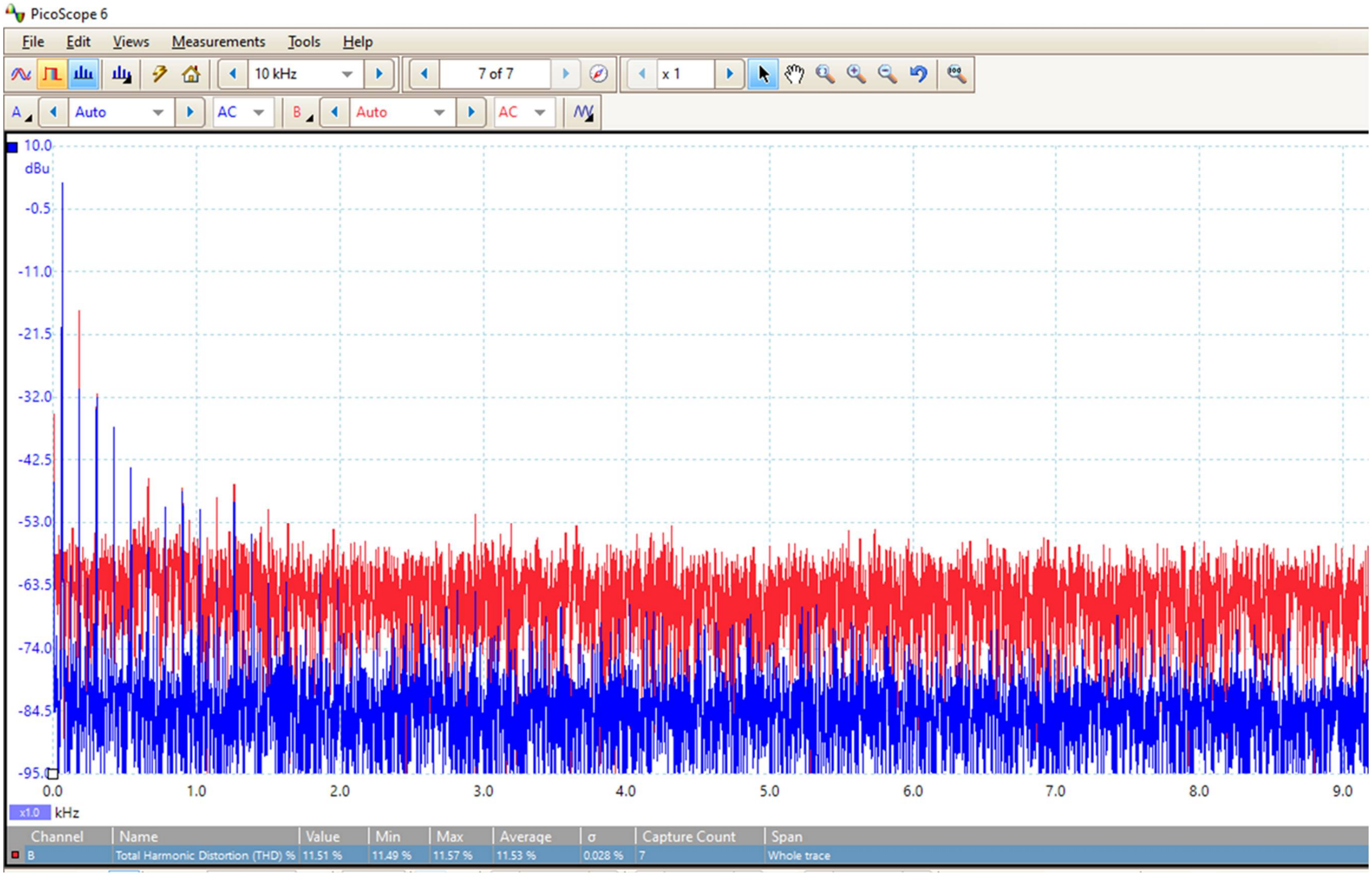
Volts: Peak = 167.7 Volts AC; RMS avg = 122.6 Volts AC; 0.37 Amps AC RMS Avg; 0.54 Amps AC peak; Frequency = 16.72 ms/cycle = 59.8 Hz;

Phase Angle: t_d=2.773 ms; 53°; 0.92 radians; PF=60.2%; V*I = 45 Watts (PR), DC Average = 29.4 Watts, PF = 65.3%



Graph 4: Utility Line - Oscillating Fan Load (fan oscillation causes some distortion, > 5%)

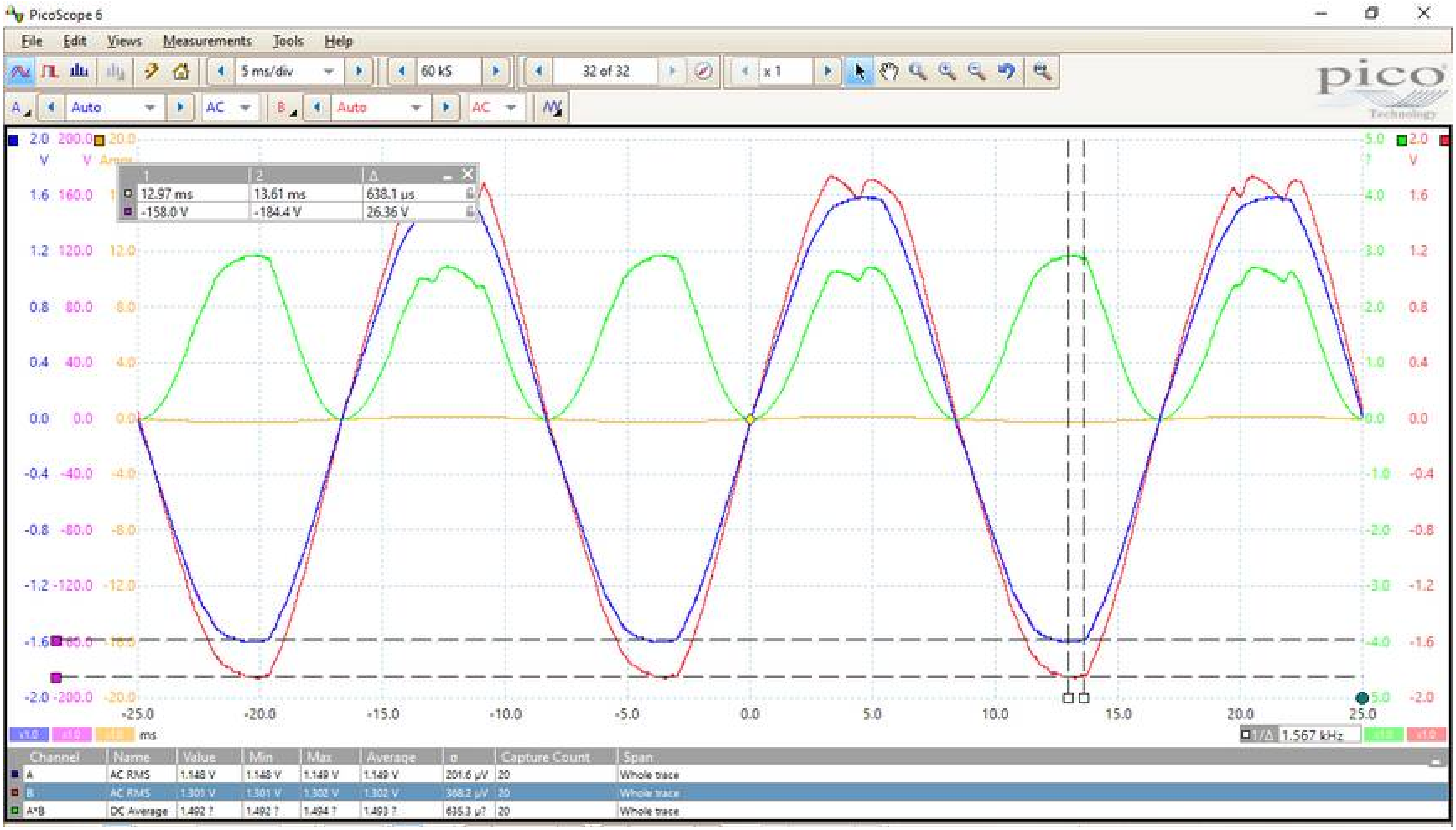
Total Harmonic Distortion, %= Avg. 11.5% (Channel B current probe)



Graph 5: Utility Line - Hair Dryer Load (Current and Power measurements consistent with dryer specifications; resistance heater illustrates high power factor efficiency – most of the power going into generate heat)

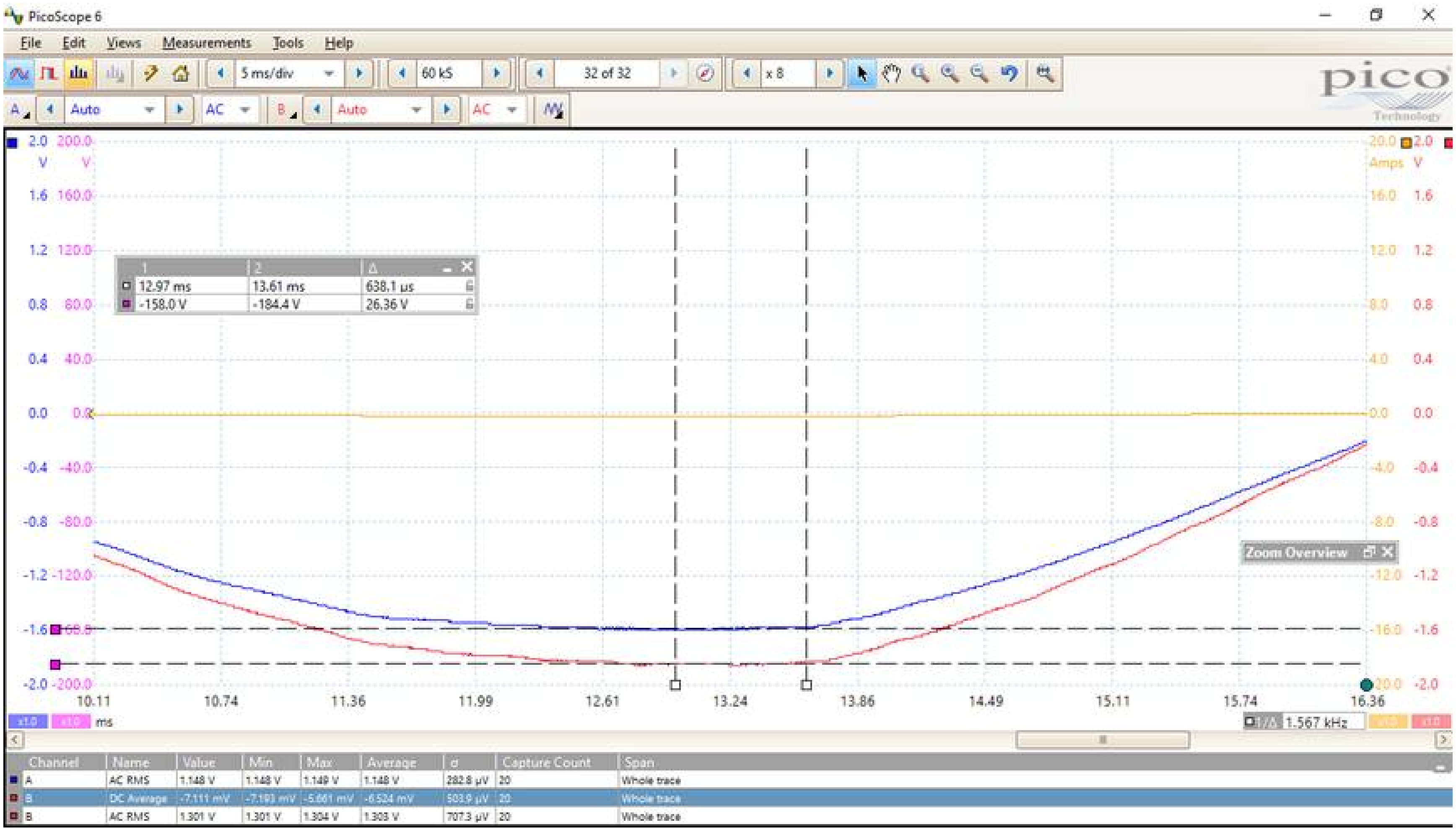
Volts: Peak = 157.2 Volts AC; RMS avg = 114.8 Volts AC; 13.03 Amps AC RMS Avg; 18.4 Amps AC peak; Frequency = 16.65 ms/cycle = 60 Hz;

Phase Angle: t_d= 0.31 to 0.92 (range) ms; 6.7° – 19.9°; 0.11-0.35 radians; PF= 99.3-94%%; V*I = 1491 Watts (PR), DC Average = 1490 Watts, PF = 99.9%



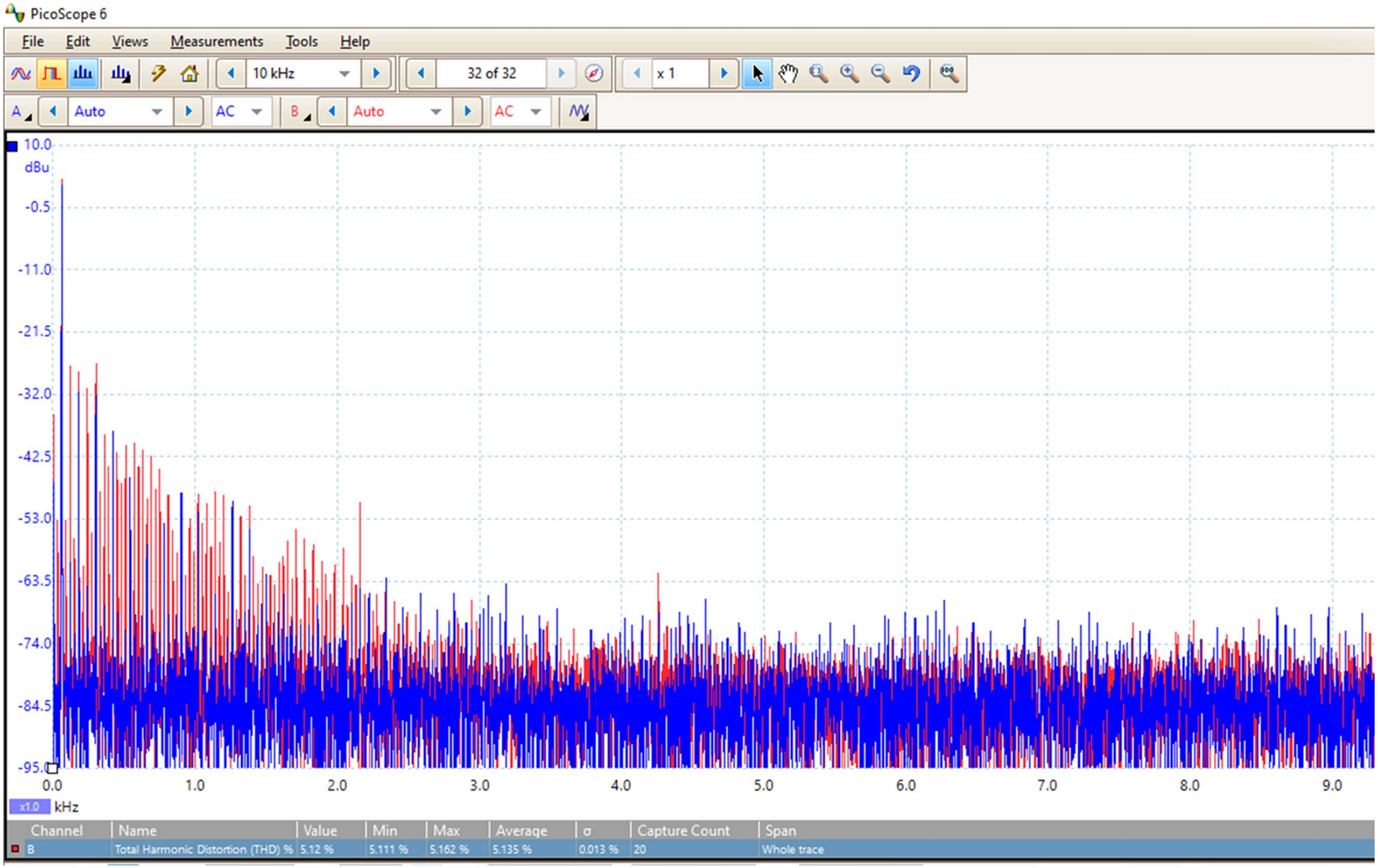
Graph 6: Utility Line - Hair Dryer Load

Measuring phase angle time between peaks (for hair dryer very small difference illustrates high power factor).



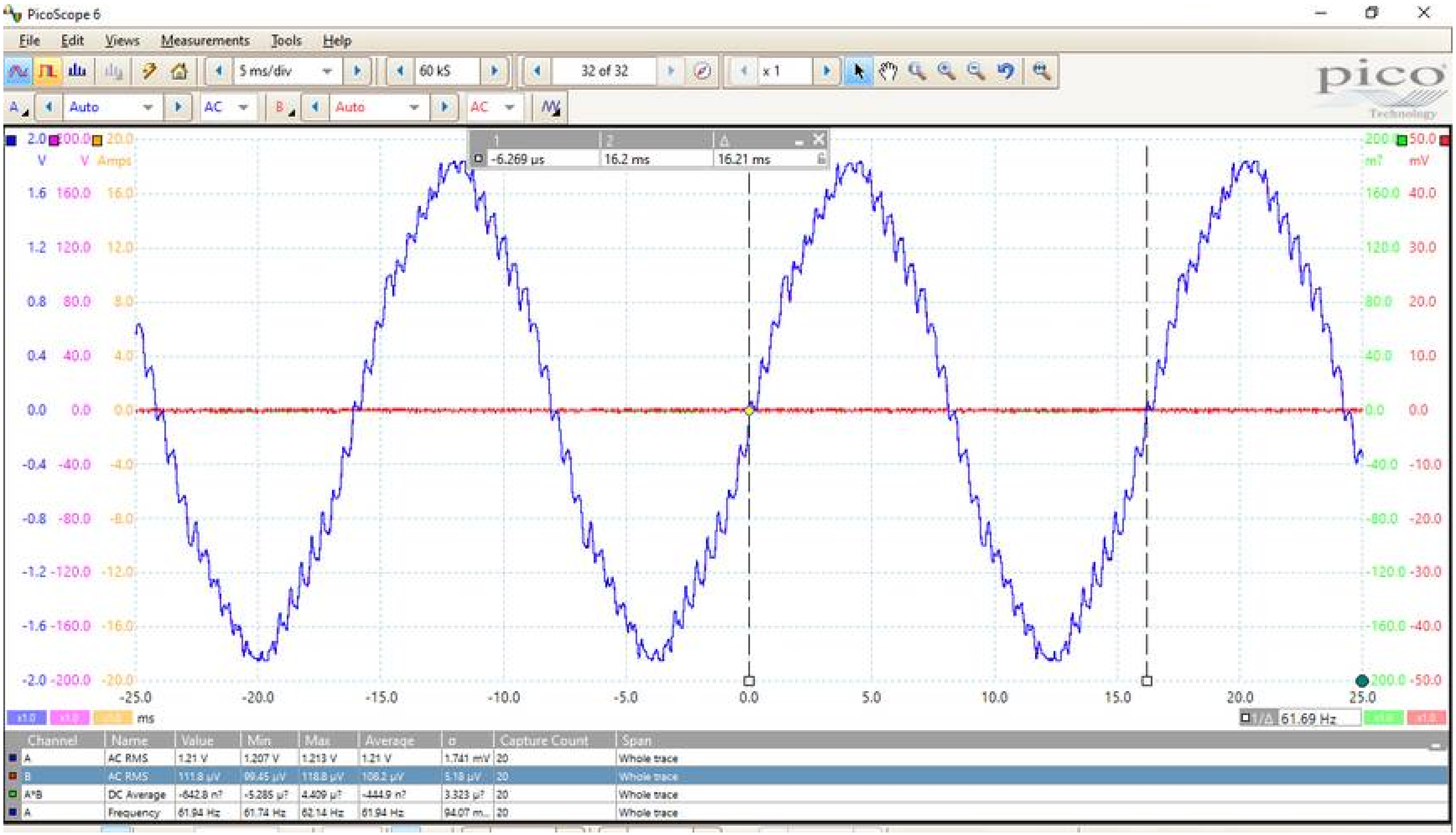
Graph 7: Utility Line - Hair Dryer Load (constant resistance load suggests little interference with current distortion)

Total Harmonic Distortion, %= Avg. 5.13% (Channel B current probe)



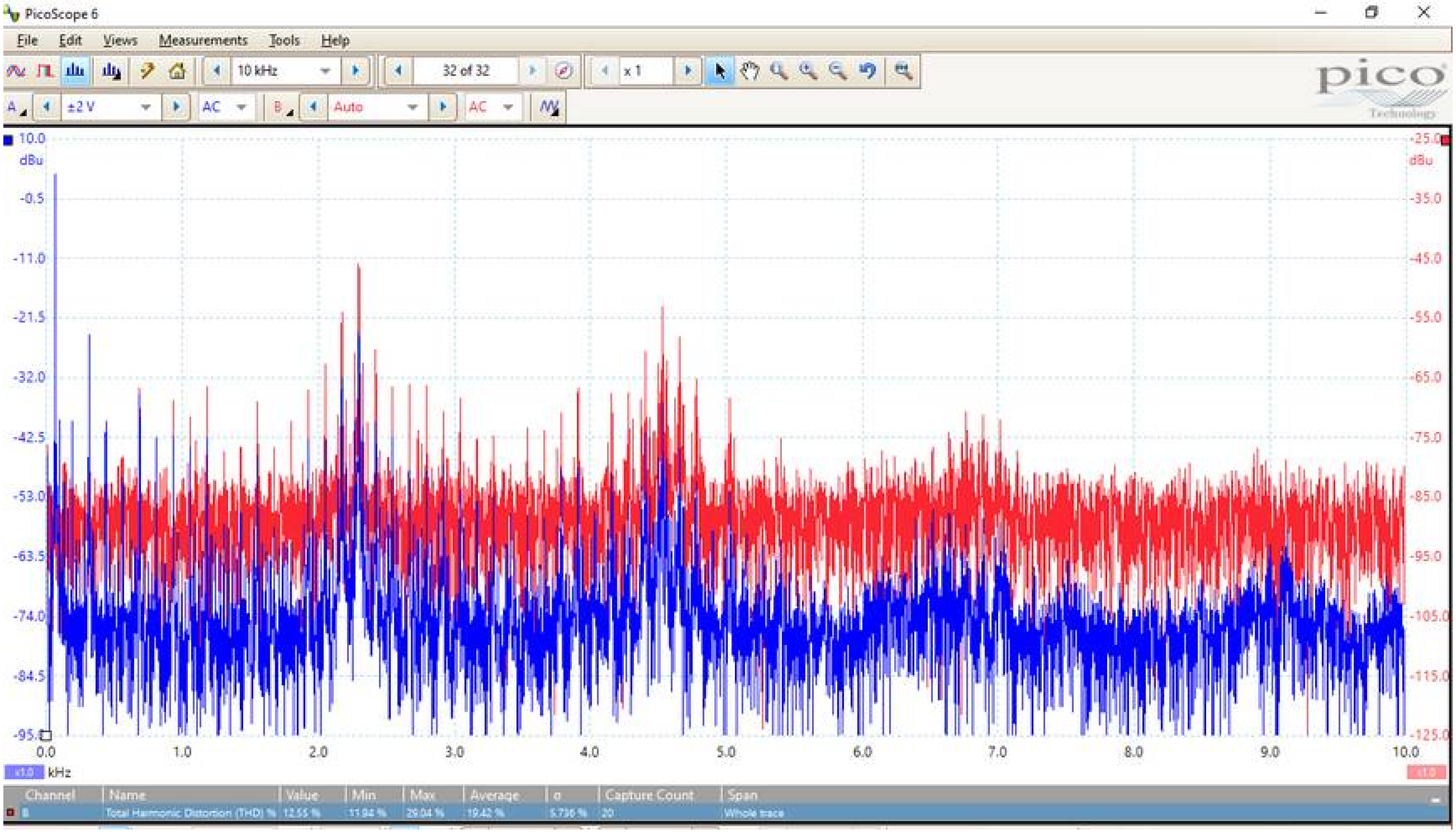
Graph 8: Generator (Without Power Conditioner) no load (voltage and frequency within generator specification; voltage wave pattern is choppy consistent with portable generator quality)

Volts: Peak = 183.3 Volts AC; RMS avg = 121.2 Volts AC; 0 Amps (no load); Frequency = 16.21 ms/cycle = 61.9 Hz



Graph 9: Generator (Without Power Conditioner) – No Load (illustrates high total harmonic distortion, >5%, consistent with non-inverter portable generator power production)

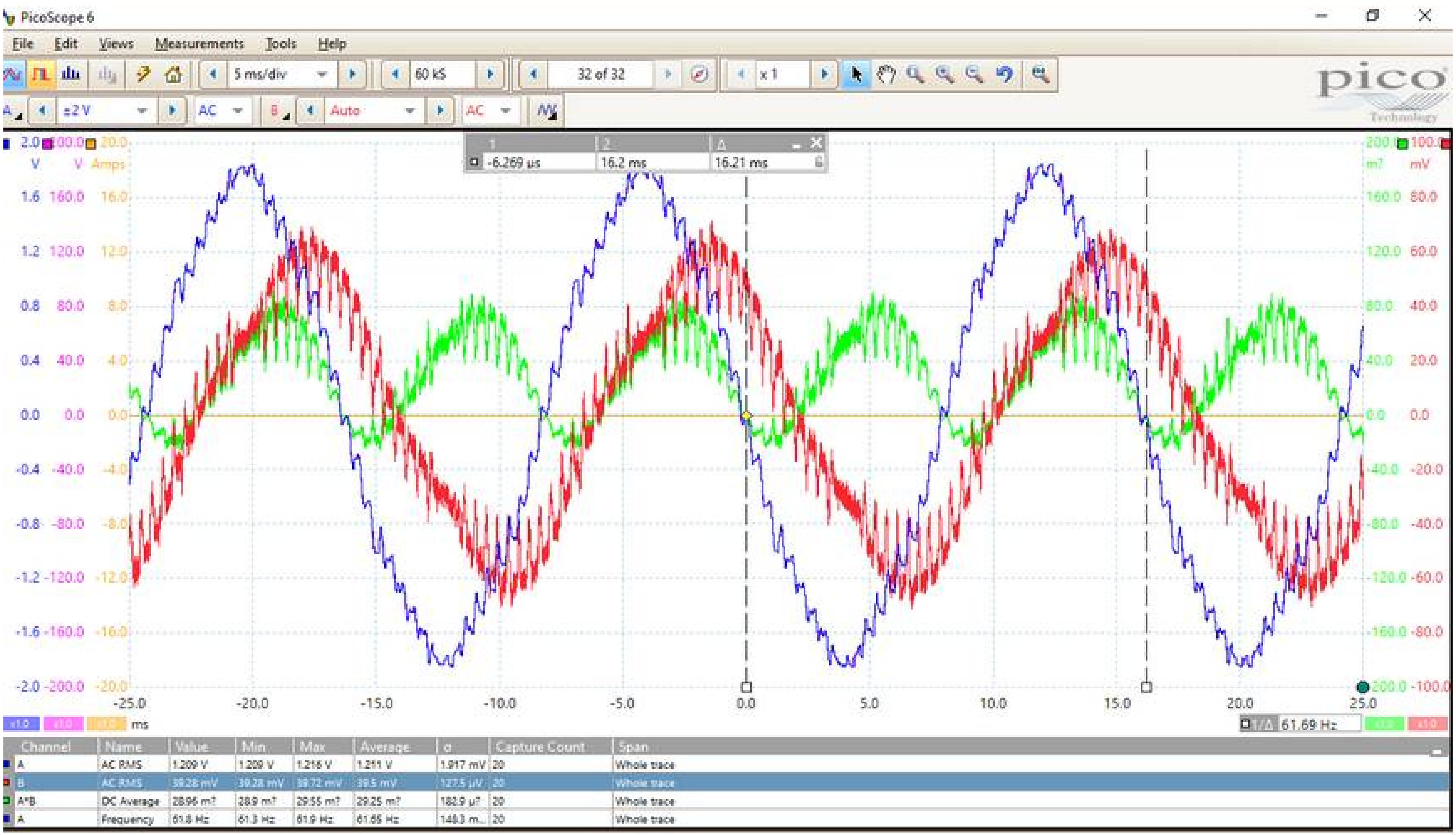
Total Harmonic Distortion (A Channel, voltage), %= Avg. 19.4% (Channel A voltage probe)



Graph 10: Generator (Without Power Conditioner) Oscillating Fan Load

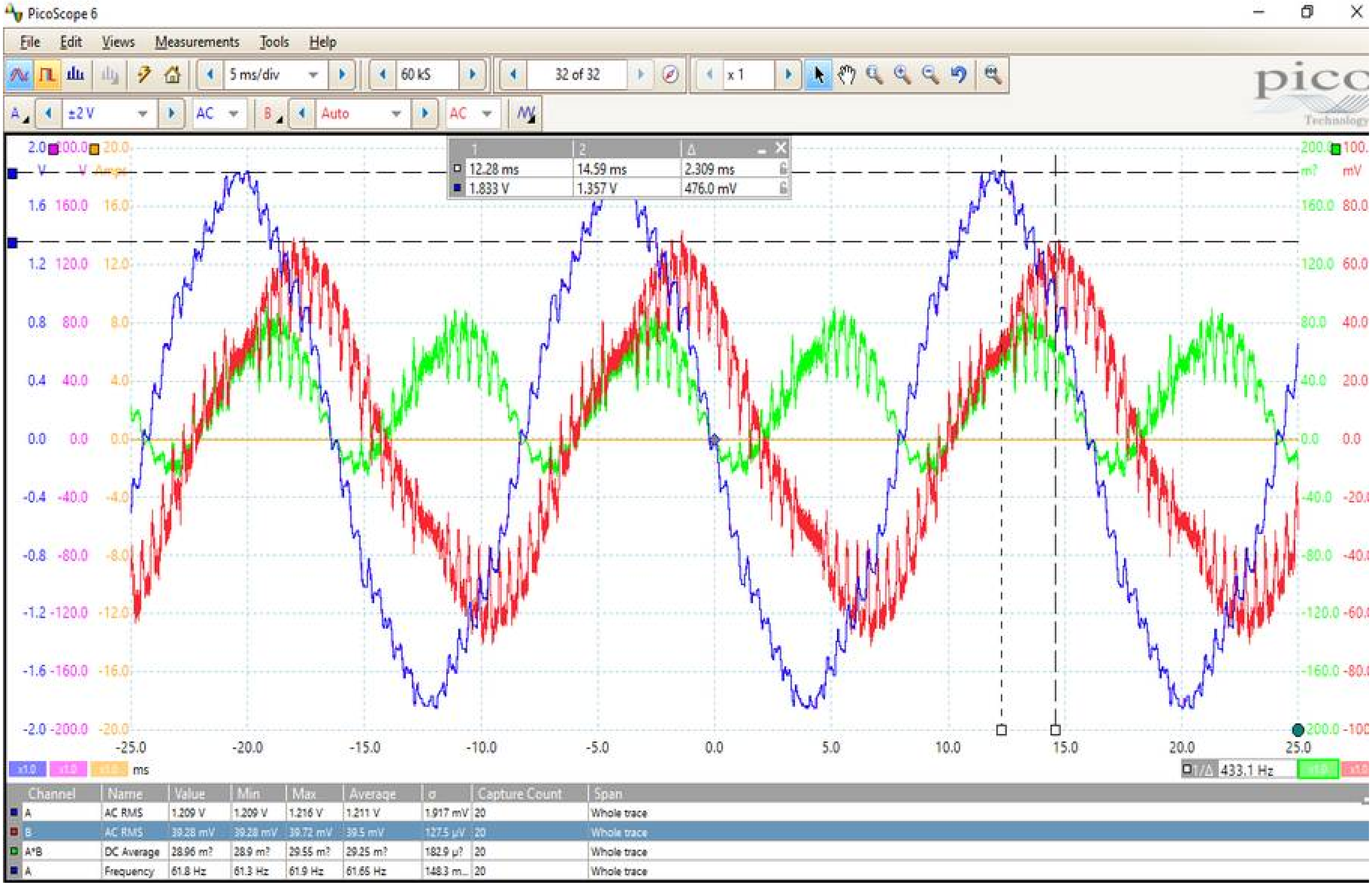
Volts: Peak = 185 Volts AC; RMS avg = 121.1Volts AC; 0.39 Amps AC RMS Avg; 0.68 Amps AC peak; Frequency = 16.21 ms/cycle = 61.6 Hz;

Phase Angle: t_d=2.6 to 2.3 ms; 57.5° to 51°; 1 -0.89 radians; PF=53% to 63%; V*I = 45 Watts (PR), DC Average = 29.2 Watts, PF = 61.9%



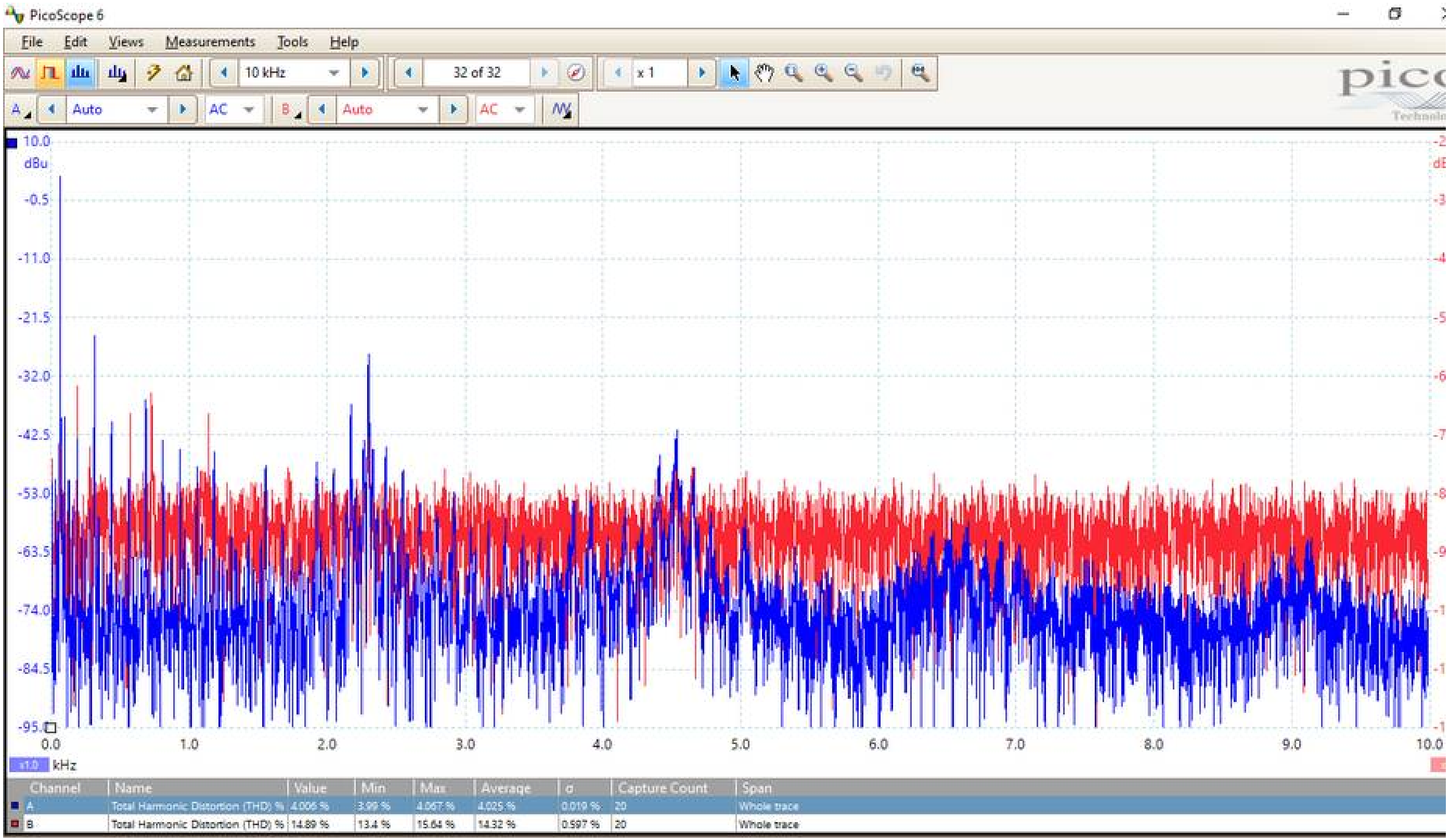
Graph 11: Generator (Without Power Conditioner) Oscillating Fan Load

Measuring phase angles



Graph 12: Generator (Without Power Conditioner) Oscillating Fan Load (THD higher than utility mains)

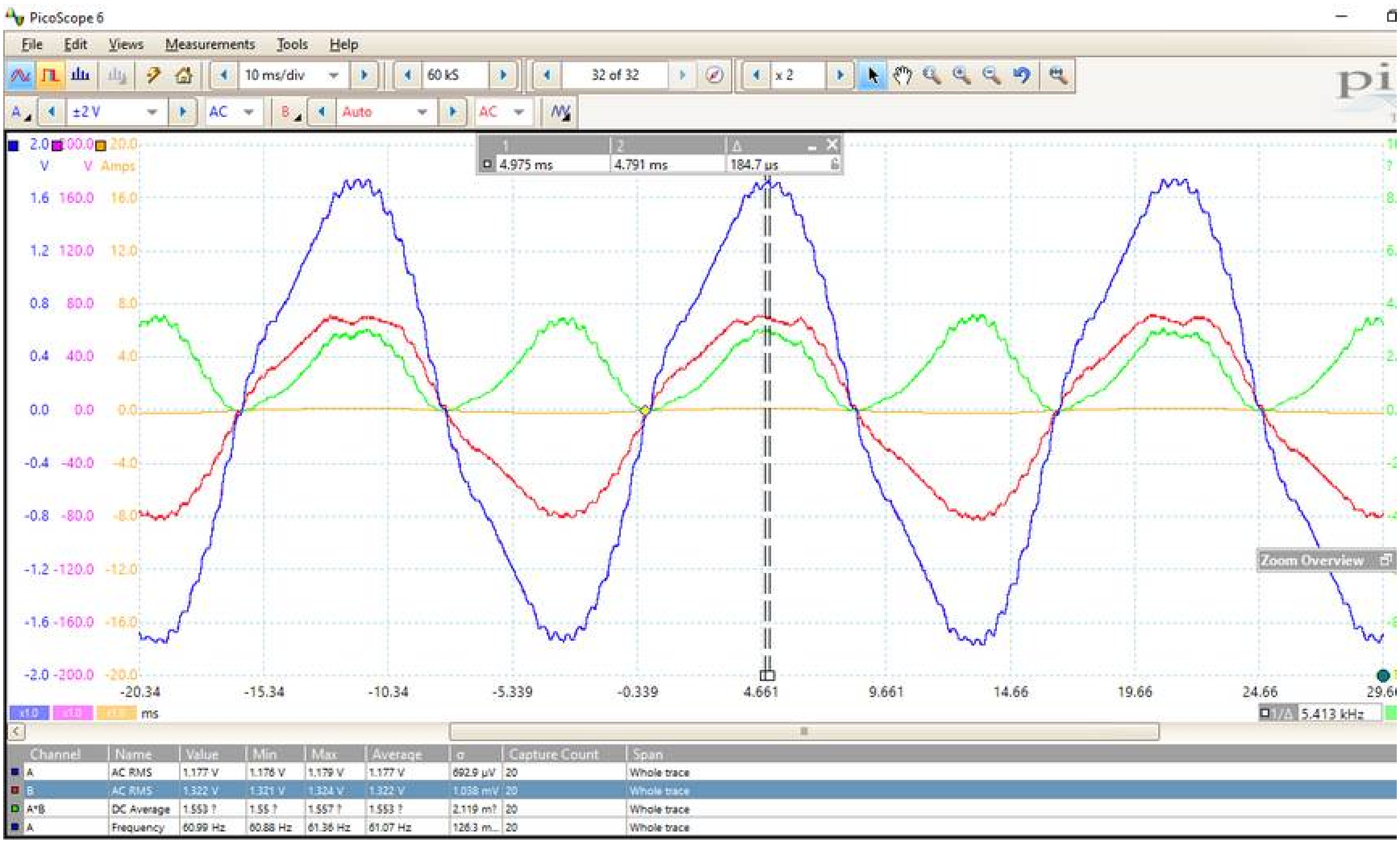
Total Harmonic Distortion, %= Avg. 14.3% (Channel B current probe)



Graph 13: Generator (Without Power Conditioner) - Hair Dryer Load

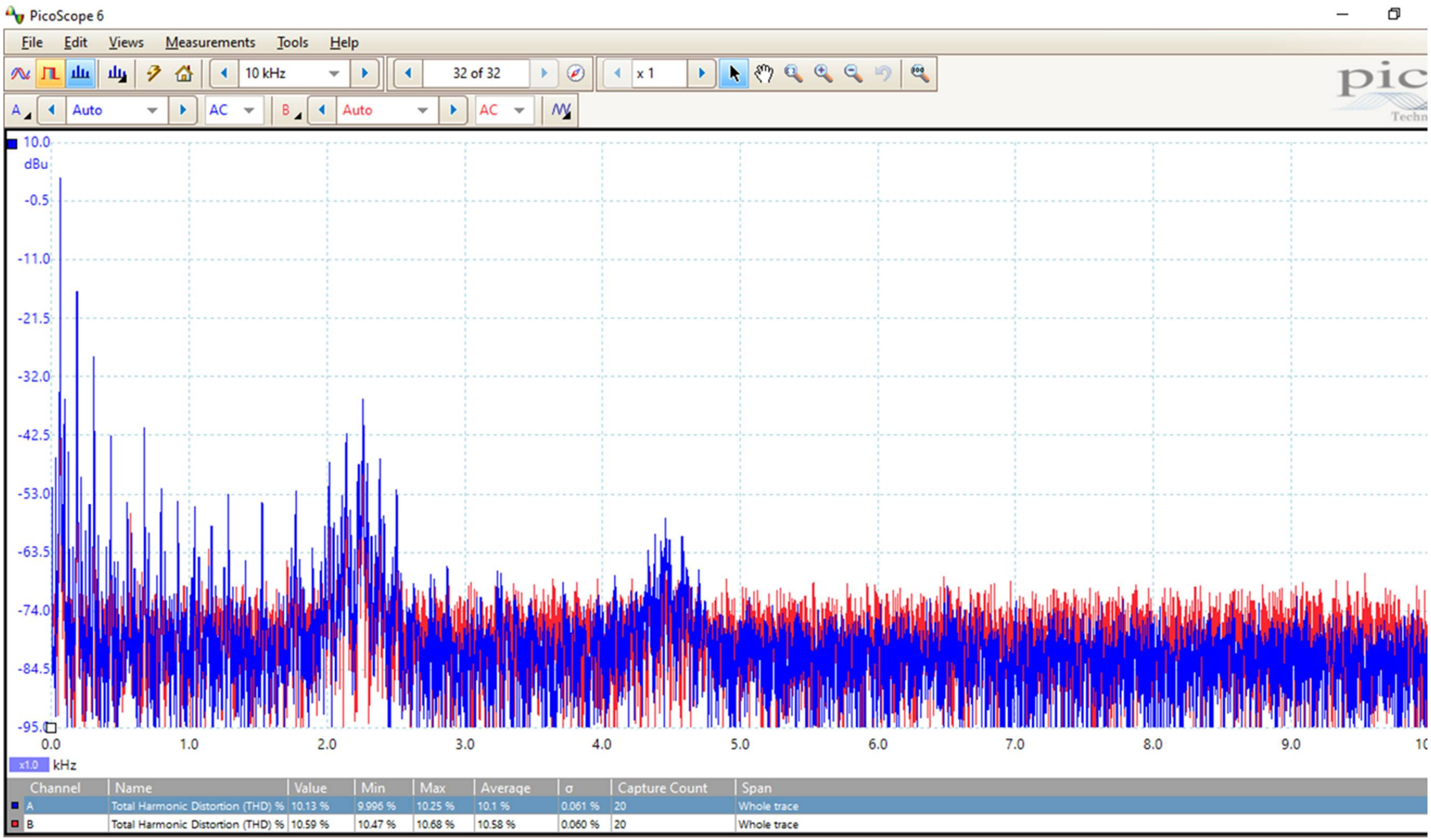
Volts: Peak = 171.5 Volts AC; RMS avg = 117.7 Volts AC; 13.25 Amps AC RMS Avg; 18.2 Amps AC peak; Frequency = 16.44 ms/cycle = 61 Hz;

Phase Angle: t_d= 0.18 ms; 3.9° ; 0.068 radians; PF= 99.7%; V*I = 1551 Watts (PR), DC Average = 1556 Watts, PF = 99.7%



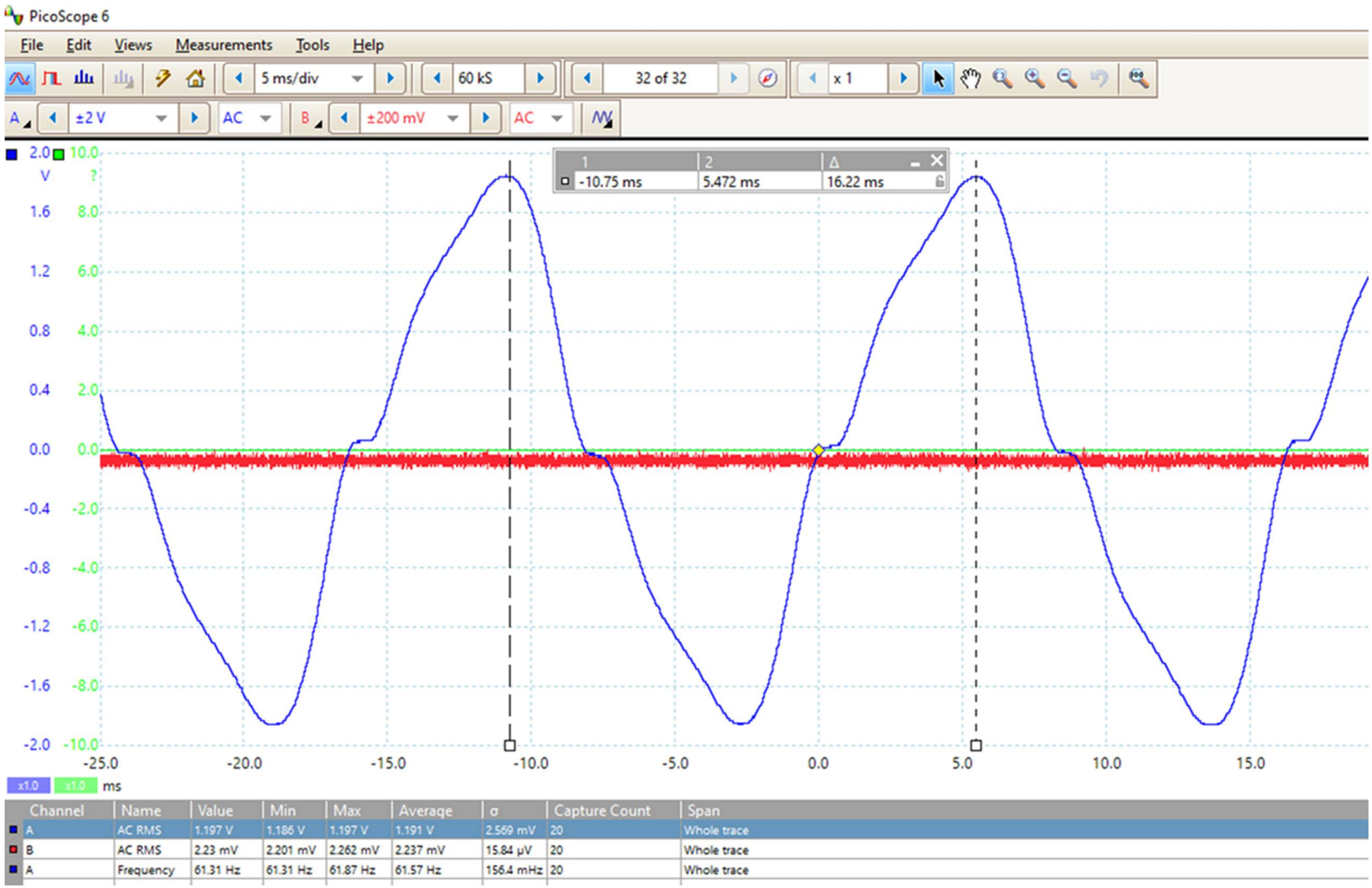
Graph 14: Generator (Without Power Conditioner) - Hair Dryer Load

Total Harmonic Distortion, %= Avg. 10.6% (Channel B current probe)



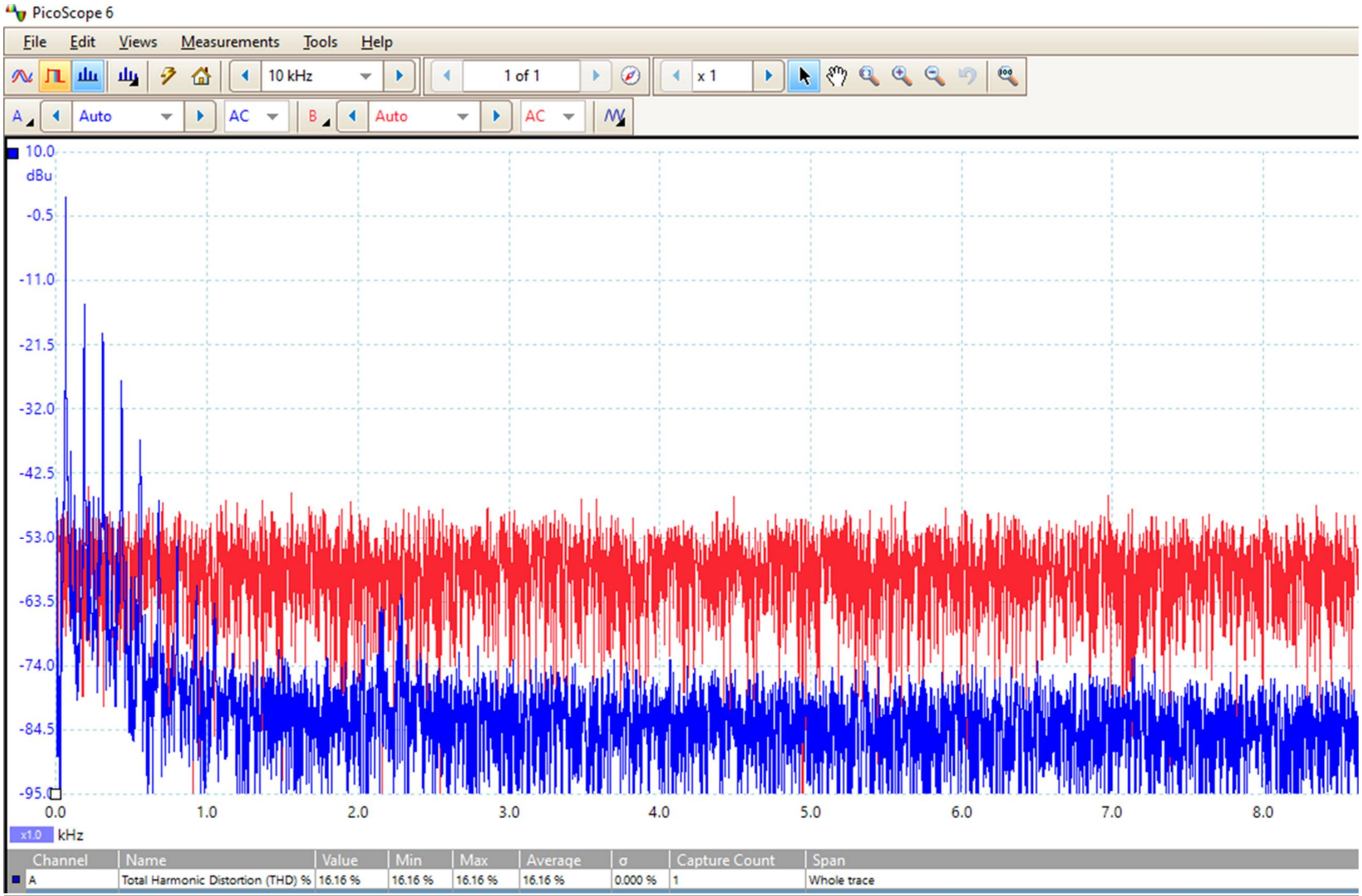
<u>Graph 15: Generator (with power conditioner) no load (voltage and frequency within generator specification; voltage wave pattern is almost choppy free consistent with power conditioner expectation)</u>

Volts: Peak = 185 Volts AC; RMS avg = 119 Volts AC; 0 Amps (no load); Frequency = 16.22 ms/cycle = 61.5 Hz



Graph 16: Generator (with power conditioner) – no load (illustrates total harmonic distortion, >5%, consistent with non-inverter portable generator power production though power conditioner appears to have improved Total Harmonic Distortion by reducing its average from 19.4% without the conditioner to 16.2% with the conditioner, 16.5% improvement)

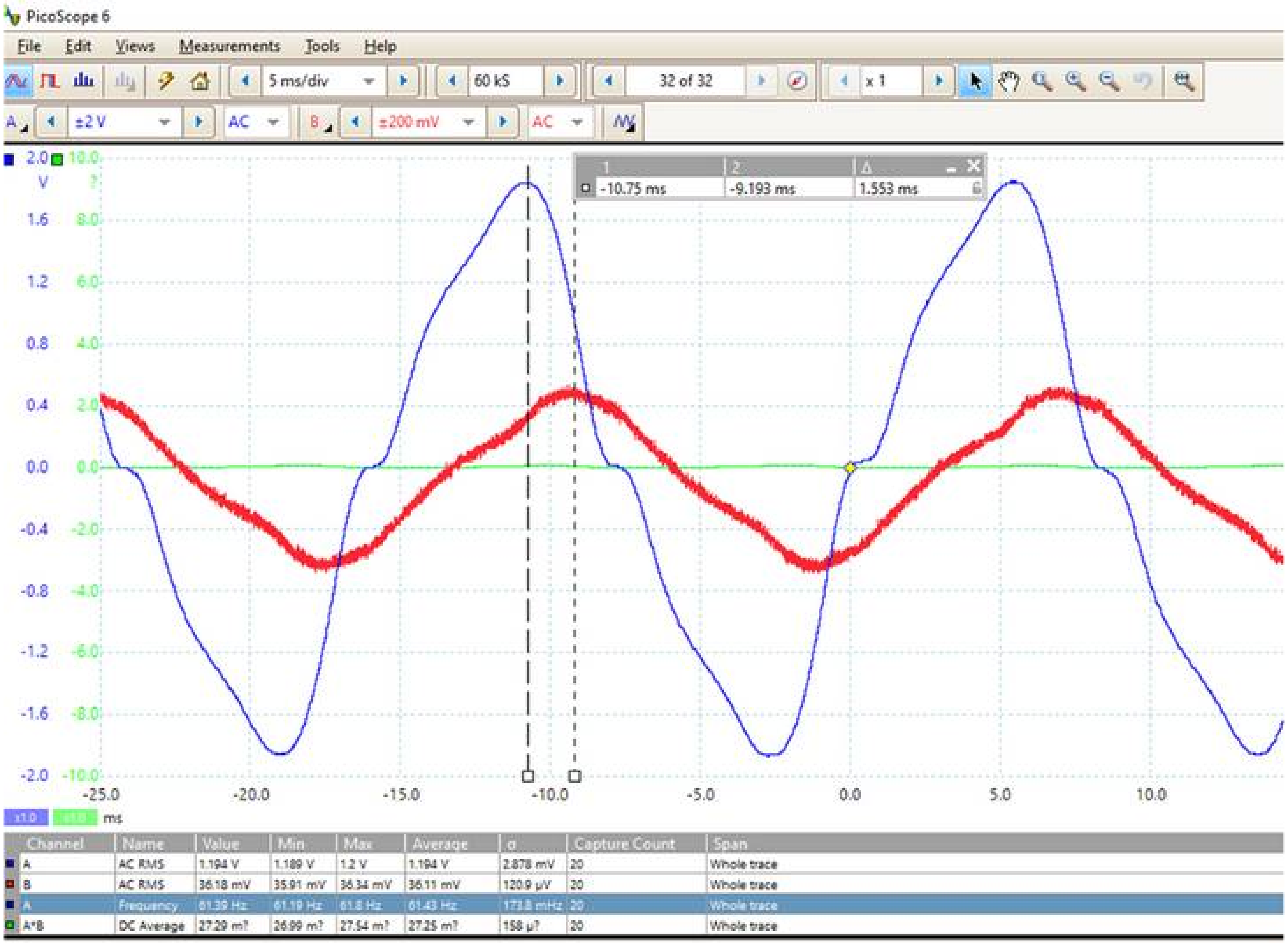
Total Harmonic Distortion (A Channel, voltage), %= Avg. 16.2% (Channel A voltage probe)



Graph 17: Generator (with power conditioner) oscillating fan load (illustrates much less choppiness in voltage, current and power curves, improved power factor;).

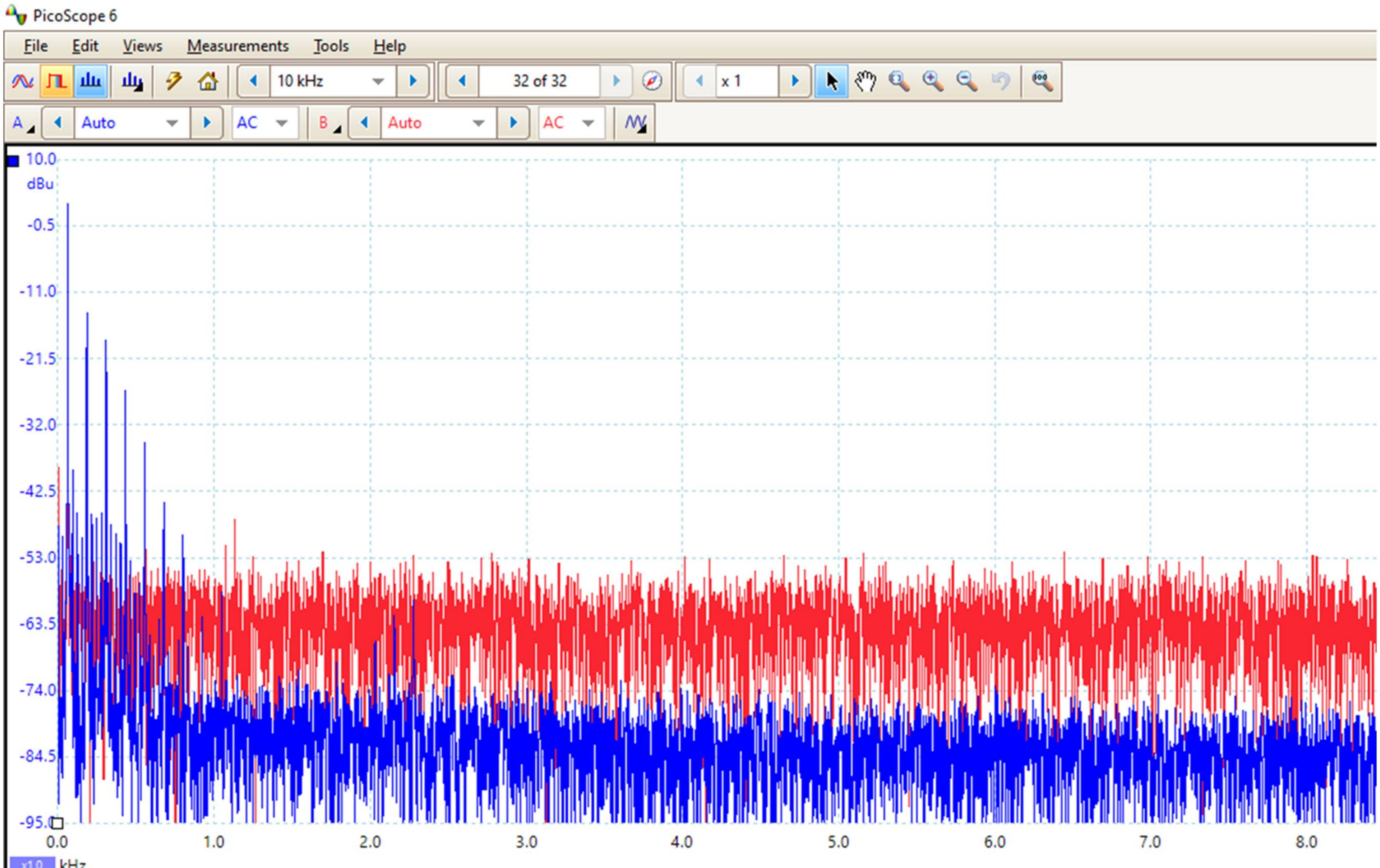
Volts: Peak = 186.6 Volts AC; RMS avg = 119.3 Volts AC; 0.36 Amps AC RMS Avg; 0.36 Amps AC peak; Frequency = 16.22 ms/cycle = 61.5 Hz;

Phase Angle: t_d ~ 1.55-1.8 ms; 34.4° – 40°; 0.6-0.7 radians; PF=82.5% - 76.6%; V*I = 42.9 Watts (PR), DC Average = 27.4 Watts, PF = 63.8%



Graph 18: Generator (With Power Conditioner) Oscillating Fan Load (THD higher than utility mains; Total Harmonic Distortion appears to have improved from avg. of 14.3% without conditioner to 10.9% with conditioner, a 24% improvement)

Total Harmonic Distortion, %= Avg. 10.9% (Channel B current probe)

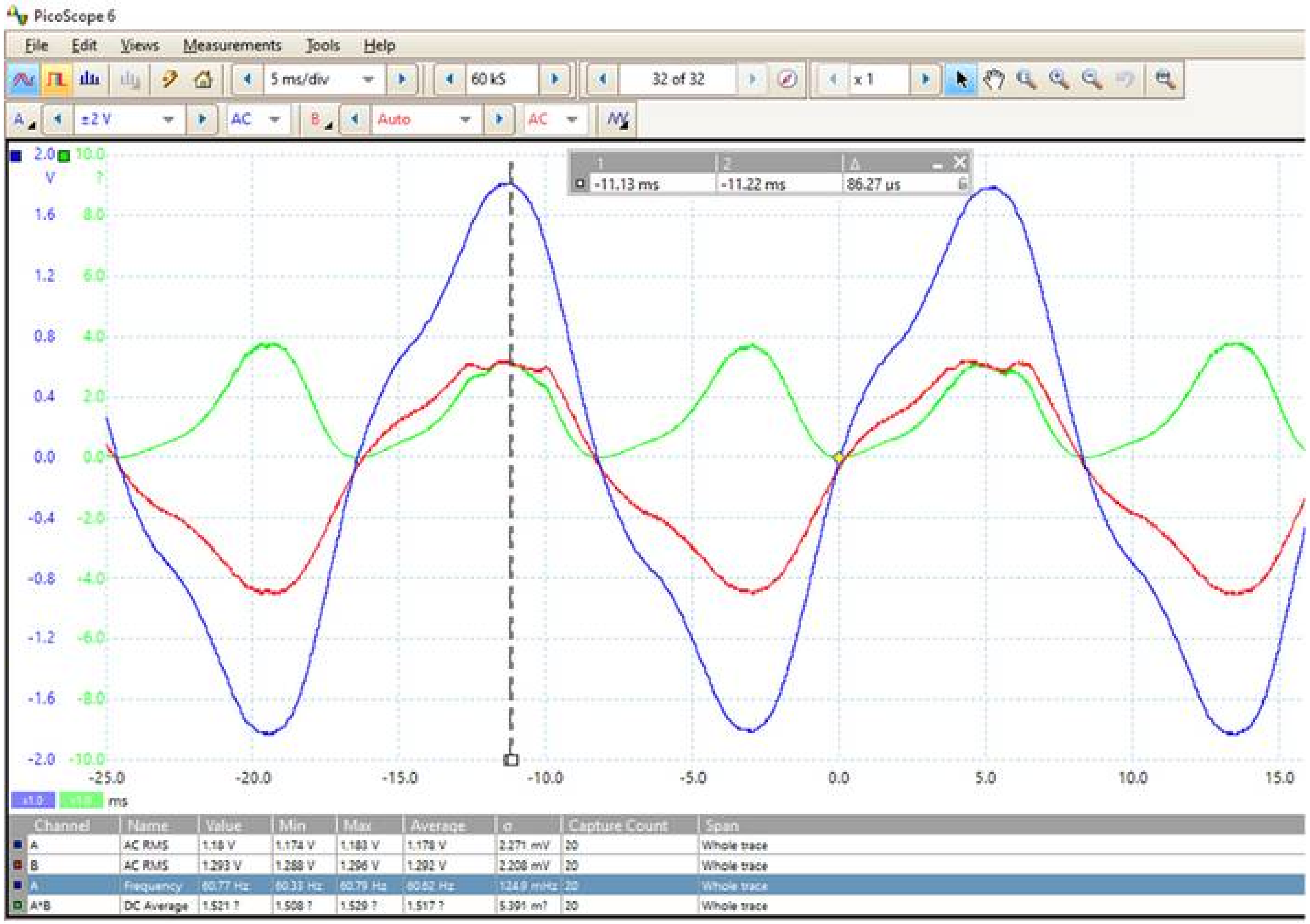


Channel	Name	Value	Min	Max	Average	σ	Capture Count	Span
B	Total Harmonic Distortion (THD) %	11.03 %	10.8 %	11.17 %	10.99 %	0.083 %	20	Whole trace

Graph 19: Generator (With Power Conditioner) - Hair Dryer Load; slight improvement in already high Power Factor)

Volts: Peak = 182 Volts AC; RMS avg = 118.4 Volts AC; 12.96 Amps AC RMS Avg; 12.98 Amps AC peak; Frequency = 16.48 ms/cycle = 60.5 Hz;

Phase Angle: t_d= <0.1 ms; 2.2° ; 0.04 radians; PF= 99.9%; V*I = 1534 Watts (PR), DC Average = 1520 Watts, PF = 99.1%



Graph 20: <u>Generator (With Power Conditioner) - Hair Dryer Load (THD for this test showed reduced performance: Utility THD ~5%; Generator without conditioner ~ 11%; Generator with conditioner ~ 15% even though Power Factor had some improvement with conditioner and wave voltage, current and power wave patters were much less choppy).</u>

Total Harmonic Distortion, %= Avg. 15.6% (Channel B current probe)