APPLICATION NOTE

Megger

Solar Energy

Renewable energy sources can include solar photovoltaic (PV), solar hot water, geothermal, wind and biomass.
Of all of them solar prices are dropping the quickest. So we are seeing this grow the quickest. This is most notably true in the residential and small commercial markets.

History
French physicist, Edmund Bequerel, first discovered the photoelectric effect in 1839. He found that some materials would produce small amounts of electric current when exposed to light. In 1905 Albert Einstein wrote a paper on the photoelectric effect. In this paper he described how photons striking atoms in metal would put electrons in that metal into motion. He won a Nobel Prize for his work on this paper. In 1954, Bell Laboratories created the first semi-conductor PV solar cells. These were then packaged together. This was the birth of the solar panel. At this point the technology was too expensive for commercialization. In the 1960s, NASA started using this technology in the space industry. The energy crisis in the 1970s, brought solar technology into the view of the government and the public. Now it is seen and a clean source of renewable energy.

How does the solar panel generate electricity?

Solar cells are made of semiconductor materials that exhibit the photoelectric effect. These semiconductor materials are treated so one side forms a positive electric field and the other a negative electric field. When light strikes the solar cell, electrons are freed from the atoms in the semiconductor material. If a load is placed across the solar cell the resulting electrons will flow through that load creating an electric current.

When multiple solar cells are electrically connected to each other in series and or parallel configurations they form a solar panel. Multiple panels can be wired together to form solar arrays. These solar panels and arrays output direct-current (dc). An inverter is required to convert the dc current to an ac current.

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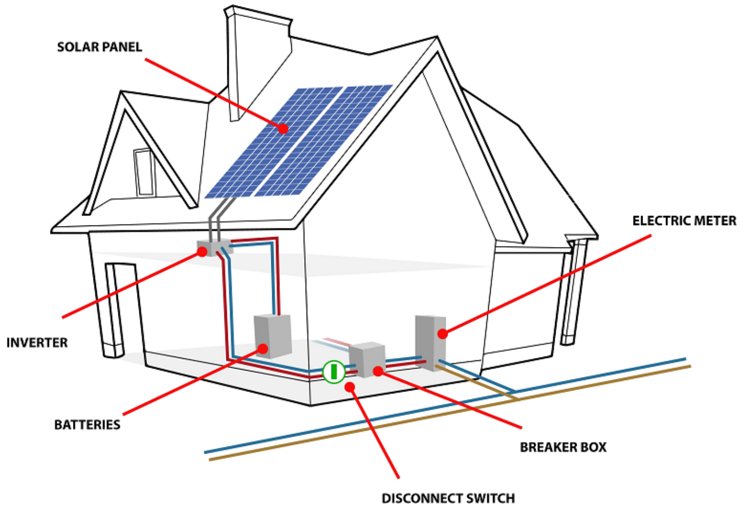


Solar Photovoltaic (PV) Panels

The PV panels convert sunlight to direct current (DC).

Batteries

Batteries may or may not be part of the solar system. Due to their cost (or local regulations) many times they are not used. When they are used they provide energy storage. This way energy can still be supplied when there is no solar light. Batteries need to be chosen based on capacity requirements and characteristics. Batteries used on solar applications should be cyclic batteries, such as deep cycle. They need to be able to cope with the heating effects of continuous charging and discharging. Many different types of chemistries can be used for solar back up power. These include Vented Lead Acid (VLA), Valve Regulated Lead Acid (VRLA) or Lithium Ion.
Vented Lead Acid (VLA): Commonly known as flooded batteries are relatively inexpensive and can have long life spans when maintained. These batteries can be large and they do vent hydrogen. So they need to be kept in ventilated areas. These will provide the longest life span but they also require a monthly inspections and bi annual maintenance.
Valve Regulated Lead Acid (VRLA): Commonly known as maintenance free batteries (because you cannot add water) are low cost batteries. These batteries do not have long life spans and do require monthly inspection and quarterly maintenance. (Despite the term maintenance free) If not properly maintained they can pose a safety hazard. These types of batteries need to be kept in a temperature controlled environment. If they overheat they will release hydrogen and can experience a thermal runaway.

Lithium Ion: These are relatively expensive batteries. They have the highest energy density. They have a longer life than VRLA batteries but not as long as VLA. They require less maintenance than the lead acid batteries. Note that their capacity can be de-rated year to year.

So although they may be rated for 10 years after 3 years you may only have 70% capacity. Over 5 years the capacity may be down to 50%...etc. In addition of not installed and charged properly they can also present a safety hazard.

There is no ideal battery. You need to choose the right battery for your application.

Inverters

The inverter converts the DC output of the solar panel to a useable AC output. There are several different types of inverters, these include the following.

String Inverter: These inverter are designed to operate with single series strings of PV panels. They convert the DC output from each string into an AC output

Central Inverter: These inverter are designed to operate with the entire PV array. These convert the DC output from all the panels into an AC output

Micro Inverter: These inverter are designed to operate with single PV modules. These convert the DC output from each panel into an AC output.

Inverters are designed differently for different application.

Stand-alone inverters: These draw DC current from batteries, which are charged by the solar cells. These are typically used on isolated systems.

Grid-tie inverters: These types of inverters match its AC phase output with that of the utilities phase. For safety reasons, these types of inverters are designed to shut down automatically upon loss of utility power. This ensures that no line workers sent to fix the outage can be injured.

Battery backup inverters: These draw DC current from batteries, which are charged by the solar cells. These types of inverters export excess energy to the utility grid and will supplying AC energy to loads during an outage.

Disconnect switch

The disconnect switch is used to isolate the solar PV panels from the inverter in case of a fault or for maintenance.

Fuse box or breaker box

The breaker box houses the breakers. These breakers will open should excessive current be drawn on any particular circuit.

Solar Energy

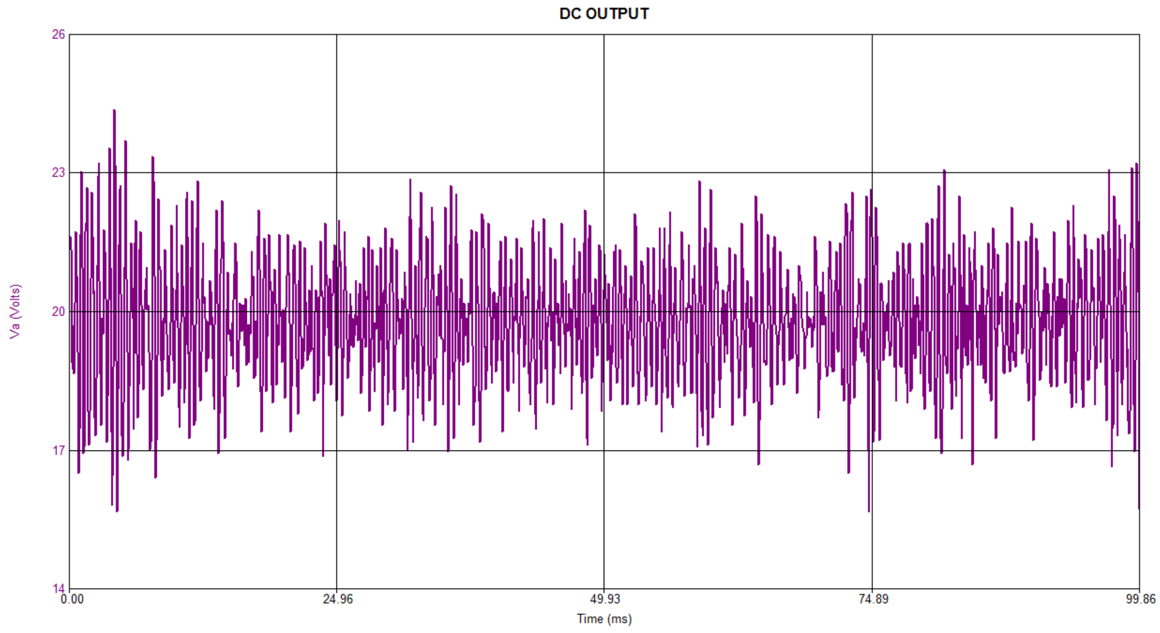
Electric meter

This electricity meter will monitor both incoming electricity from the grid as well as outgoing electricity to the grid.

Issues that solar energy can cause

Solar energy is a good way to save energy. It is important to keep in mind that the electric grid is a dynamic system. When something gets attached it does change the system to a degree. When solar systems are attached to the grid we may see power quality problems occur for both the solar site as well as the utility.

The output of a solar panel is always fluctuating. Below is a graph of the DC output of a solar panel.



This output goes through an inverter in order to convert the DC to AC. An unconditioned AC voltage can create various power quality issues.

Some of these issues include:

a. High Voltage – When the solar array is placed on a location that location can experience higher voltage than normal. This will depend on the voltage conditioning equipment. High voltages can cause the following problems.

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Premature motor failures: High voltage can cause core saturation, causing excessive heating. In addition it can cause higher than normal inrush currents. This causes excessive heating. This can be seen on motors that turn on and off multiple times a day; such as in, air conditioners, washers, dryers, refrigerator…etc.

Premature lighting failure. High voltage can cause incandescent as well as florescent lights to burn brighter, producing more heat and reducing their life.

b. Unbalance - This is a problem the utility will experience. If the solar array is not connected to all phases then an unbalanced voltage condition can occur. The greater the number of single phase solar arrays connected to the grid the worse this problem becomes. Unbalanced voltages can cause serious problems in 3 phase motors. The resulting current unbalance in a motor will be 6 to 10 times higher than the voltage unbalance that creates it. This creates excessive heating and can burn out coils. A voltage unbalance of just 2% can equal a current unbalance of up to 20%. Utilities are having to change the tap settings on their transformers in order to compensate for these unbalanced conditions.

c. Transients – Solar panels react nearly instantaneously to changes in solar radiation. The bandwidth of the solar radiation that effects solar panels is wider than our visual range. This means even on clear days the solar panels can be changing rapidly due to pollutants we do not see. The means the output of solar panels can change very rapidly. If the solar system does not have proper voltage conditioning this can create high speed transients. These high speed transients can have adverse impacts on residential and commercial electronics. Modern electronics do have input filters that do filter out transients. These can fail when being exposed to repeated transients. This will lead to failures in these electronic devices. These can include flat screen televisions, microwave ovens and computer equipment.

d. Harmonics – Inverters concert the DC current to AC current. These devices are non-linear devices so they create harmonics. Inverters tend to operate at relatively higher frequencies in order to maximize their efficiency. However the higher the frequency the inverter functions at the higher order harmonics it creates. It is not uncommon to see harmonic orders up above the 40^{th} order.

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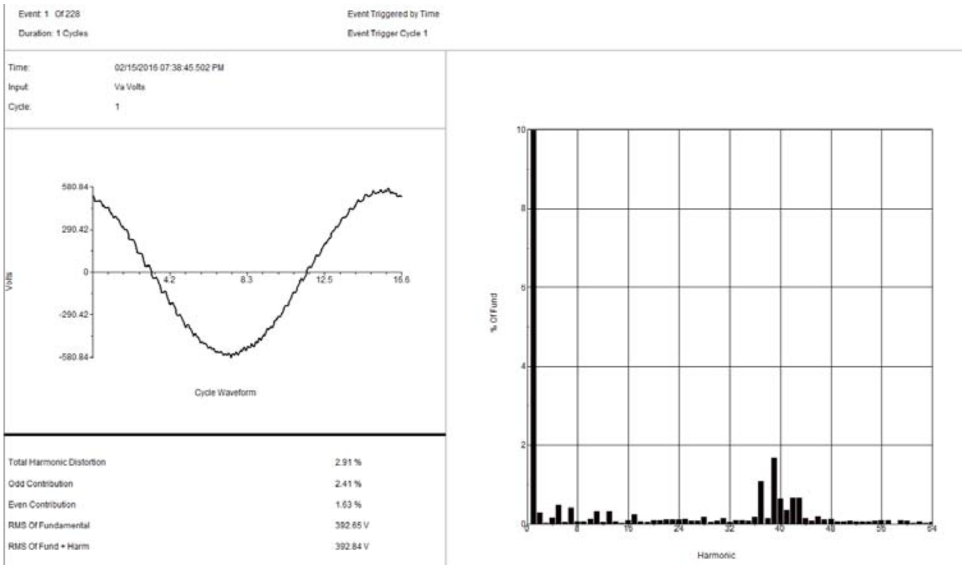

Harmonics generate eddy currents in wires. These eddy currents cause what is known as skin effect, which generates heat in wires. Coils are just wound wire. Therefore harmonics generate heating effects in equipment that contains coils, such as transformers and motors. The higher the frequency of the harmonic the greater the eddy currents, the greater the skin effect the more heating. In high enough magnitudes these can create premature failures in motors and transformers as well as sensitive electronics.

e. Power reversals – The standard distribution power grid was designed in a radial fashion. This means that it was designed with the assumption that power would always flow from the source to the load. Now with the spread of distributed generation, such as solar this no longer always holds true. Residential and commercial location that utilize solar systems can act as either a load or a source, depending on whether they are drawing power from the grid or supplying power to the grid. This means the power flow reverses direction from time to time. This creates an issue for the utility. To set the proper voltage levels utilities will adjust the tap settings on their transformers. Tap changers are mechanical assemblies. Since they are moving mechanical assemblies they have a limited life span, perhaps a few thousand cycles. However when power flow is changing directions possibly multiple times a day this causes the tap changers to switch excessively. This wears them out prematurely.

Solar PQ Setup

When examining potential power quality issues associated with solar panels your power quality analyzer should be programmed to capture the following.

Parameter	Setting	Notes
Power Wiring Configuration	Either single phase or split phase for residential	The power wiring configuration will depend on

	applications. Three phase for utility applications.	the location and region of the world.
Demand Interval	Should match the demand interval of the revenue meter.	Revenue meters can aggregate data differently depending on their aggregation rate and window. The MPQ can be programmed for multiple aggregation rates using either fixed or sliding windows.
RMS	Enable (MIN, AVG and MAX) and set the interval to 10 minutes.	The MPQ will record the minimum and maximum RMS values that occur during every 10 minute interval. In addition the MPQ will record the average RMS value for every 10 minute interval.
Unbalance	Enabled	The MPQ will measure the balance between phases. On single phase applications this will not be applicable. In these cases the option will be disabled.
Voltage Dip / Sag	-10% of nominal voltage	The MPQ will measure the RMS value every ½ cycle and compare it to this limit. If the RMS voltage drops below 90% of nominal this will trigger a DIP / SAG event. This can occur when loads turn on or on islanded systems with no battery backup, when there is a change in solar radiation.
Voltage Swell	+10% of nominal voltage	The MPQ will measure the RMS value every ½ cycle and compare it to this limit. If the RMS voltage rises above 110% of nominal this will trigger a swell event. This can occur when loads turn off or due to voltage increases from the solar panels on systems

		with limited voltage conditioning.
Voltage Sub-cycle Events	20V on 120V applications and 40V on 230V applications.	The MPQ will compare each sample to the corresponding sample of the previous cycle. If the sample deviates by more than the limit programmed (20 or 40V) then a sub-cycle event occurs. This will capture waveform distortions that occur due to sudden impedance or voltage changes.
Phase Angle Deviation	Disabled	
RVC (Rapid Voltage Change)	3%	The MPQ will capture rapid changes in RMS voltage over 3%. This can be caused by rapidly changing outputs from the solar panels and can cause flicker in lighting systems.
Fast Transients	210V on 120V Applications 420V on 230 Applications	The MPQ will verify that no samples exceed the programmed value. (210V or 420V) If a sample does exceed this it will be recorded as a fast transient. Repeated fast transients can breakdown insulation and cause electronic failures.
Voltage THD Limit	8%	The MPQ will measure the total harmonic distortion of each channel over a 200ms period. I fit exceeds 8% a THD event will be triggered. This will identify harmonic distortions that can be overheating and damaging motors and electronics.
Timed Waveform Capture	One every 30 minutes capture 10 cycles.	Detailed analysis of this data helps indicate the nature and source of the harmonic distortion.

Exceedance Waveform Capture	3 Pre-Triggers and 10 Post Triggers	Every time an out of limits trigger is exceeded the MPQ will record 3 cycles prior to the event, the event cycle and 10 cycles following the event. Detailed analysis of these waveforms help determine the cause of the event.
THD Recording	Enabled – 10 minute interval	The MPQ will record gapless continuous Total Harmonic Distortion. The data will be aggregated every 10 minutes. Examination of this data helps determine if and when excessive harmonic distortion is occurring.
IEC Harmonic Recording	Enabled – 10 minute interval	The MPQ will record gapless continuous individual harmonic orders through the 50th order. The data will be aggregated every 10 minutes. Examination of this data helps determine the predominant harmonic orders.
IEC Inter-Harmonic Recording	Enabled – 10 minute interval	The MPQ will record gapless continuous inter-harmonic order through the 50th order. The data will be aggregated every 10 minutes. Examination of this data helps determine if inter-harmonics are occurring. These can cause light flicker among other things.
Default Frequency	As required 50Hz for 50Hz regions and 60Hz for 60Hz regions.	The MPQ automatically determines the frequency and uses a phase lock loop to sync on the frequency. This setting simply tells the unit what frequency to default to

		in the case of a loss of signal on Phase A voltage.
Clock Hour Orientation	Enabled	This delays the start of the recording until an even time interval is reached. This just makes the analysis of the data easier.
Flicker	Enabled	The MPQ will record changes in the voltage magnitude at different rates and compare them against a weighted curve. This will determine if voltage fluctuations are cause flicker in incandescent lighting systems.
Frequency	Enabled	The MPQ will record the voltage frequency on the Phase A voltage.
Mains Signaling	Disabled	This function is not required in this application. This function looks for communication signals sent over the power lines.

When analyzing the power quality data from a solar panel application check the following.

RMS – Regulation
Verify the RMS regulation is within +/-10% of the nominal voltage for 95% of the time. In addition verify the voltage does not exceed +10% or -15% of nominal for 100% of the time. These are the standard recommendations for low voltage systems in both Europe and the United States. High voltages can cause premature motor failures, such as in, air conditioners, washers, dryers, refrigerator…etc. Premature lighting failure. High voltage can cause incandescent as well as florescent lights to burn brighter.

Unbalance
Verify the voltage negative sequence unbalance does not exceed 2% for 95% of the time. Unbalanced voltages can cause serious problems in 3 phase motors. The resulting current unbalance in a motor will be 6 to 10 times higher than the voltage unbalance that creates it. This creates excessive heating and can burn out coils. A voltage unbalance of just 2% can equal a current unbalance of up to 20%.

Dips / Sags

Examine any voltage dips that fall below 10% of nominal. These can be associated not only with fluctuations in voltage but also with loads turning on. Always examine the current during a dip. When a load turns on it will draw an inrush of current. This sudden inrush of current can cause the voltage to dip. This can cause lights to dim or equipment to trip off line. In residential application it is not uncommon to see voltage dips occur when cooling systems turn on and off. Long duration events that last over a minute can cause heating issues. When a motor operates it outputs continuous torque. This means it requires constant power. If the voltage drops this means the current must increase to maintain the power. This will increase the heating effects. $P = I^2 \times R$ As the current increases so does the heat.

Swells
Examine any voltage swells that rise 10% above nominal. These can be caused by poor regulation from solar panels and also from loads turning off. Examine the current during a swell. When a load turns off a drop in current will be seen.
In solar systems with poor voltage conditioning over voltage conditions can be seen. This can cause light outputs to swell or breakers to trip off line. Over voltages can also cause motor cores to saturate. In residential applications there are many motors that turn on and off multiple times a day. These can include air conditioning motors, refrigeration motors, washing machine…etc. Over voltage conditions will cause larger inrush currents. These again contribute to higher heating, thus causing higher levels of stress, reducing the life of the motor.

Sub-cycle events and transients
Examine both sub-cycle distortions and transients. Sub-cycle distortions can be caused by many different factors. These include notching from motor commutation as well as noise. A common cause of sub-cycle distortions is low frequency transients. These can either be in the form of oscillatory transients or impulse transients. Oscillatory transients will have a ringing out associated with them. These are normal and will be seen when the utility switches in capacitor banks to compensate for large inductive loading. Impulse transients will be unidirectional. These are associated with equipment turning on and off as well as induced currents from lightning. These sub-cycle events can cause breakers to trip off line. It is not uncommon to see Ground Fault Circuit Interrupter breakers to trip due to sub-cycle events. This can be due to grounding issues.
Due to the fast response time of solar panels high speed transients can also be seen on solar systems with poor voltage conditioning. These will have time durations in the micro-second range. High speed or fast transients can have adverse impacts on residential and commercial electronics. Modern electronics do have input filters that do filter out transients. These can fail when being exposed to repeated transients. This will lead to failures in these electronic devices. These can include flat screen televisions, microwave ovens and computer equipment.

Rapid Voltage Change (RVC)
Rapid voltage change or RVC events can be seen when the voltage is rapidly changing more than 3% but less than 10%. If it is greater than 10% then it is a dip or a swell event. RVC will not typically cause equipment to trip off line but it can cause lighting fluctuations in all different

types of lighting systems. As the output in solar systems change rapid voltage changes may be seen, causing lighting fluctuations. In these cases the voltage regulation needs to be addressed.

Flicker

Flicker is another measurement of light fluctuations. The flicker measurement examines the voltage variations and applies a weighted to curve to the measured variations. This waited curve is based on incandescent lights. If incandescent lights are flickering then examine the Pst and Plt levels. If the Pst level exceeds 1.0 or the Plt level exceeds 0.8 then the voltage variations can be the cause of the incandescent light flicker. In these cases the voltage regulation needs to be addressed.

THD & Harmonics & Inter-Harmonics

Total Harmonic Distortion (THD) is a sum of the individual harmonic orders. Harmonics cause heating effects on wires, motors and transformers. This heating effect can cause fuses to open and breakers to open. The higher the magnitude or the frequency of the harmonic the grater the heating effects. Certain harmonics known as zero sequence harmonics will cause high neutral currents that can overheat neutral lines. Harmonics can cause intermittent failures in sensitive electronics. Harmonics also can cause resonance that can cause appliances or equipment to vibrate. In extreme cases resonance can lead to catastrophic failure.
Harmonics are a common distortion caused by rectifies. These are devices that convert AC to DC current. Almost all equipment today operates off DC, from computer equipment, flat screen televisions and electronics in appliances. Inverters used on solar panels create higher frequency harmonics. The problem comes when the harmonic content gets too high.
The recommended limits for individual harmonic orders vary in different regions. However most regions recommend that the voltage total harmonic distortion or THD does not exceed 8%. In general individual voltage harmonic orders should not exceed 5%. In some European countries where EN50160 standards apply the limits will be different for different orders. Please refer to the standard.

IEC Inter-Harmonics

Harmonic frequencies are always a multiple of the fundamental frequency. The 3rd harmonic order on a 50Hz system would be 150Hz (3 x 50). The third harmonic on a 60Hz system would be 180Hz (3 x 60). Inter-harmonics are waveform distortions that occur at the frequencies in between the harmonic orders. Inter-harmonics on not as common as harmonics and are typically at lower levels. Inter-harmonics can cause flickering in lighting systems and resonance issues that can cause vibration in equipment and appliances. Some sources of inter-harmonics include arcing loads, electronic frequency converters, variable load drives and power line communications. Typically voltage inter-harmonic values should not exceed 2%.

Below are some general guidelines when analyzing harmonics.

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1. It is recommended that Voltage THD not exceed 8% on low voltage systems.
2. Zero sequence harmonics can cause high neutral currents. These include the 3rd order, the 9th order as well as the 15th and 21st orders.
3. Negative sequence harmonics can cause poor efficiency in motors and motor vibration. These include the 5th order, the 11th order as well as the 17th and 23rd orders.
4. The majority of harmonic orders should be odd values because rectifiers operate symmetrically on the AC waveform. Even voltage harmonics in excess of 2% can be a sign of a faulty rectifier.
5. Inverters and high frequency converters create higher frequency harmonics. These harmonics will typically be in the 35th to 49th order.
6. Current harmonics will be much larger than voltage harmonics. This is normal. As current harmonics get too large they will create harmonics on the voltage.
7. Be cautious when measuring current harmonics and current THD. Since harmonics and THD are measured as a percentage of the fundamental, these values can appear very high when the current values are very low. It is best to analyze Total Demand Distortion when examining current harmonics.
8. In reported case of flicker lights be sure to check inter-harmonic levels.

Examine Timed Waveform

Examining the timed current waveforms can help determine the source of harmonics.
Since modern electronics function off of DC they will use rectifiers to convert the incoming AC to DC. There are different types of rectifiers that are used for different applications. These different type of rectifiers have different harmonic profiles. The different rectifiers will create a number of pulses. The dominate harmonic order will be the number of pulses minus 1.

Commercial electronics such as computers and printers use simple full wave bridge rectifiers. These are 4 pulse rectifiers so their harmonic signature will consist of a dominate 3rd harmonic followed by the 5th harmonic.

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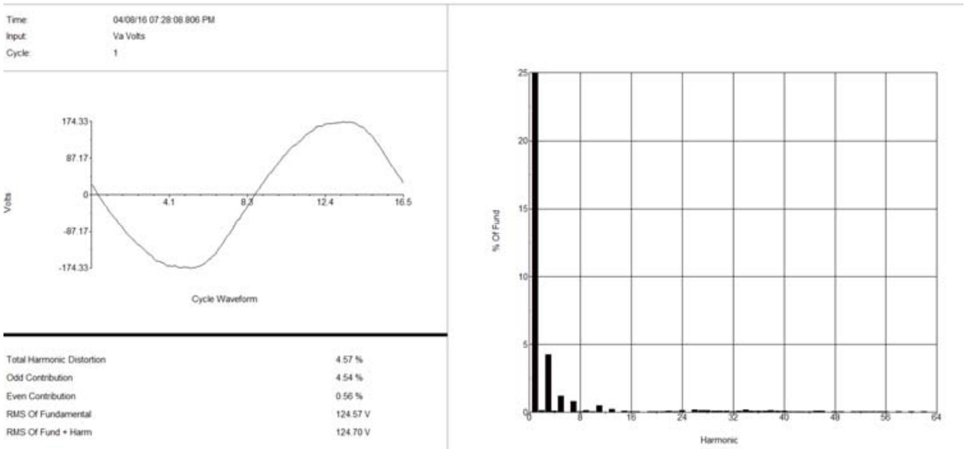
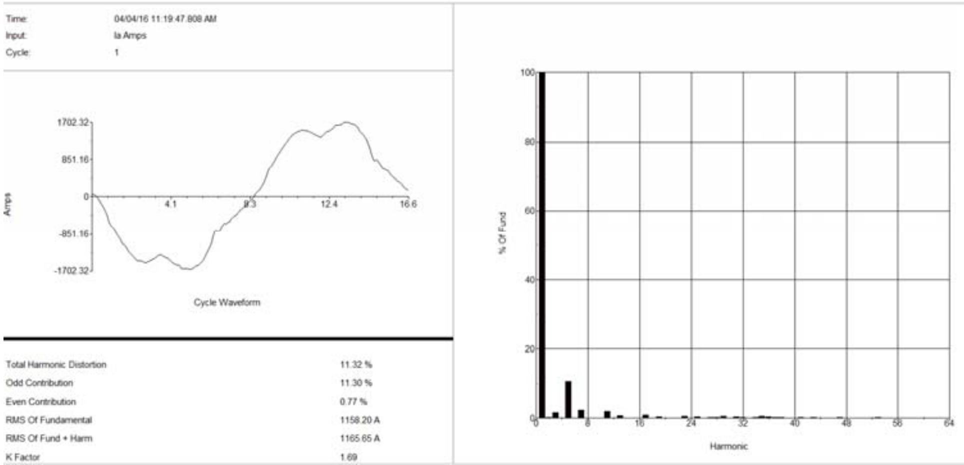


Third harmonic is zero sequence. These harmonics will add together and will cause higher neutral currents.

Industrial equipment that operates off 3 phase power may use a 6 pulse converter to rectify the AC. Their harmonic signature will consist of a dominate 5th harmonic followed by the 7th harmonic.



Some industrial equipment may use a 12 pulse converter to rectify the AC. Their harmonic signature will consist of a dominate 11th harmonic followed by the 13th harmonic.

Both the 5th and 11th order harmonics are negative sequence harmonics. These harmonics will create counter rotational torques in motors. This will reduce their efficiency and can cause them to vibrate.

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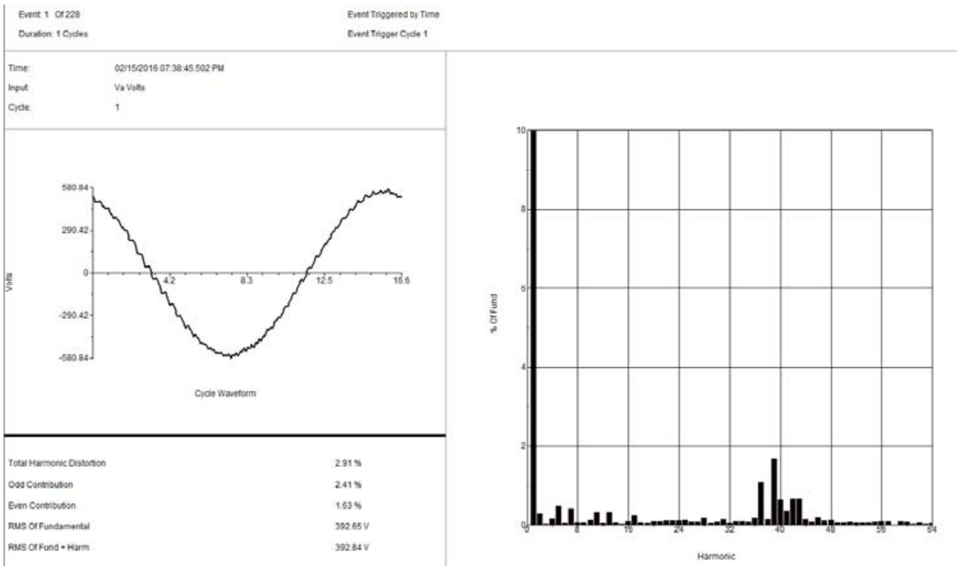
High speed switching devices found in both high speed switching power supplies and inverters will cause higher frequency harmonics. Inverters used on solar applications create these higher frequency harmonics. These will be seen as harmonic orders between the 35th and 49th harmonic.



Higher frequency harmonics increase heating effects in wires and coils.

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