

# 3-Phase Efficiency, Power Factor, and Harmonics

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## Introduction

The goal of this paper is not to make engineers, but to help our sales rep partners understand some of the terminology that the end user may use in specifying La Marche equipment.

In the first installment of “Efficiency/ Power Factor / Harmonics” from the 2012 La Marche Trade Fair, the basic principles of these quantities were introduced for single phase systems. The necessity for efficiency in power systems has a growing importance. The proliferation of new electricity demands compounded by decommissioning of older Nuclear and Fossil power generation facilities exacerbate the problem. Refer back to the first installment for a refreshment on the concepts and definitions. This second installment introduces 3-phase systems and how the 3-phase devices prevalent in higher power applications have an advantage over single phase systems when it comes to efficiency, power factor and harmonics. As the original paper’s goal was to introduce these properties, the goal of this paper is to expand on the original content for 3-phase applications.

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## A brief history of poly-phase systems

You may be aware of the debate over which electrical power distribution technique was superior; Thomas Edison's DC (direct current), or George Westinghouse's AC (alternating current). This "War of Currents" goes as far back as the 1880's. It wasn't until Westinghouse purchased Nicola Tesla's patents for 3-phase generators, motors and transformers, that the currents would shift from the dominant DC distribution of the day towards AC power.

The biggest problem with DC mass distribution was distribution losses of the standard generating voltage over distance when measured at the load. Edison was locating small power plants within 1-2 miles of the load to combat the wire losses. The DC system was upgraded to 3-wires; +110V, Neutral-Return, and -110V, as a method of distributing the user's 100V loads between two circuits and lowering the wire losses. With balanced DC load currents, the Neutral-Return wire current will cancel to zero, When the DC loads were not balanced about the + & - 110Vdc rails, the Neutral-Return wire will carry the un-balanced load current differential.

AC power could use transformers to step-up the voltage to very high levels, requiring less current to flow over long transmission lines for low wire losses of the same power level. At the load-side, another transformer steps the voltage down to usable levels. This method has advantages of efficient transmission over long distances compared to DC at the time, could use fewer but larger power plants of lower operating expenses, and customized voltages could be provided to the end user. The Westinghouse original designs were single phase using only 2-wires. Even with step-up/step-down transmission strategies, the high transmission voltages generated were limited to the insulation properties of materials available at the time, which limited AC power's benefit of higher transmission voltages.

The only prevalent electrical loads at the time were incandescent light bulbs and motors, both could be efficiently utilized with DC or AC power. The cost and availability of wire and electrical components were a real premium at the time.

Nicola Tesla envisioned 3-phase AC power distribution over single-phase AC power. With the addition of only 1-more wire than a single phase AC system could almost double the total amount of power transmitted. Adding one more wire adds only 50% more cost than the original 2 wires, and yields 73% more power for the same voltage; a great cost/benefit ratio! 4, 5, or 6 phases could just as easily been introduced as well, but cost and added complexity diminished the benefit, with 3-phases being the most optimal solution.

# The basics of 3-phase; compare to single phase.

Single phase required a minimum of 2-wires to transmit power to the load and 3-phase requires a minimum of 3-wires. Please see the attached figure 1 & 3.

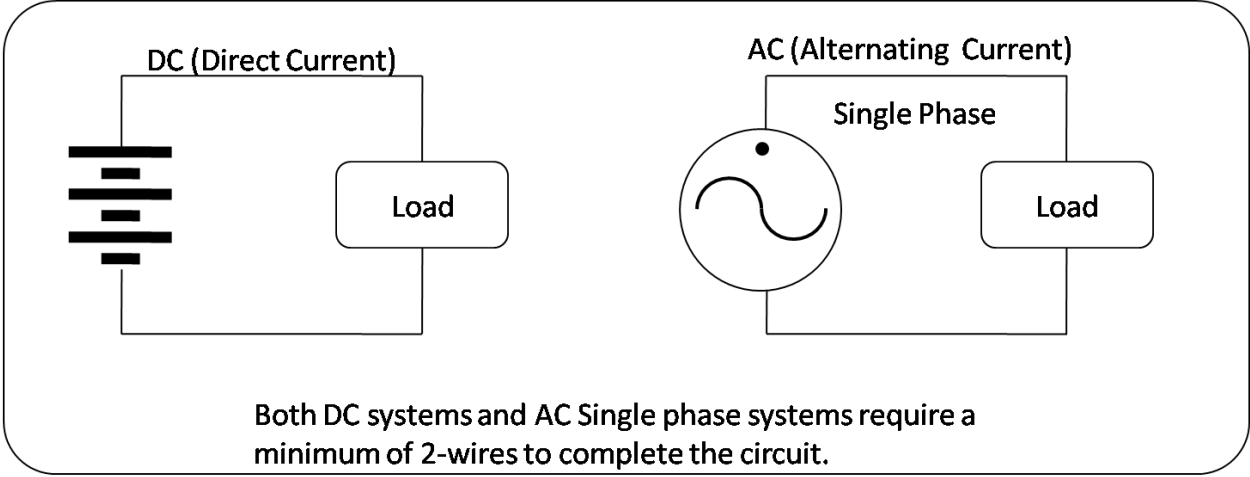


Figure 1. Basic DC System and basis Single-Phase AC system

3-Phase power is obviously more complicated than single phase. Single phase power has only 1 voltage waveform applied to the load; see figure 2. 3-phase systems have 3 concurrent voltage waveforms offset from each other by 120degrees. Please see figure 4.

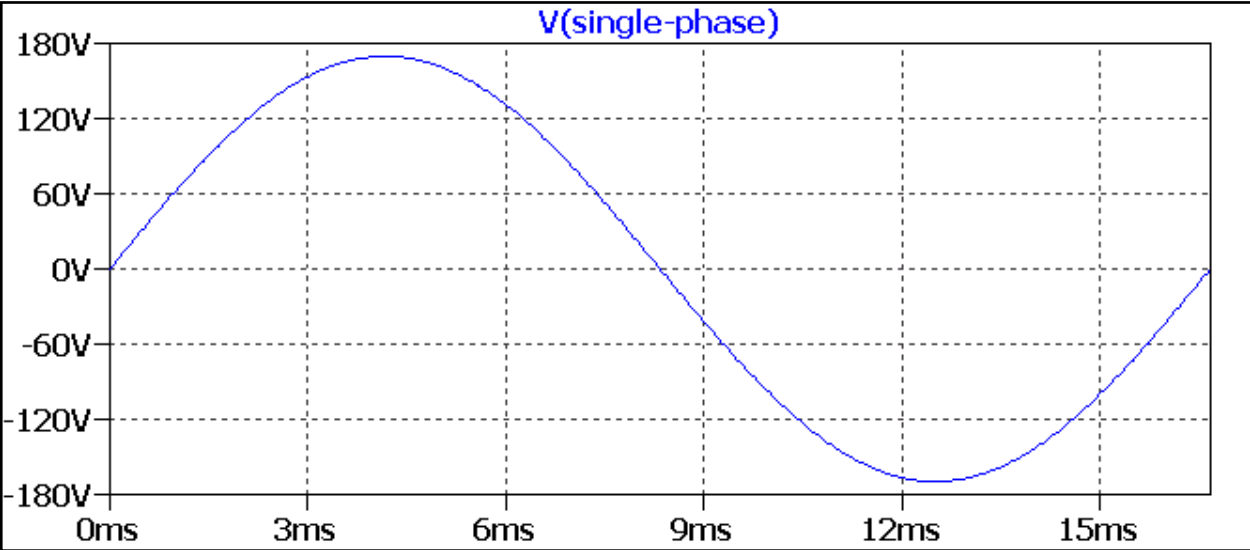


Figure 2. Single-Phase voltage waveform

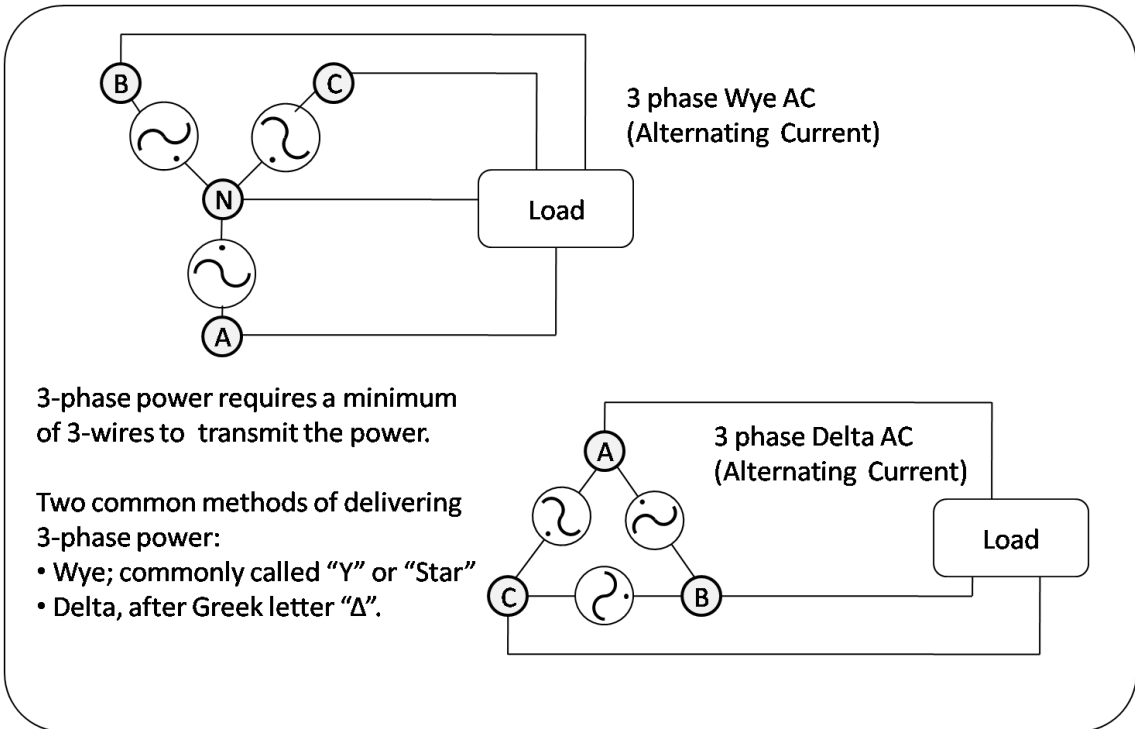


Figure 3. basic wiring diagrams for 3-phase

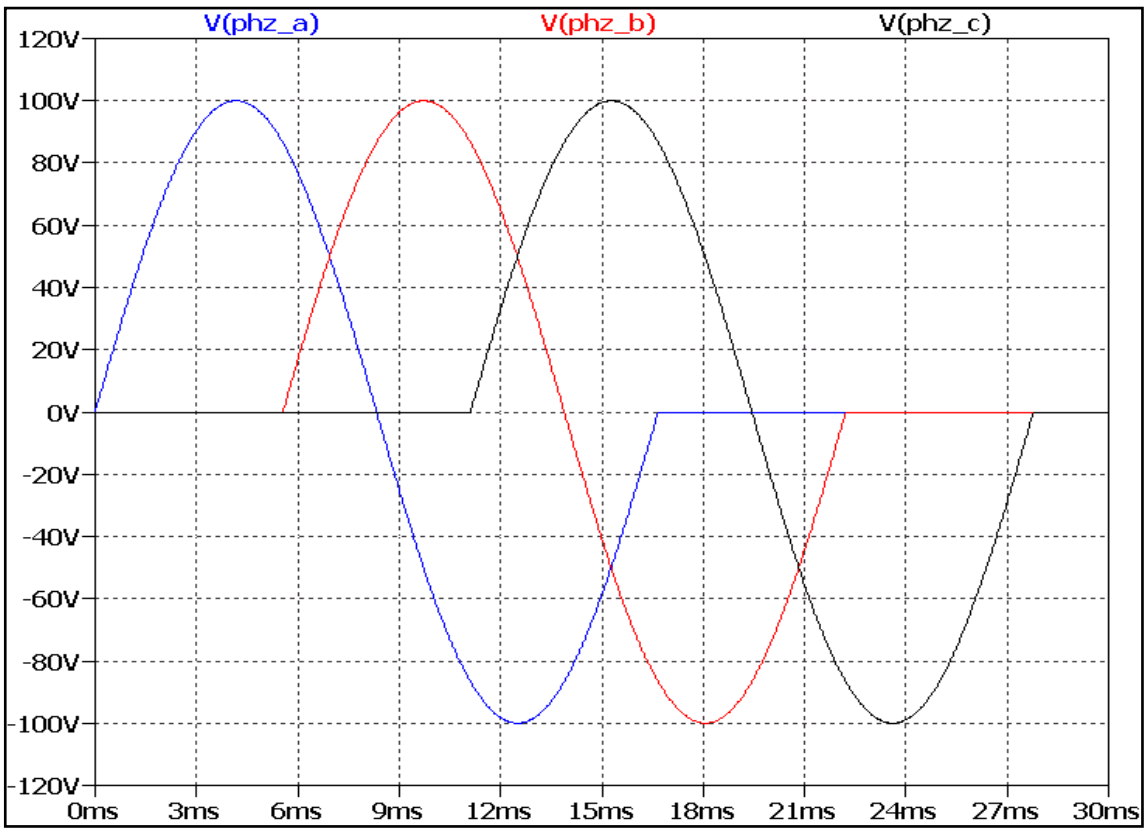


Figure 4. Concurrent Voltage waveforms for 3-phase offset by 120°.

In single phase AC systems or DC systems, most voltage measurements are referenced to a common node, sometimes called a “ground” or more properly “common”; sometimes this will be a Neutral. When referring to voltage measurements in 3-phase systems, it may or may not be referenced to a common Neutral. Please see figure 3 & 5.

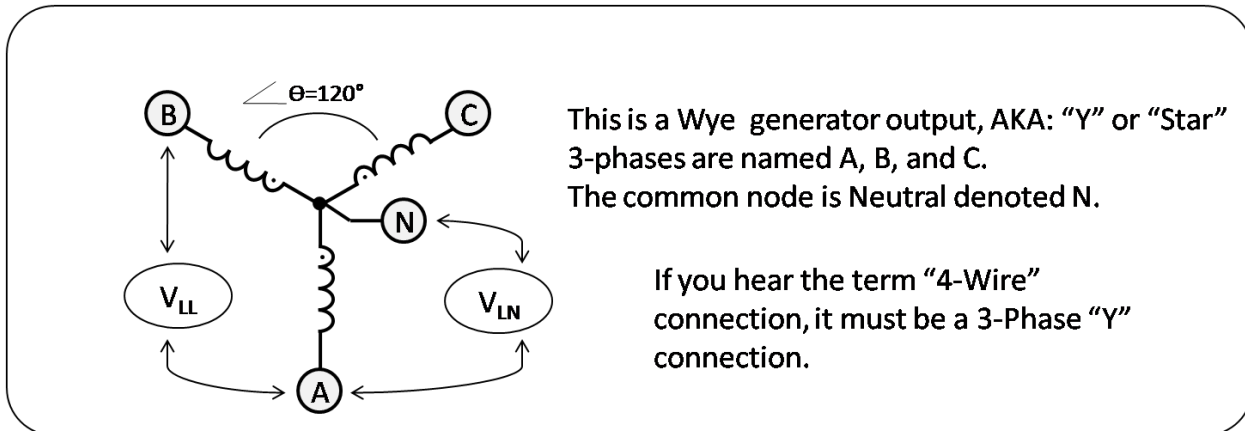


Figure 5. Wye diagram & voltage nomenclature

The voltage nomenclature for documenting measurements or specifications is strait forward. It is generally accepted that voltage measurements of 3-phase systems are the RMS values.

- $V_{LL}$  = Voltage Measured Line-to-Line; AKA Phase-to-Phase.
- $V_{BA}$  = Voltage Measured Line-to-Line; Specifically from Phase-B to Phase-A.
- $V_{LN}$  = Voltage Measured Line-to-Neutral; AKA Phase-to-Neutral.
- $V_{CN}$  = Voltage Measured Line-to-Neutral; Specifically from Phase-C to Neutral.

If the voltage is listed as simply  $V_{Phase-A}$  then it is implied to that it was measured from Phase to Neutral.

Here is an ideal example of voltages in a 480V “Y” commercial power or generator output.

- $V_{LL} = 480V$
- $V_{LN} = 277V$

In our ideal scenario, the voltages are balanced such that each of the three  $V_{LL}$  measured equally, and each of the three phases to neutral measured equally as well. In the US, it is common that a “Y” output generator or a “Y” output distribution transformer gets the Neutral terminal connected to Earth Ground at a single point within the master breaker panel board. When the 3-phase load equipment has a Neutral connection, there will be a total of 5-conductors ran to the load; Neutral, Ground, and all 3-phases.

If you have been given the voltage in terms of Phase-to-Neutral, you can calculate the voltage from line-to-line.

$$V_{LL} = V_{LN} \times \sqrt{3} \quad 480V_{LL} \approx 277V_{LN} \times \sqrt{3} \quad 480V_{LL} \approx 277V_{LN} \times 1.732$$

The phases named A, B, and C in this paper are sometimes called R, Y, and B. Europe and some parts of Canada name the phases R, S, and T.

It may also be likely to encounter a Delta system in which there is no Neutral connection. When Delta's are used as a generator output or a distribution transformer secondary, they may create a ground asymmetrically at a center tap of a phase-to-phase winding, but not always. Delta outputs are not as popular as Wye outputs, partly because of asymmetric secondary grounding. There are several grounding methods for 3-phase Deltas that are outside the scope of this paper.

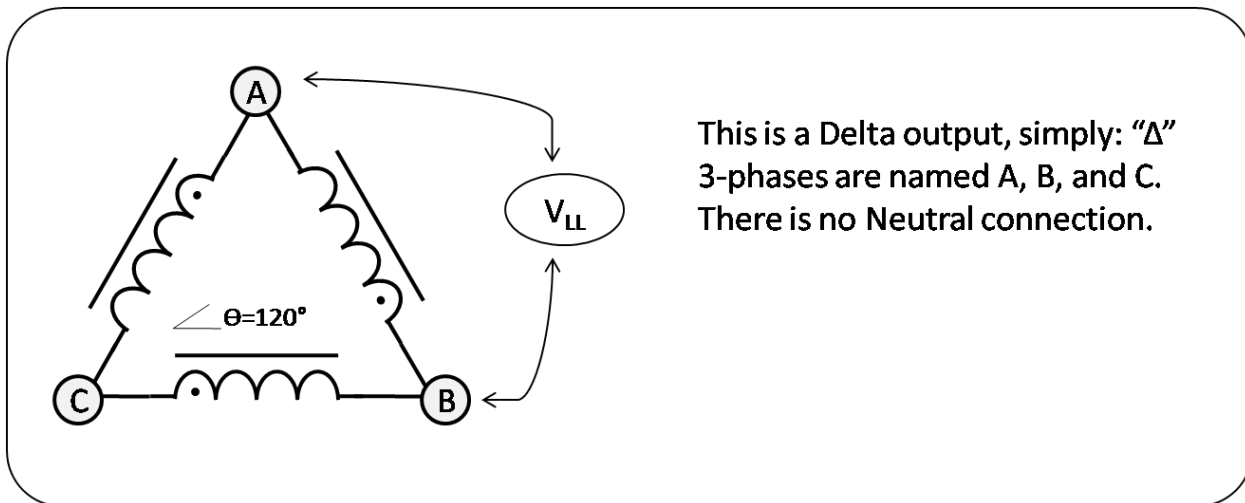


Figure 6. Delta diagram and voltage nomenclature.

## Does a La Marche Charger require a “Y” or a “Δ” supply?

3-Phase La Marche Battery chargers are designed specifically to not require a Neutral connection by running rather balanced currents per phase. Our chargers require only the 3-Phase wire connections plus a safety ground wire terminated from our enclosure to Earth Ground.

La Marche 3-phase chargers such as A75D(E), A12B, TPSD, A36D, A70B, A35M, A45M, A75MD can all operate from either a “Y” or a “Δ” supply equally well. What is important is that the supplied  $V_{LL}$  is matched to the nominal input voltage of the charger and the voltage is well balanced. As with all high potential electrical equipment, the enclosure needs to be Earth Grounded according to NEC or other local electrical codes.

## Common 3-Phase transformer configurations in use:

3-Phase transformers can be wound in several different ways. There are pros/cons associated with each winding configuration looking at cost, weight, and several electrical performance parameters.

The transformer primary winding can be configured for either “ $\Delta$ ” or “ $Y$ ”, and the secondary winding can be configured for either “ $\Delta$ ” or “ $Y$ ”. A transformer’s primary and secondary could be mixed “ $\Delta$ ” or “ $Y$ ” in any order.

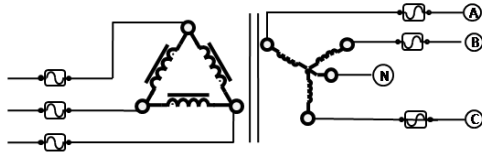
The general nomenclature for designating how the transformer is configured is strait forward.

- $\Delta/\Delta$  = a Delta primary and Delta secondary
- $\Delta/Y$  = a Delta primary and Wye secondary
- $Y/\Delta$  = a Wye primary and Delta secondary
- $Y/Y$  = a Wye primary and Wye secondary.

When at the site of charger installation, you generally don’t know if the voltage transformer on site is  $\Delta/\Delta$ ,  $\Delta/Y$ ,  $Y/\Delta$ , or  $Y/Y$ . The La Marche charger is indifferent to this. The La Marche A75DE 3-phase microprocessor controlled SCR battery charger uses an internal  $\Delta/Y$  for reasons that will be explained shortly.

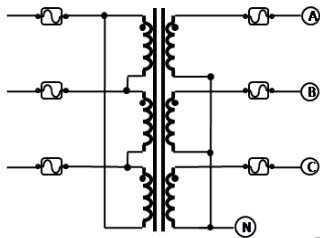
As you can tell from Figure 7, the specific wiring of each phase starts adding complexity and cluttering a schematic sheet very quickly. Many end-users such as a power utility draw their substation wiring diagrams as “single-line-diagrams” to save thousands of connections in triplicate. The Delta/Wye ( $\Delta/Y$ ). transformer shown in figure 7 was chosen so you can see how both  $\Delta$  and  $Y$  windings are actually connected in a 3-phase transformer. The  $\Delta$  and  $Y$  connections are made outside the transformer by connecting the beginnings and the endings of each winding properly.

## Delta / Wye Transformer schematic representations.



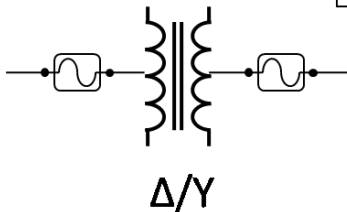
Conceptual  $\Delta/Y$  transformer with fuses.  
Seldom drawn this way, but it is very clear.

Equivalent



Typical equipment schematic diagram of  $\Delta/Y$  transformer with fuses. Shows all wiring connections orthogonally.

Equivalent



Typical “one-line-diagram” schematic of  $\Delta/Y$  transformer with fuses. Only shows single run, but all phases are implied, and it is implied that there is one fuse per phase.

Figure 7. Delta / Wye Transformer diagrams

- Generally, single-line-diagrams are reserved for “outside the box” wiring.

The single-line-diagram is obviously quicker and cleaner, but requires trained installation electricians to understand the implied connections in order to install the devices properly.

- Generally, detailed schematics showing each connection are reserved for “inside the box” wiring.

While inside the equipment, such as a La Marche battery charger, the schematic shows all connections for consistent quality control and a clear understanding of every connection made. Installation electricians may need to refer to the equipment schematic diagram to be certain all their field wiring connections are correct.

When measuring current in 3-phase systems with an oscilloscope or power analyzer, it is necessary that the current probe direction points in towards the load to obtain proper relationship with the voltage measured.

Phase currents are documented as RMS values such as: **12Amps<sub>Phase-A</sub>**. The Neutral current should also be measured and documented in RMS terms.

Figure 8 shows what typical dry laminated transformers look like for 3-phase applications with the primary and secondary wires protruding out of the coils. The transformers shown could be wired in any combination of “ $\Delta$ ” or “ $Y$ ”. As you will see later, there is an advantage to using a single 3-phase transformer as opposed to using three separate single phase transformers.



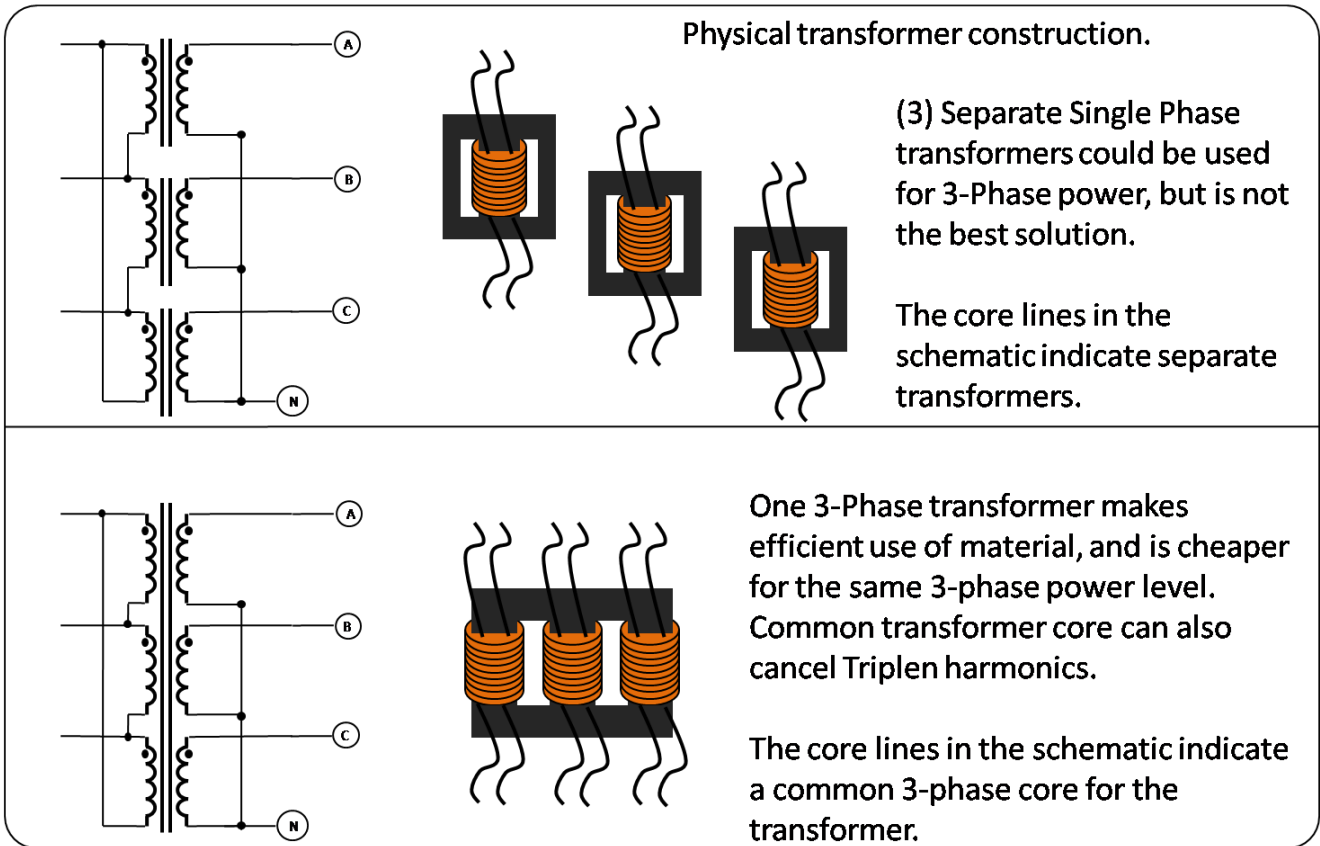
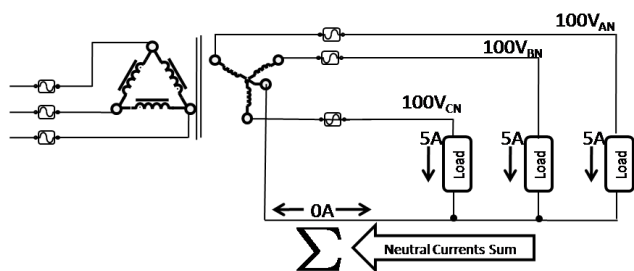


Figure 8. Physical transformer construction

## Some common 3-Phase waveforms:

The following waveforms in figure 9, 10, 11, & 12 show the currents in 3-phase systems. Note that for balanced load current, the neutral current summation is zero amps in figure 9. It is important to understand how the current flows in ideal systems before we can progress to non-ideal systems.

**Neutral Current is the instantaneous summation of all phase currents.**



Balanced Y system.

The summation can cancel to zero by combining:

- balanced load voltage
- balanced load currents
- little or no harmonic current flow.

In this example, the Neutral current canceled out to zero amps.

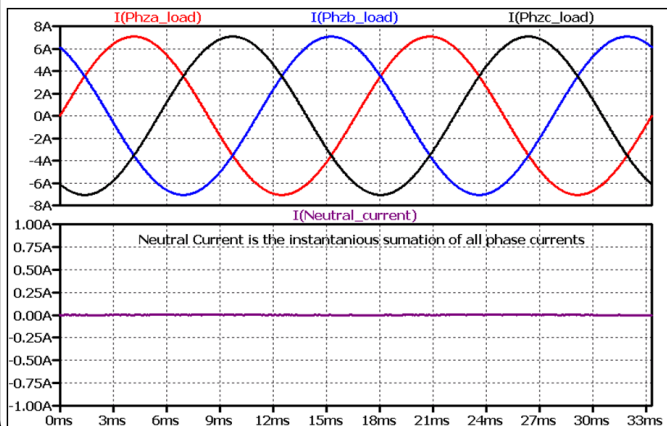
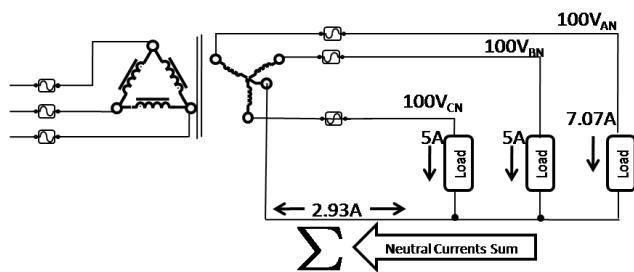


Figure 9. Balanced System Neutral Current.

**Neutral Current is the instantaneous summation of all phase currents.**



The summation can cancel to zero by combining:

- balanced load voltage
- balanced load currents
- little or no harmonic current flow.

This example shows:

- Balanced voltage
- No harmonic currents
- Unbalanced load results in Neutral current

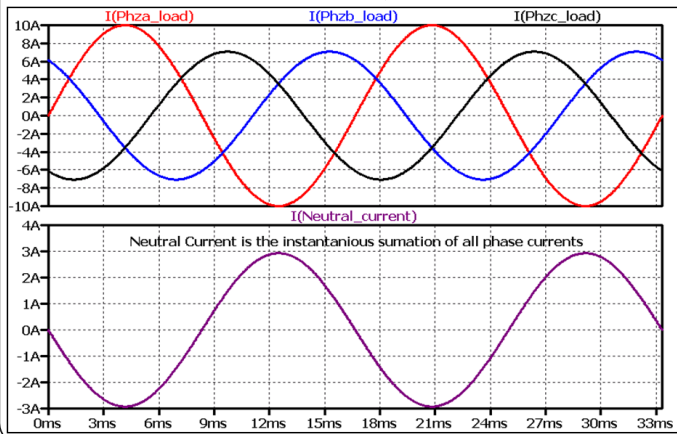
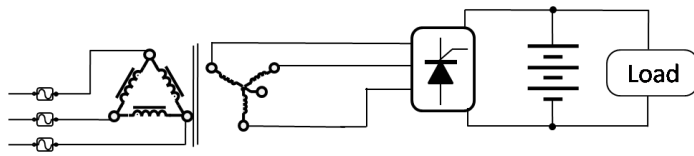
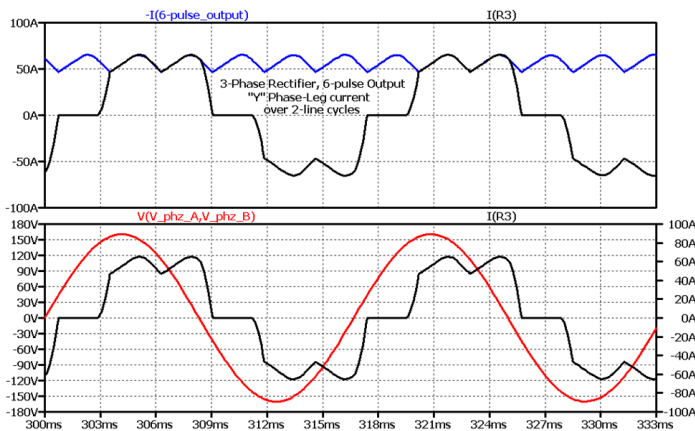


Figure 10. Un-Balanced System results in Neutral Current  
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**Typical 3-phase rectifier waveforms. "Y" Phase leg current**



Examine "Y" Wye phase current



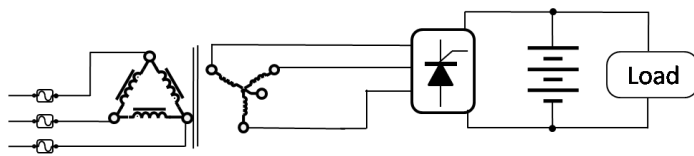
Battery Charger  
A75DE

This example shows:

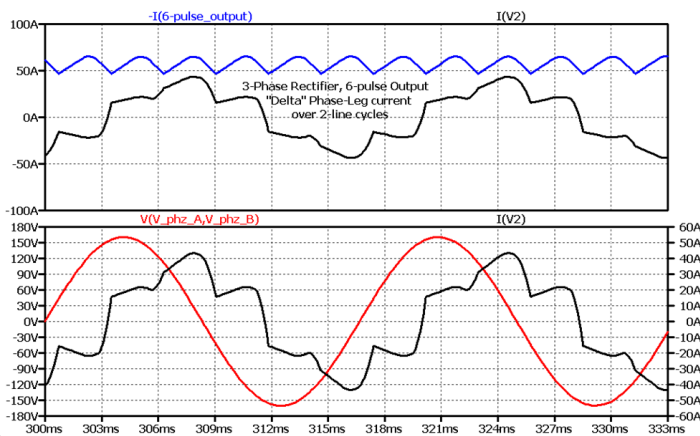
- 3-phase  $\Delta/Y$  transformer inside charger.
- 6-Pulse SCR rectifier shown 2 line cycles.
- 6-pulses over 1 line cycle.
- Each pulse in DC output is a rectifier pair.
- "Y" Phase leg current.
- Pulses visible in Y-leg current are rectifier pulses.

Figure 11 Shows typical Rectifier "Y" phase leg current

**Typical 3-phase rectifier waveforms. "Δ" Phase leg current**



Examine "Δ" Delta phase current



Battery Charger  
A75DE

This example shows:

- 3-phase  $\Delta/Y$  transformer inside charger.
- 6-Pulse SCR rectifier shown 2 line cycles.
- 6-pulses over 1 line cycle.
- Each pulse in DC output is a rectifier pair.
- "Δ" Phase leg current.
- Pulses visible in  $\Delta$ -leg current are rectifier pulses.
- "Δ" primary has lower THD than same power in "Y".

Figure 12 shows typical rectifier "Delta" phase current

## Triplen Harmonic Elimination in Delta transformers.

3-Phase  $\Delta/Y$  transformers are arguably the most common voltage transformers in use because they can eliminate Triplen Harmonics generated by secondary loads from getting through to the primary input current.

The original Efficiency / Power Factor / Harmonics white paper from the La Marche 2012 Trade Fair went into great detail about harmonics. In short, harmonics are generated by non-linear loads that are multiples of the fundamental supply frequency, and are detrimental to the Power Factor and Efficiency. For further details on harmonics, please refer back to the original white paper.

Triplen Harmonics are not only multiples of the fundamental commercial power supply frequency, but also odd multiples of 3. For United States 60Hz commercial power, Triplen harmonics are: 3<sup>rd</sup> (180Hz), 9<sup>th</sup> (540Hz), 15<sup>th</sup> (900Hz), and so on. Triplen harmonics are generally in-phase with the fundamental.

As demonstrated in figure 10, un-balanced phase currents will manifest as neutral current as the vector sum of the phase currents.

In a  $\Delta/Y$  transformer, any Triplen harmonics developed on the secondary Wye side, will get trapped and circulated by the primary Delta, as there is no Neutral node. In a balanced 3-phase system Triplen harmonics are circulating in the primary Delta transformer winding adding heat to that coil, but does not make it back to the utility. Un-balanced systems will add additional 3<sup>rd</sup> harmonic content to the circulating current in the primary Delta adding heat, and decreasing efficiency.

## What are the advantages of 3-phase systems over single-phase?

3-phase systems have an advantages over single phase systems primarily when it comes to high power levels.

- Higher power levels in smaller volume than equivalent single-phase systems.
- 3-phase chargers naturally produce less ripple, and they require less capacitors to maintain than the equivalent power single phase chargers.
- 3-phase chargers naturally eliminate Triplen harmonics, that a comparable technology single phase charger will produce. Generally, the 3-phase chargers have lower harmonic content than a similar size single phase unit.
- For the same power level, 3-phase chargers allow you to run smaller AC input wiring than the single phase counterpart.

## When would you recommend a 3-phase or single-phase charger?

There are two primary drivers in the decision to recommend single-phase or 3-phase chargers.

- A. Do they have 3-phase power available at the site of installation?
- B. How large is the steady-state load? There is no single magic threshold to decide single-phase as opposed to three-phase chargers. Suffice to say we wouldn't recommend a three-phase charger for a

1Kwatt DC output, and we wouldn't recommend a single phase charger for applications greater than 13Kwatts. Even though a single phase charger may generate Triplen harmonics, at small power levels, they may be insignificant.

However, if the steady state DC load is greater than a few KW, and they have 3-phase power available, suggest a 3-phase charger.

## List of commonly used 3-Phase Power equations:

When using the formulas below, it is assumed that the voltage balance is within 3% Per ANSI C84.1

- Solve Voltage or imbalance according to ANSI C84.1\_2011: (note, the percentage of current imbalance uses the same formula; simply replace "V<sub>LL</sub>" with "Current<sub>Phase</sub>").

$$\text{Percent\_Voltage\_Imbalance} = 100 \cdot \left( \frac{\text{Max\_Deviation\_From\_Average\_V}_{LL}}{\text{Average}(V_{LL})} \right)$$

- Note, IEEE has at least 2 different formulas specifying the percent imbalance in 3-phase systems that do not match ANSI C84.1. The IEEE formulas have about a 1% spread between different results as compared to the C84.1 formula.
- Note, NEMA PE 5 has yet another voltage imbalance formula with at least a 2-percent error from the ANSI C84.1 formula, and it will be revised shortly under IEEE-P2405 to the C84.1 formula shown above.

- Solve Watts when Voltage<sub>LL</sub>, Current<sub>PHZ</sub>, and PF are known:

$$W = V_{LL} \cdot A_{PHZ} \cdot PF \cdot \sqrt{3}$$

- Solve Individual line current when Input Wattage, PF, & Voltage<sub>LL</sub> are known (balanced system):

$$I_{Phase} = \frac{\text{Input\_Power(watts)}}{V_{LL} \cdot PF \cdot \sqrt{3}}$$

- Solve Individual line current when Rectifier DC output Wattage, PF, Efficiency & Voltage<sub>LL</sub> are known (balanced system):

$$I_{Phase} = \frac{\text{DC\_Output\_Power(watts)}}{V_{LL} \cdot PF \cdot \text{Eff} \cdot \sqrt{3}}$$

- Solve 3-phase PF when Watts, V<sub>LL</sub>, & A<sub>PHZ</sub> are known (balanced system):

$$3\text{phz}PF = \frac{\text{Power(watts)}}{V_{LL} \cdot A_{PHZ} \cdot \sqrt{3}}$$

- Solve KiloWatt (KW) when  $V_{LL}$ ,  $A_{PHZ}$ , and PF are known (balanced system):

$$3\text{phz\_}KW = \frac{V_{LL} \cdot A_{PHZ} \cdot PF \cdot \sqrt{3}}{1000}$$

- Solve KVA when  $V_{LL}$  &  $A_{PHZ}$  are known (balanced system):

$$KVA = \frac{V_{LL} \cdot A_{PHZ} \cdot \sqrt{3}}{1000}$$

- Approximate PT secondary phase current in a “Y” circuit from the DC rectified output current (balanced system):

$$A_{\text{Secondary\_}PHZ} \approx \left( \frac{\sqrt{2}}{\sqrt{3}} \right) \cdot Idc \quad \left( \frac{\sqrt{2}}{\sqrt{3}} \right) \approx 0.817$$

## References

INTERNATIONAL ENERGY OUTLOOK 2014 <http://www.eia.gov/forecasts/ieo/world.cfm>

IAEA International Atomic Energy Agency: The World Outlook for Electricity Investment  
[http://www.iaea.org/Publications/Magazines/Bulletin/Bull461/power\\_to\\_the\\_people.html](http://www.iaea.org/Publications/Magazines/Bulletin/Bull461/power_to_the_people.html)

Webster’s Wiley Encyclopedia of Electrical and Electronics Engineering Volume 17 1999 ISBN 0-471-13946-7

Power Electronics Converter, Applications, and Design by Mohan, Undeland, and Robbins. Published by John Wiley & Sons. 2003 ISBN0-471-22693-9

Power Electronics Course University of Wisconsin Madison School of Engineering. 2012  
[www.epd.engr.wisc.edu](http://www.epd.engr.wisc.edu)

Handbook of Electric Power Calculations 3<sup>rd</sup> Ed by Wayne Beaty. Published by McGraw-Hill 2000

IEEE Chicago Section PES Group class: Harmonics on Power Systems Workshop presented by: Roger Dugan, Sr.Technical Executive for EPRI, Knoxville, TN [www.epri.com](http://www.epri.com)

[http://my.epri.com/portal/server.pt/gateway/PTARGS\\_0\\_243352\\_317\\_205\\_776\\_43/http%3B/uspalecp604%3B7087/publishedcontent/publish/epri\\_calculates\\_annual\\_cost\\_of\\_charging\\_an\\_ipad\\_at\\_1\\_36\\_da\\_855261.html](http://my.epri.com/portal/server.pt/gateway/PTARGS_0_243352_317_205_776_43/http%3B/uspalecp604%3B7087/publishedcontent/publish/epri_calculates_annual_cost_of_charging_an_ipad_at_1_36_da_855261.html)

<http://hyperphysics.phy-astr.gsu.edu/hbase/electric/powerac.html#c4>

<http://greenliving.nationalgeographic.com/energy-efficient-bulbs-halogen-vs-fluorescent-vs-incandescent-3228.html>

[http://www.energyconsultants.org/power\\_factor.htm](http://www.energyconsultants.org/power_factor.htm)

<http://www.austinenergy.com/About%20Us/Rates/Commercial/Power%20Factor/powerFactorBilling.htm>

Voltage Imbalance: <http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=1045567>

ANSI/NEMA C84.1\_2011 American National Standard for Electric Power Systems and Equipment

IEEE 519\_2014 IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.

## Glossary

1Joule = 1amp x 1volt at any instantaneous moment in time.

1Watt = Volt x Amp POWER averaged over 1-second. Example: 10Joule pulse that lasts 1/10<sup>th</sup> of a second = 1watt of power. Unit of power measuring work performed over a period of time.

CFL = Compact Florescent Light

EPRI: The Electric Power Research Institute, Inc. [www.epri.com](http://www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public as an independent nonprofit.

Fundamental: The root frequency and generally the intended sine wave to carry power. In the U.S., the fundamental is 60Hz.

Harmonics: Sine waves that are integer multiples of the fundamental frequency.

Harmonic order: 3<sup>rd</sup> order harmonic would be a frequency 3-times the fundamental, in our case 180Hz. A 6<sup>th</sup> order harmonic would be 360Hz.

HP=Horse Power. 1HP = 746Watts. 1/4HP=186Watts

IAEA: International Atomic Energy Agency

Inter-harmonic: generally even-ordered harmonics and very rare in power systems.

K-Factor Transformer: A transformer that has been specially designed to handle high-harmonic current content.

Magnetostriction: a deformation of a magnetic material causing mechanical strain. This can cease a motor.

ODD-ordered harmonics, 3<sup>rd</sup>, 5<sup>th</sup>, 7<sup>th</sup>, 9<sup>th</sup>, etc are most common.

PCC: Point of Common Coupling; The lowest voltage utility distribution node that both you and a neighboring building share. This is where IEEE-519 would measure voltage enter your building and its harmonic content.

PF: Power Factor; Ratio of Watts to VA

PFC: Power Factor Correction, can be found on higher quality switch-mode power-supplies. A circuit that actively manipulates the input current wave shape and displacement to eliminate harmonics, and make the PF very close to a perfect "1". This circuit will make a load appear as a purely resistive load.

TCO = Total Cost of Ownership.

THD: Total Harmonic Distortion is the measure of how distorted a signal is from the intended sine wave usually expressed as a percentage.

Triplen-Harmonics: multiples of 3<sup>rd</sup> order harmonics, 3<sup>rd</sup>, 9<sup>th</sup>, 15<sup>th</sup> 27<sup>th</sup>. Triplen harmonics have special properties when evaluating 3-phase power systems.

VA: Volt Amp product; unit of Apparent Power

VAR: Volt Amp product of Reactive circulating energy; unit of Reactive Power due to non perfect PF.