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Power Factor Correction (Part 1): Why We Need It And How It Evolved

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The application of power factor correction (PFC) in switched-mode power supplies is well established and the circuits used to implement active PFC are widely known. Academic R&D has explored different pathways to optimizing PFC circuits along the lines that all power conversion circuits are optimized—high efficiency, high power density, lowest cost, etc. along with high power factor. Meanwhile, the semiconductor industry has produced the PFC controllers and reference designs to pursue these same goals in practice, usually with the requirements of specific applications and PFC regulations in mind. Lately, we've even seen PFC hailed as the "killer app" for GaN power transistors, as these devices have enabled PFC boost converters to obtain the benefits of the totem-pole PFC topology.

Along with knowledge of these PFC circuits and components, many engineers likely have an awareness of the PFC standards that govern product compliance. But when it comes to why these PFC requirements are in place and what were the industry or market conditions that drove their adoption, the record is not so clear. Some engineers may have a general conception that PFC benefits the power utilities, but likely do not know just how important PFC is to the power grid and the history of why it was adopted. The short answer is that the purpose of PFC is to maximize the electrical energy transferred from the power generating stations to the loads. But there's much more to this story, which involves technical issues affecting the reliability of the power grid, as well as geo-political events and financial pressures that affected how the utilities generate power.

Here in part 1 we review the history of how PFC evolved and the technical requirements it produced. This discussion includes a review of the IEC 61000-3-2 power factor standard and the limits it imposes on harmonics generated by non-resistive loads, and where PFC is currently required. This leads into the subject of power factor-related distortion of ac line currents, especially on the neutral leg. In part 2 of this article, we'll delve into the relationship between line frequency harmonics and distortion, and the role of the delta-wye transformer in correcting this distortion on the power grid.

A Look Back

Today, electrical energy is generated in a number of ways including nuclear, coal-fired power plants, wind generation, hydroelectric, and solar. But that was not always the case. There was a time when much of power generation relied on oil and coal. Power plants that ran on oil, much of which was imported, had a higher cost than those that ran on coal.

Then almost 50 years ago, an event known as the Arab oil embargo (1973) disrupted the supply of oil from the Middle East to the U.S. and other countries, and drove up oil prices. Another energy crisis occurred in the late 70s when the Iranian revolution disrupted oil imports. Meanwhile, closer to home in Dauphin County, Pennsylania, an incident at the Three Mile Island nuclear plant changed attitudes toward nuclear power, and halted the growth in building of nuclear power generation. Utilities seeking to increase their power generation found they could not float a bond to build new nuclear power plants. So these plant designs were changed over to coal and oil.

But overall these events had two impacts. One was that some utilities converted their plants from oil to coal. Another was that the industry looked for new ways to meet growing energy demands. Studies were done to analyze electrical power usage and how it could be made more efficient.

For example, in the 1980s the U.S. Department of Energy (DoE) determined that electrical energy usage is approximately 50% inductive loading (motors) and 33% lighting loads (includes offices, street lighting, fluorescents and now LEDs), with the balance considered resistive and heating. The DoE created several programs to help address this issue to reduce energy usage. One program was the Motor Challenge which caused the industry to not use aluminum wire in induction motors and forced the motor manufacturers to have higher energy efficiency. But this was a benefit to be gained in the long term because it was costly to replace motors.

So the utilities needed a way for consumers of electrical energy to save energy in the short term. There were studies and products that showed converting lighting from a magnetic ballast to an electronic high-frequency ballast saved between 15% and 35% of the electrical energy used while keeping the light on the workspace the same. The electrical utilities on the east coast of the U.S. devised a rebate program for business to change their lighting ballasts to electronic ballasts. Companies like Triad-Urad, Thomas Industries, Motorola Lighting, Robertson Transformer and others developed products that met the industry needs.

However some of the initial electronic ballasts did not have a power factor correction circuit. Once installed, the new electronic ballasts caused excessive currents to flow in the neutral line which led to overheating of power transformers, causing them to blow. This was the impetus for PFC in lighting.

But to better understand why PFC is needed, and how it's applied, we need to understand how power is transmitted across the grid.

Transmission Of Electrical Energy

Most utility power generation is three-phase. The electrical energy is transmitted using high-voltage transmission lines, as shown in Fig. 1. Today the power generating stations include both coal- and gas-fired stations along with hydroelectric generation systems. In addition, wind farms are now becoming prevalent in parts of the U.S.

The first power factor correction technique used by the electrical power generating corporations was the use of natural-gas-fired peaking stations. These peaking stations help correct the inductive or lagging current by driving a generator to create a leading current to correct the power factor. Graduate electrical engineering courses at universities go into greater detail on how this technique is performed.

As shown in Fig. 1, electrical energy is transmitted using a three-phase delta system up to the stepdown transformers to the primary and secondary customer sites. In these stepdown transformers, the transmission is changed to a wye (Y) with a neutral line added. The stepdown transformers that create the delta-to-wye transformation cancels the third-order harmonic current created by the load. This cancellation will be discussed further in part 2 of this article.

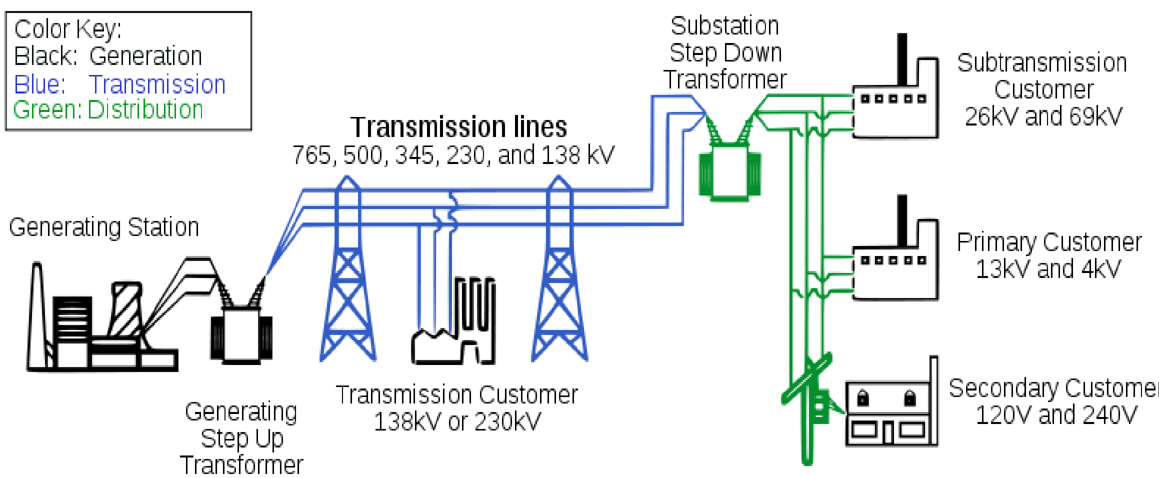

Fig. 1. Block diagram of a utility transmission system. Courtesy of Cirrus Logic's Power Meter presentation given by Alan (Ya Long) Zha in 2010.

The electrical energy is distributed to the industrial customers (primary and secondary customers in Fig. 1) as a three-phase wye using various distribution voltages: mainly 600 Vac (60 Hz) and 480 Vac (60 Hz) in the U.S. and 380 Vac (50 Hz) in Europe. The voltage delivered to the residential and light commercial customers is 240 Vac and 120 Vac, 60 Hz, single phase in North America or 220 or 240 Vac, 50 Hz single phase in Europe.

The utility companies require their industrial customers (primary customers in Fig. 1) to correct poor power factor by using special ac capacitors. This poor PF was due to the large inductive loading by the induction motors used to move the air inside the building. But as previously noted, lighting is a major user of electrical energy in office buildings and retail outlets. As a result of the problems experienced initially with use of electronic fluorescent ballasts, requirements arose for use of ballasts with higher PF.

The National Electrical Code and many municipal building codes mandated use of electronic ballasts with a Certified Ballast Manufacturers (CBM) label, which required a high power factor. The lighting industry responded by creating fluorescent ballasts that had a power factor greater than 90%. In addition, these high power factor ballasts limited the third-order harmonic currents.

Office Electronics

As the electronics industry progressed, more office products were created that enhanced office productivity. These included copiers, printers, fax machines, and computers. Unfortunately, because of their poor power factors, these products caused distortion on the neutral ac line in office systems and office cubical systems.

The scope photo, Fig. 2, which was taken at the Illinois Institute of Technology (IIT) engineering lab in 1989, shows the neutral line current and phase A of a three-phase wye distribution system. In this measurement we see that the neutral line carries three times the current as phase A. It was this overloading of the neutral line in building electrical distribution systems that caused supply transformers to overheat (as noted above), blowing fuses, and shutting down electrical power.

This problem also occurred in office buildings where cubical office spaces were used with some fuses being blown as a result of adding equipment to the office cube that was not power factor corrected. The daisy chaining of the office cubes often overloaded the neutral line. To solve some of these overcurrent conditions in the neutral, additional neutral wires were added.

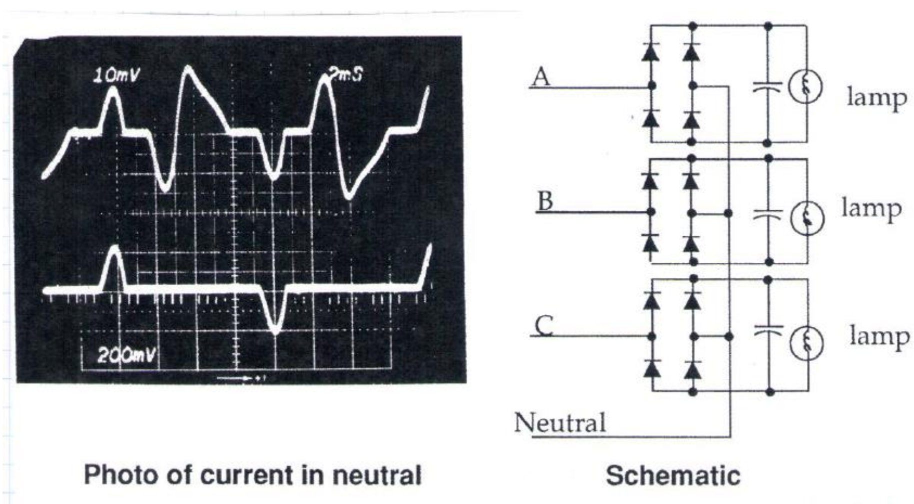

Fig. 2. Measurements of line and neutral currents in a three-phase-wye distribution system. The top trace is the neutral while the bottom is phase A. The neutral can carry 3x the phase current at 3x the frequency.

IEC Standards

In both North America and Europe, the lighting industry was aware of the power factor issue and high currents in the neutral line. The industry accepted power factor (PF) rules on fluorescent lamp ballasts requiring the PF to be above 90% and the third-order harmonic was limited to less than 25% of the fundamental. Europe created the IEC 555-2 in 1982; and there have been many updates to the IEC 555-2 which is now referred to as IEC 61000-3-2[1] for per-phase line currents less than 16 Aac. The IEC 61000-3-12[2] also addresses the harmonic currents for line currents between 16 Aac and 75 Aac per phase, which is considered industrial.

There are four classes of power factor correction per the IEC 61000-3-2 power factor standard. Class A is for three-phase motors, class B is for portable tools, class C is for lighting, and class D is for consumer products less than 600 W. A flow diagram for the limits is shown in Fig. 3. The lighting industry adapted the class C limits all over the world.

In addition to the class C harmonic limits, the electronic ballast manufacturer working with the local utilities improved the power factor system even more. There were rebate programs to help commercial and office building owners to convert to the newer energy saving lighting systems. The various utilities asked that the ballast and power supply system have less than 10% total harmonic distortion (THD) on the input current draw. This occurred over a period of time starting with a THD of less 32% and going down to 5%.

As an example, the Motorola corporate building in Schaumburg, Illinois had an electronic ballast with less than 10% THD installed on a number of office space floors. This improved the overall power quality of the building's electrical draw. The data was used by Commonwealth Edison and others to show the benefits of low THD ballasts to the power grid.

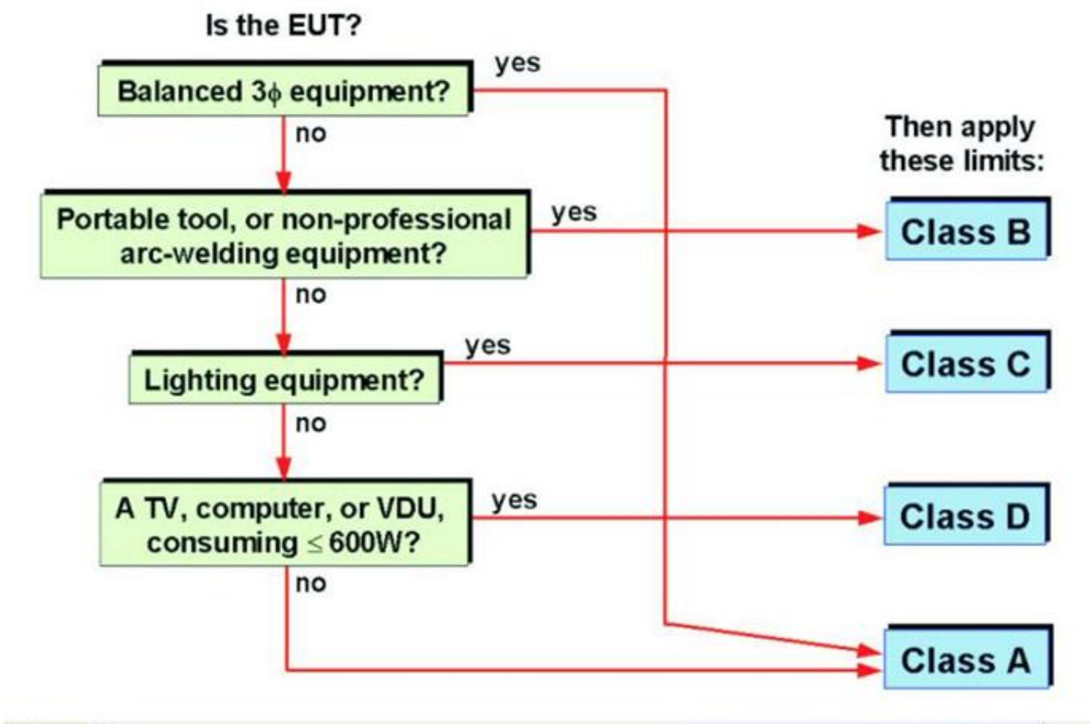

Fig. 3. Flow chart for the various classes of products to determine which limits on harmonic currents apply.

The current limits for each class in EN 61000-3-2 Ed.2: 2000 are shown in the table. There are some updates to the IEC 61000-3-2 standard for 2018. Also, this table does not list limits on equipment and appliances that do not require PFC such as USB cell phone and tablet chargers:

1. If the load is less than 60 W, no PFC circuit is needed for single-phase loads.

2. If the lighting load is less than 25 W, no PFC is needed. This became important because of the increasing use of compact fluorescent lamp ballasts and LED systems to replace the standard incandescent lamps. In the IEC 61000-3-2 standard, there are a number of relaxations to the current limits including those for dimmer circuits or circuits controlled by a phase angle triac. You must read the standard to understand how to apply the limits to the product or appliance.

Table. EN 61000-3-2 Ed.2: 2000 emissions limits expressed as current limits per phase. Relaxations for transitory emissions are specified in the standard.

Harmonic order, n	Max current			
	class A	class B	class C (% of fundamental current)	Class D (but no more than Class A)
2	1.08 A	1.62 A	2%	Not specified
3	2.30 A	3.45 A	30λ%	3.4 mA/W
4	0.43 A	0.645 A	Not specified	Not specified
5	1.14 A	1.71 A	10%	1.9 mA/W
6	0.30 A	0.45 A	Not specified	Not specified
7	0.77 A	1.155 A	7%	1.0 mA/W
8 ≤ n ≤ 40 (even harmonics only)	0.23 (8/n) A	0.345 (8/n) A	Not specified	Not specified
9	0.40 A	0.6 A	5%	0.5 mA/W
11	0.33 A	0.495 A	3%	Not specified
13	0.21 A	0.315 A	3%	0.35 mA/W
15 ≤ n ≤ 39 (odd harmonics)	0.15 (15/n) A	0.225 (15/n) A	3%	(3.85/n) mA/W

Power Factor Correction Circuits

There are many methods to achieve the power factor correction: passive, active (control ICs) and combinations (hybrid approaches). Passive power factor correction was used in the early color TV sets and in many printers and copiers. This PF circuit consisted of an inductor followed by a capacitor. This approach was sensitive to ac line frequency. In other words, components selected for 60 Hz would not produce the same PF result for 50 Hz.

To make PFC solutions compatible with universal worldwide designs, the industry started using a boost converter topology for power factor correction. There are many control ICs to cover all of the active approaches, but most applications use boost converter circuits for PF. The lighting industry drove the use of the boost converter topology to achieve power factors above 95% and low total harmonic distortion (THD).

The boost converter not only improved PF and THD but also increased holdup time, which was an issue for the power supplies in the first personal computers used in offices. Because of inadequate holdup time, when there was an ac power dropout, the computer would automatically reset, causing the user to lose data.

Passive techniques for PF were published in the proceedings of the 1991 IEEE APEC[3] and 1991 IEEE IAS[4] conference. Many of these passive approaches are called valley-fill techniques. Some hybrid approaches are given in the references including one published in 1985.[5]

IEC 61000-3-2

The IEC 61000-3-2 standard is written around three-phase input and is written to solve the three-phase harmonic currents. The most critical harmonic is the third-order harmonic which causes issues in the neutral, see Fig. 2. Most consumer products being shipped to Europe use single-phase ac electrical energy, which requires PF. Industrial motors use three-phase ac input, which is Class A. The highest volume for power factor correction circuits is for lighting power supplies, which are also single phase.

In North America, the only place where power factor correction is demanded is for lighting loads above 25 W. Most consumer products do not need to have a power factor correction circuit unless the product has a universal ac input voltage from 85 Vac to 264 Vac. In that case, the product can be sold to other parts of the world where PF is required for other products. Many power supply companies are trying to build only one product to be sold worldwide. The companies simply add a PFC stage and market the same product throughout the world.

80 Plus

In the computer power supply server market, products with both high energy efficiency and high PF are demanded. 80 Plus is a program that requires high efficiency and high PF for computer power supplies. The 80 Plus specification is available online.[6]

In this standard, four classes are listed: 115 V internal, 230 V internal, 115 industrial, and 230 EU internal. The specifications are listed for various power loads and PF (Fig. 4).

Fig. 4 The voluntary 80 PLUS certification program for computer power supplies defines five classes of increasing energy efficiency and also specifies PF.

The 80 Plus program applies to power supplies where the power draw is greater than 600 W and is a single-phase power input. There is a high PF circuit that also has high efficiency—it's called a "bridgeless" PFC circuit. This allows nearly 95% or above energy efficiency and little heat. Bridgeless PFC circuits utilize special converters to achieve high power factor and high energy efficiency. There are conference papers from APEC describing bridgeless PFC circuits. There are many semiconductor companies offering both application notes and ICs to achieve both high PF and high efficiency.

Summary

This edition of How2Power Today's Safety and Compliance column presented the basics of power factor correction and why it's important in the electrical industry for both generators and users. Power factor correction is a means to allow more electrical energy to reach the load. This makes electrical energy generation more efficient.

In part 2 of this series, the math will be presented to explain how ac current harmonics cause distortion in the power delivery system and how a delta-wye transformer cancels third-order harmonics. PF is characterized by two parameters—distortion and phase shift. The power factor equation will be presented that includes both the displacement portion which is the phase shift for the fundamental, and the distortion factor.

References

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About The Authors

Kevin Parmenter is an IEEE Senior Member and has over 20 years of experience in the electronics and semiconductor industry. Kevin is currently director of Field Applications Engineering North America for Taiwan Semiconductor. Previously he was vice president of applications engineering in the U.S.A. for Excelsys, an Advanced Energy company; director of Advanced Technical Marketing for Digital Power Products at Exar; and led global product applications engineering and new product definition for Freescale Semiconductors AMPD - Analog, Mixed Signal and Power Division.

Prior to that, Kevin worked for Fairchild Semiconductor in the Americas as senior director of field applications engineering and held various technical and management positions with increasing responsibility at ON Semiconductor and in the Motorola Semiconductor Products Sector. Kevin also led an applications engineering team for the start-up Primarion.

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For many years, he worked as a field applications engineer (FAE) for Motorola Semiconductor, On Semiconductor, Cirrus Logic, and Active Semiconductor, assisting customers in using semiconductors. He published numerous application notes and conference papers at a variety of conferences: APEC, ECCE, IAS, and PCIM. Topics included power factor correction, lighting, and automotive applications. As an FAE, he traveled internationally giving switch-mode power supply seminars in Australia, Hong Kong, Taiwan, Korea, Japan, Mexico, and Canada.

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For further reading on power supply-related safety and compliance issues, see How2Power's special section on Power Supply Safety and Compliance.