ISSUE: February 2021

Demystifying Three-Phase PFC Topologies

by Didier Balocco, ON Semiconductor, Vélizy, France and Oriol Filló, ON Semiconductor, Munich, Germany

Three-phase power factor correction (PFC) systems (also called active rectification or active front-end systems) are becoming of great interest, experiencing a sharp increase in demand in recent years. There are two main drivers propelling this trend. Fig. 1 summarizes some of the most common applications that require a PFC front end.

First and foremost, there is vehicle electrification, which, after several years of development, is gaining strong traction with growth projections of ~30% CAGR over the next five years. The charging infrastructure, especially fast dc electric vehicle (EV) chargers, needs to keep pace with the growth of electrical vehicles for an effective and wide roll out of e-mobility. These ac-dc conversion systems require three-phase PFC topologies at the front end to efficiently and effectively deliver power above 10 kW. As EV fast and "ultrafast" dc charging ranges from 50 to 400 kW, it is no wonder that the PFC stage is becoming a cornerstone of e-mobility.

Besides EV charging there are also other flourishing markets where their applications require a three-phase interconnection, like bidirectional converters for grid energy storage systems (ESSs) and large uninterruptible power supplies (UPSs) for industrial sites and datacenters. Furthermore, with the increase of switching power systems connected into the grid, stricter regulations on EMI limitations and harmonic distortion into the grid are being deployed, as for example, IEC-6100-3/12, an EMC standard which limits the injection of harmonic currents onto the grid. Various forms of PFC are commonly adopted to reduce the interference and harmonic content generated by switching power systems.

The second driver for the spread of three-phase PFC topologies is the advent of silicon carbide (SiC) power semiconductors. Their higher breakdown voltages and lower switching losses allow high efficiencies at what are considered high frequencies for silicon-based switches, and therefore devices deliver well-rounded solutions in terms of size, cost and performance. In other words, SiC MOSFETs and diodes are enabling higher power and higher voltage applications for power electronics, including three-phase PFC systems.

This article introduces the key advantages of three-phase systems and dives into the essential design considerations for a three-phase PFC system. Furthermore, it presents the most common three-phase PFC boost topologies on the market, and discusses their pros and cons. Overall the article provides guidance on how to approach a three-phase PFC design from scratch and on the suitability of the different topologies based on the application requirements.

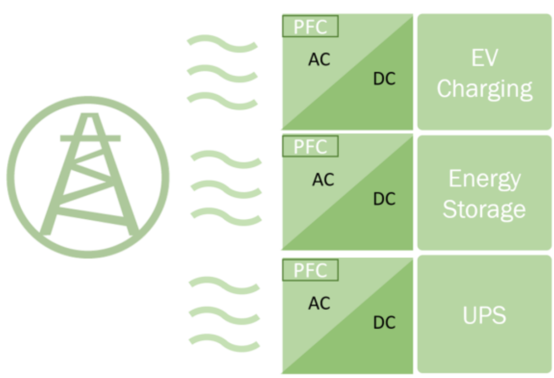

Fig. 1. EV charging is accelerating the need for three-phase-based PFC for ac-dc conversion. Other applications that are driving its implementation are energy storage systems (ESSs) and uninterruptible power supplies (UPSs) for industrial sites and data centers.

What Are The Advantages Of Three-Phase Systems?

Three-phase systems enable higher power systems with higher power density, reducing the required wiring, size or weight per watt compared to one-phase configurations. Additionally, a three-phase system delivers a constant power output, while single-phase systems have a variable output power and normally require a large low-frequency filter to power the loads.

If we look at the power delivered by a single-phase distribution system (with two wires, phase and neutral) for a dedicated voltage (Vrms) and load (R), we get:

$$V_{Line} = Vrms\sqrt{2}\sin\omega t$$

and

$$I_{Line} = \frac{V_{Line}}{R}\sqrt{2}\sin\omega t$$

If we multiply the voltage and the current to get the instantaneous power and average it, we get:

$$P_{Line} = 2\frac{Vrms^2}{R}\sin^2\omega t$$ and

$$\overline{P_{Line}} = \frac{Vrms^2}{R}\sin^2\omega t$$ or $$\overline{P_{Line}} = Vrms \times Irms$$

Fig. 2 illustrates these equations and unveils an important characteristic of single-phase systems. The instant output power is not constant, but rather a function of V_{Line}.

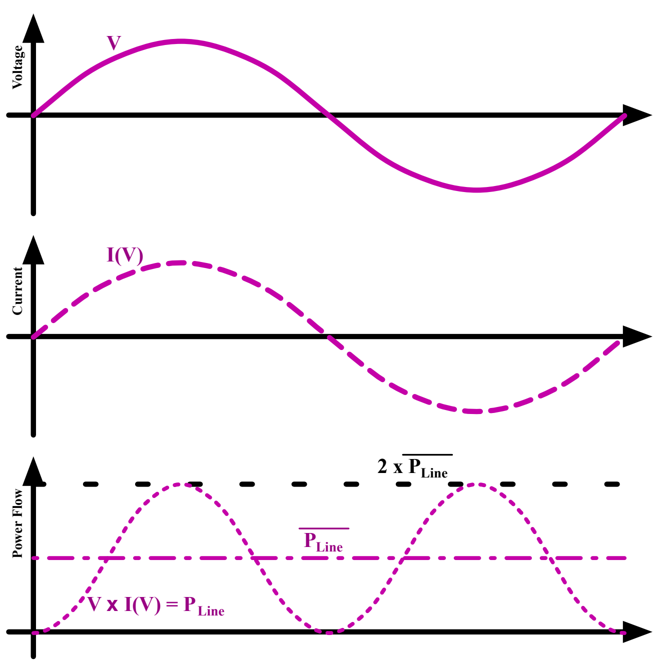

Fig. 2. Power flow from a single-phase grid.

Another basic characteristic of the single-phase distribution systems is related to power density. If we want to triple the power using the same wire cross-section or gauge, we need to triple the number of wires, having three wires for the phase and three wires also for the neutral.

However, the situation changes with three phases. For a balanced three-phase distribution system, every single voltage has a ±120° phase shift with the other voltages. If we do the sum of those three voltages, we get:

$$Vrms\sqrt{2}\sin(\omega t-120°)+Vrms\sqrt{2}\sin(\omega t)+Vrms\sqrt{2}\sin(\omega t+120°)\ =0$$

If we use the vector model to represent the voltages and then sum them, we obtain zero at all times. Those vectors represent a perfect equilateral triangle.

The consequence of this equation is that with only three wires carrying three sinusoidal voltages with a phase shift of ±120° between them, we do not need a neutral wire. We can carry three times the power with only three wires instead of six (using three single-phase connections). This reduces considerably the amount of wiring needed to carry the same power.

Another consequence of this ±120° phase shift comes when we look at the power delivered to three loads, R, attached to each line (in Δ or Y configurations). We get the following equation for a Y configuration (similar results are also obtained with Δ configuration):

$$P_{3phase}=2\frac{Vrms^2}{R}sin^2(\omega t-120°)+2\frac{Vrms^2}{R}sin^2(\omega t)+2\frac{Vrms^2}{R}sin^2(\omega t+120°)$$

which simplifies to:

$$P_{3phase}=3\frac{Vrms^2}{R}$$

Now, the power amount available at any time is constant and equal to three times the average single-phase system power. So, there is no need for a large passive storage element (inductor or capacitor) to filter the instantaneous power and deliver a constant power as needed in single-phase PFC. Fig. 3 demonstrates this characteristic, in contrast to single-phase systems.

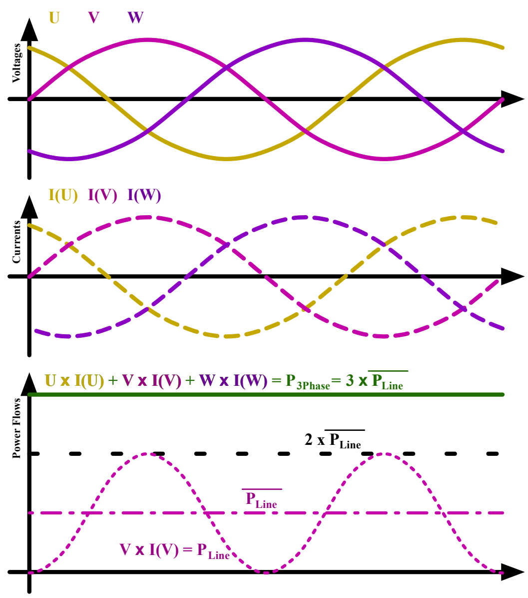

Fig. 3. Power flow from a three-phase grid.

Why Do We Need PFC In A Three-Phase System?

In the past, loads were essentially linear (resistors, inductors or capacitors). If the three loads applied to a three-phase distribution system are identical, the system is said to be "balanced" and the sum of the three-phase system currents is equal to zero. As explained in the previous section, the neutral connection is not needed in this case.

But nowadays, loads integrate nonlinear devices like diodes and transistors. So the input current shape could be very different from a sinusoidal waveform. On top of that, if we are not careful, a different load is sometimes applied to each phase due to transients in the system. This leads to an unbalanced three-phase system. Without a neutral wire the voltage middle point is unbalanced and not equal to zero, leading to unequal voltage amplitudes in each line and possibly overvoltage or undervoltage faults.

A common belief is that three-phase-connected loads are automatically balanced and no PFC is needed. However, this is not true with non-linear loads like a power supply.

As in single-phase voltage distribution, to optimize the power delivered to the load, the current needs to have the same shape as the voltage to maximize the power factor and bring it as close to 1 as possible. The line voltage from the ac grid is a sinewave, so the current should be.

The same applies also in three-phase systems. All three-phase currents should have the same shape as the three-phase voltage. Additionally, three-phase system currents also have to be balanced (i.e. the currents' sum should be zero). Therefore, in a three-phase system, the PFC must not only regulate the three sinusoidal input currents so that they are as in-phase as possible with the input voltages, it must also balance them. This requirement introduces another level of complexity compared to single-phase systems.

Power Delivery Trends

As we have seen, along with the increased power capability and the facilitation of new applications, three-phase systems clearly bring advantages in power distribution and power conversion, which have spurred and accelerated their adoption. First and foremost, the power density is higher, as three wires allow for three times the power of single-phase two-wire distribution.

Secondly, if we assume a constant, linear load or a PFC front end, three-phase power distribution delivers a constant power level at all times while the single-phase power distribution varies as a sinusoidal waveform raised to the power of 2 (Fig. 2). To reshape that waveform into a constant value, a large low-frequency storage element is required to filter and deliver a constant power to the load. This storage element (generally an electrolytic capacitor) is bulky and is the weak element of single-phase PFC that limits system lifetime.

What Key Areas Should I Consider When Designing A Three-Phase PFC Stage?

For three-phase PFC, several topologies are possible depending on the application requirements. Applications will differ in the power flow direction(s), size, efficiency, environmental conditions and cost constraints, among other parameters. There are several considerations the designer should address when implementing a three-phase PFC system. Following are some of the most significant:

1. Unipolar vs bipolar (two-level or three-level) switching
2. Switching frequency versus power devices
3. Modulation scheme
4. Losses and thermal management
5. Bidirectionality and power flow direction optimization
6. Topology

Each of these areas will influence the outcome and overall performance of our system and therefore are crucial in meeting the requirements of the application. In the discussion below, we assume an input voltage of three-phase 400 Vac (EU) or 480 Vac (U.S.).

Unipolar Or Bipolar (Two-Level or Three-Level) Switching

One of the first key decisions is whether to use a two- or three-level topology. This has a big influence on efficiency, dependent mainly on switching losses in switches and diodes and high frequency losses in the inductors, and EMI. It will also strongly influence the topology, as not all of them provide three-level capabilities.

The differences between two-level and three-level switching are shown in Figs. 4 and 5.

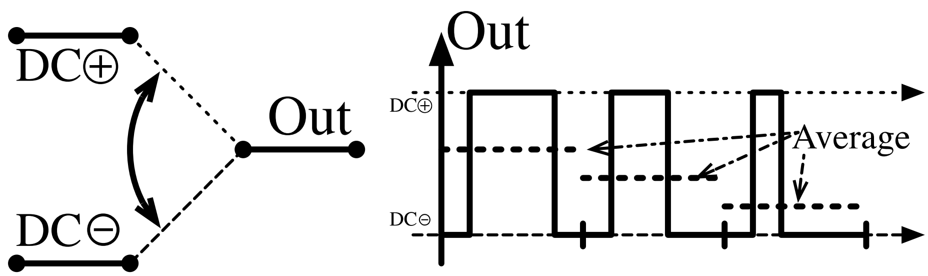

Fig. 4. Unipolar or two-level switching principle.

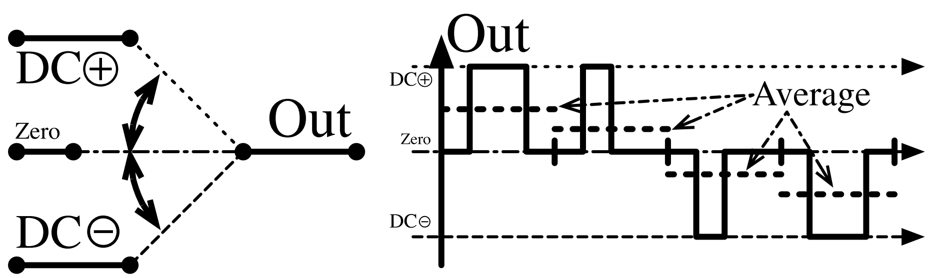

Fig. 5. Bipolar or three-level switching principle.

There are three advantages to using three-level topologies. First, they offer smaller switching losses. Generally, switching losses are proportional to the voltage applied to switches and diodes to the power of two (*switching losses* α $V^2_{switch\ or\ diode}$). In three-level topologies, only half of the total output voltage is applied to (some) switches or (some) diodes.

Another advantage is lower current ripple in the boost inductors. For the same inductor value, the peak-to-peak voltage applied to the inductor is also half of the total output voltage in three-level topologies. This leads to less current ripple, making it easier to filter and with a smaller inductor, which allows for more-compact inductor designs and reduced cost. Also, part of the inductor losses are directly proportional to current ripple. So, a lower ripple will help to cut down the losses in the inductor as well.

Finally, there is reduced EMI. Conducted EMI is mainly linked to current ripple. As just noted, three-level topologies reduce the current ripple so filtering is easier and it produces lower conducted EMI. Meanwhile, there is also a benefit with regard to radiated emissions.

Radiated EMI is linked to dV/dt and dI/dt. First, three-level topologies reduce peak-to-peak switching voltage, leading to smaller electric fields radiated by switching node pc-board traces. Secondly, three-level topologies reduce peak-to-peak switching currents. This leads to smaller magnetic fields radiated in switching power stage loops.

Switching Frequency Versus Switch Technology

Switching frequency has many impacts on the electrical design, but it also affects system specs like size and weight, which in turn can influence other costs such as those for shipping and handling. With increased switching frequency, the size of passive components can be decreased, resulting in a lighter system and reduced cost. Naturally, switching losses increase with frequency. However, this challenge is addressed by new switch technologies.

Regarding switch technology, IGBTs are the slow operating devices. So, they are used in converters with low switching frequencies (several tens of kHz). They are also preferred over MOSFETs for very high current when $V_{CE(SAT)}$ is lower than $R_{DS(ON)}$ x I_D. Another option, silicon superjunction MOSFETs are used up to about one hundred kHz switching frequency. Beyond that silicon carbide (SiC) MOSFETs can be used.

Regarding diodes, Schottky SiC diodes could be used in place of fast silicon diodes for the boost diode in three-phase PFC in complement with MOSFETs to reduce switching losses and allow higher operating frequency for superjunction silicon MOSFETs.

Schottky SiC diodes could also be co-packed with IGBTs to reduce reverse-recovery losses. This configuration (silicon IGBT + SiC co-pack diode) is called a hybrid IGBT. A hybrid IGBT can operate with lower switching losses in half-bridge or back-to-back configurations for various topologies. Then, if switching losses are lower, switching frequency can also be increased to optimize the system performance.

Finally, application requirements must be also considered. For an "on-board" charger (such as would be found in EVs) where size and weight are critical, high frequency is necessary to reduce the passive components' size. This will require high-frequency switches and diodes. In this case, wide-bandgap components (like SiC) are generally preferred.

On the other hand, for "off-board" chargers (installed outside the EVs), size and weight are less important. Here, charging time and cost are more critical. To reduce charging time, IGBTs are often used to achieve charging power of several hundred kilowatts. Cost constraints are another reason to adopt less expensive solutions with regular silicon devices.

Modulation Schemes

In a balanced three-phase system, there is no neutral current. The voltage sum is always equal to zero and so are the currents. We have the following equations (where U, V, W are the names of the three-phase lines):

$$V_U(t) + V_V(t) + V_W(t) = 0$$

and

$$I_U(t) + I_V(t) + I_W(t) = 0$$

This means that the current flowing for one or two phases will return to the grid by the other two or one phases, respectively. The current split depends on the phase of the grid waveform. There are twelve different combinations or states (depending on the U, V, W values). Those states are called "sectors" and are illustrated in Fig. 6.

For example, during sector 1, the current flows from (U and V) to W. During sector 4, the current flows from V to (U and W). The modulation technique will be based on those sectors and will determine the PWM sequence applied it to the required switch(es).

To drive the switches, several modulation techniques can also be used. The most common is *space vector modulation*. Most of the time, *symmetrical PWM modulation* is also used to reduce spectrum frequency content. In addition, this helps to reduce EMI versus *leading-* or *trailing-edge PWM modulation*.

To reduce voltage stress on switches and diodes, so called "third harmonic injection" is often (or almost always) used to obtain the space vector modulation patterns. Other modulations schemes used are *flat bottom modulation* or *discontinuous modulation*, which mainly help reduce the stress on diodes but introduce a higher distortion and power factor degradation.

The control is done using Clark and Park transforms. The Clark transform converts a three-phase voltage system to a single-phase system with the same line frequency as the three-phase system.

The Park transform converts a single-phase system to a static system with active (real) and reactive components, acting as a kind of demodulation technique. Generally, the input voltage is considered to be a pure active voltage and used as the reference for the phase-shift measurement. When the input current active and reactive values are known, the goal of the control system is to regulate the reactive current component to sum zero. This is the prime objective of any PFC. The active part is tuned, by the control, to deliver the required power to the load.

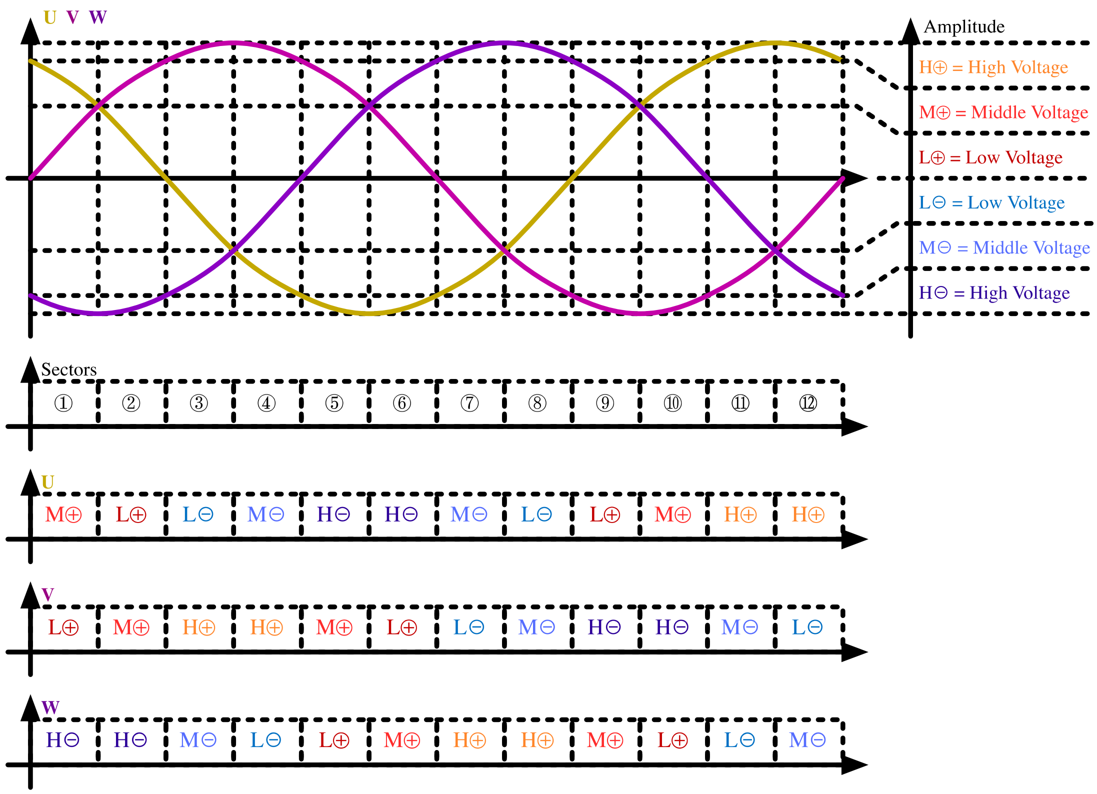

Fig. 6. Three-phase voltages and sectors.

Losses And Thermal Management

Losses, and therefore efficiency, depend on many parameters such as switching frequency, switch and diode technology, converter topology and passive components. We all know that if losses decrease, efficiency increases and thermal management becomes easier.

As discussed above, based on switching frequency, we can select the appropriate switch and diode technology. This selection will dictate the losses in active and passive components.

In active components, two approaches are possible to deal with thermal management. For low power, designing with discrete power devices is the preferred solution. It provides flexibility in sourcing and production. The downside of using a discrete configuration is it normally requires a very complex mechanical assembly. However, higher power designs with discretes are also achievable without resorting to complex assembly. In this case, the complete system is split into several lower power converters (or power stages) running in parallel. Such an architecture simplifies power management by spreading the losses across several blocks.

Nevertheless, higher power converters can reap the full benefits of power modules, which integrate several power devices in a single package. These modules facilitate thermal management and simplify mechanical assembly because they only require a single module (or a reduced set of modules) to be attached to a heat sink. In addition, modules are optimized for heat transfer with very low thermal impedance material. This is more difficult to obtain with discrete assembly.

Another advantage of module versus discrete design is the parasitic or leakage layout inductance. Inside the module, distances are smaller compared to discrete assembly, which helps to reduce parasitic inductances and so also losses. In addition, lower parasitic inductances reduce voltage spikes, which increases reliability due to lower stress on the switches and diodes. Lower voltage spikes also lead to reduced high-frequency radiated emissions.

Bidirectionality And Power Flow Direction Optimization

Typically, three-phase inverters (for UPSs, solar inverters or motor drives) can be bidirectional and behave as an ac-dc converter when operating in reverse mode (or reactive mode for UPS or braking mode for motor drive). There is a significant point to highlight here, though.

In general, power converters, and in particular their topologies, are optimized for one use case and one direction of the power flow through the selection and relative sizing of the switches and diodes. Three-phase inverters used as ac-dc converters in PFC mode will not be as efficient as an optimized ac-dc PFC converter. Even dc-ac topologies designed to be bidirectional will show better performance in one direction than the other. So, it is important to bear in mind what will be the most common use case.

This article, and the applications discussed in it, focus on three-phase PFC converters, and therefore, systems optimized to draw power from the grid (even if they might be bidirectional). Also, bidirectionality will not be achievable with all topologies as we will see, so selecting the right one upfront is an important factor.

Three-Phase PFC Topologies

The selected topology for a PFC stage is another essential consideration to fulfill the requirements of the application. Together with the other considerations discussed above, the topology will shape the overall solution and performance. Furthermore, not all requirements can be met with all topologies. As we have seen, not all topologies enable three-level switching or bidirectionality. This section will introduce some of the most common three-phase topologies and discuss their pros and cons.

Vienna Rectifier (Three-Switch Boost)

Before delving into the technical details and characteristics of the Vienna it is worth learning about its history, but even more important, we must agree on what we are talking about. The Vienna rectifier is a pulse-width modulation rectifier, invented in 1993 by Johann W. Kolar.[1] Before Kolar's invention, people were using a single phase per phase (with or without a neutral wire) and load sharing to balance phase current.

Nowadays, the term Vienna is generically used to refer, mainly, to three-phase ac-dc converters, but also sometimes to dc-ac converters, or inverters. As an example, neutral point clamp (NPC) and T-NPC three-level topologies are sometimes referred to as Vienna, even when working as inverters. It is advisable to always ask for a block diagram of the application when discussing a supposedly Vienna converter.

Looking into the characteristics of the Vienna rectifier, we see it is a kind of three-phase-connected boost PFC stage as shown in Fig. 7. A single-phase boost PFC stage is comprised of a front-end inductor with a switch and a rectifier diode. In the three-level structure, there is one boost rectifier (D_{xBy} where x represents the phase and y is the high or low side) for each half-wave or for each bus-voltage level (except for the middle which is supposed to be the common ground). Then, there is a bidirectional switch. This bidirectional switch is obtained by using a unidirectional switch (Q_x) embedded in a full-wave diode rectifier bridge (D_{xPy} and D_{xZy}). We obtain the following schematic in Fig 7.

The switches Q_X are 600-V or 650-V rated. All diodes can also be 600-V rated. This will help to reduce losses because no 1200-V-rated devices are needed. On the other hand, diodes losses are important. There are always two high-frequency diodes in series in the current path. For those diodes, it is always a compromise between voltage drop and reverse recovery.

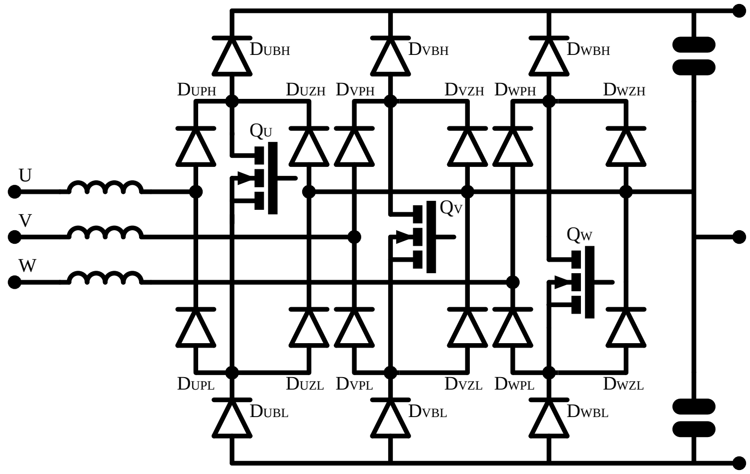

Fig. 7. Vienna PFC schematic.

For PWM, it is very simple because there is only one switch per phase. The modulation is directly applied to the switch after reverse Clark and Park reverse transforms. But, depending on the input sinewave sign, the current path changes. The diode rectifier bridge and the boost diodes are automatically involved in the current path depending on the input voltage sign and/or the current direction/flow. This is well illustrated in Fig. 8.

Note that, as explained before, as the current flows from one or two phases to the remaining two or one phases respectively, only one branch (or one phase schematic) is drawn in Fig. 8. Depending on the operating sector, the two modes (first, energy storage in the boost inductor from the phase voltage and, second, energy release to the output capacitor) for each phase (U, V or W) can be deduced using the above schemes.

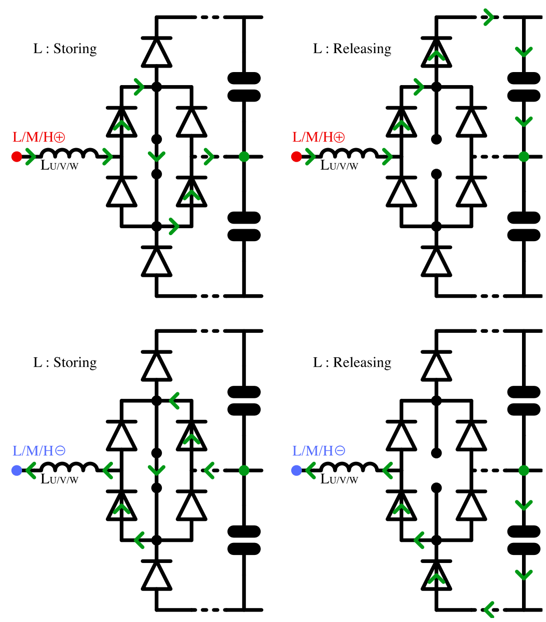

Fig. 8. Vienna boost PFC current paths (for energy storing and energy releasing modes) and phase voltage.

The major advantage of this topology is its use of a single switch per phase. It makes the control easier even if the schematic seems more complex with the number of diodes involved. The topology is also low cost because there is a very small number of switches. The topology is unidirectional.

One major disadvantage of this topology is the large number of diodes. There are always two diodes in the current path, which impacts the efficiency. All drivers are floating and need a specific floating power supply.

For switches, depending on the power level, superjunction MOSFETs or field stop trench IGBTs can be used. For higher-frequency operation and/or smaller size, SiC MOSFETs could also be used. For diodes, devices such as the silicon fast-recovery or low Q_{RR}, and, on top, the soft-recovery type, or SiC diodes are recommended.

T-NPC Boost

Compared to the original Vienna presented above, the T-neutral point clamp (T-NPC) implements the bidirectional switch differently. Instead of using a rectifier bridge to convert a unidirectional switch to a bidirectional switch, the T-NPC uses a configuration of back-to-back switches, as illustrated in Fig. 9. The switch body diode could also be used when the switch is not on and the current is flowing in the reverse direction compared to the normal switching current for this switch. This is the case for bipolar switches like IGBTs. With unipolar switches like MOSFETs, the switch can be turned on to reduce conduction losses if it makes sense.

It should be noted that the bipolar and unipolar switch structures described here are unrelated to the bipolar and unipolar switching discussed previously in the section on two-level or three-level switching.

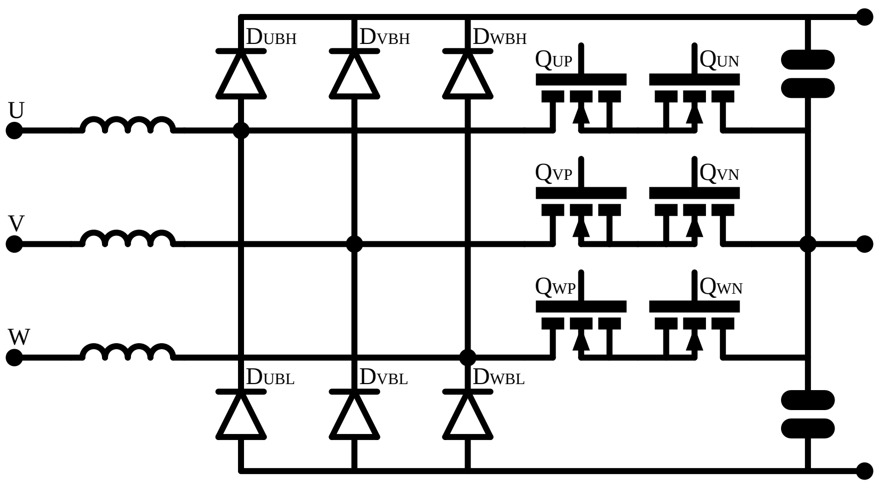

Fig. 9. T-NPC boost PFC schematic.

The switches Q_{xy} are 600-V or 650-V rated. The diodes D_{xBy} are 1200-V rated. The number of components is much lower than that of the original Vienna PFC. The conduction losses are also much lower because only one diode at a time is in series in the current flow. But, as the boost diodes are 1200-V devices, the switching losses are a little bit bigger than they would be with 600-V diodes. But as there are fewer diodes, it is difficult to predict which topology will have the best efficiency.

In practice, this T-NPC topology has better efficiency due to the lower number of diodes. Fig. 10 highlights the current paths in one of the three-phases.

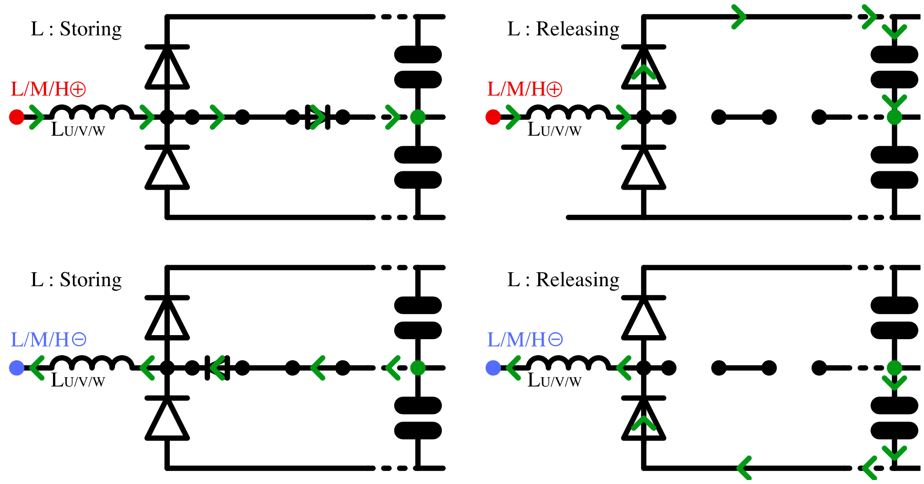

Fig. 10. T-NPC boost PFC current paths (for the storing and releasing energy modes) and phase voltage.

The same feedback technique can be used here with Clark and Park direct and reverse transforms to obtain the PWM signals.

As the two back-to-back switches share the same emitter or source pin node, the driver can drive the two back-to-back switches together with the same PWM signal directly out of the control loop. Otherwise, depending on sinewave sign (positive or negative), the corresponding switch needs to be driven. In this case, there are six switches to drive. This makes the PWM decoding scheme required to drive the correct switch a little bit more complex. In both cases, the drivers need to be floating as in the original Vienna.

One advantage of this topology is that there are many fewer active components. With the original Vienna, there are six active components per phase. If we consider the body diode as part of the switch, there are only four active components per phase in the T-NPC. One other advantage is the lower conduction losses, which make this topology more appropriate for higher power.

The T-NPC's major disadvantage is its need for 1200-V diodes. This can offset by the efficiency gain of lower conduction losses. The lower losses reduce the need for heatsinking, and together with the reduced component count, leads to lower overall cost.

The T-NPC structure is also used as an inverter. In this case, the boost diodes are replaced by switches as depicted in Fig. 11. The power flow is reversed compared to a PFC, or the PFC has a reverse power flow compared to T-NPC inverters. The all-switch T-NPC topology is intrinsically bidirectional. In this case, the control loop defines the power flow direction.

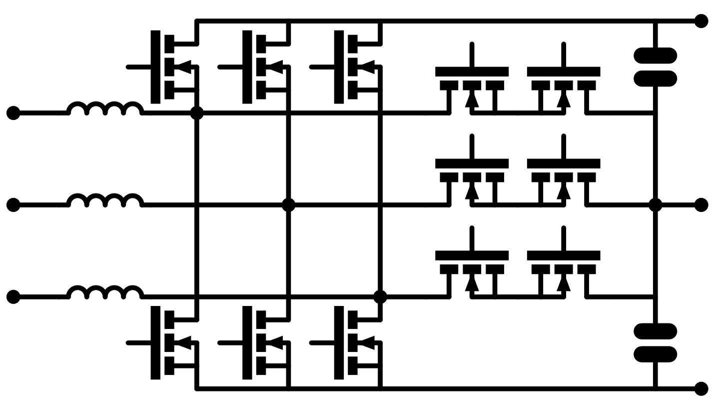

Fig. 11. Bidirectional T-NPC boost PFC schematic.

NPC And A-NPC Boost

With the NPC topology, once again, the bidirectional switch implementation has changed. The NPC uses two switches, one for each (positive or negative) sinewave half-cycles. The diode bridge is now a mixed-bridge combining diodes and active switches as illustrated in Fig. 12.

The two front-end diodes are used as a kind of gear box to switch positive or negative phase cycles to one side or the other side. Then, the diode connected to the output and the switch connected to ground act as a boost switching cell. This is obvious because all the topologies described here (Vienna, T-NPC and NPC) are operating in boost mode.

The switches Q_{xy} are 600-V or 650-V rated. All diodes (D_{xBy} and D_{xPy}) can also be 600-V or 650-V rated. This will help to reduce losses because no 1200-V rated devices are needed. One the other hand, there are always two components (i.e. one diode and (one diode or one switch)) in series in the current path. This NPC topology has higher conduction losses than the T-NPC.

The same feedback technique can be used here with Clark and Park direct and reverse transforms to obtain the PWM signals.

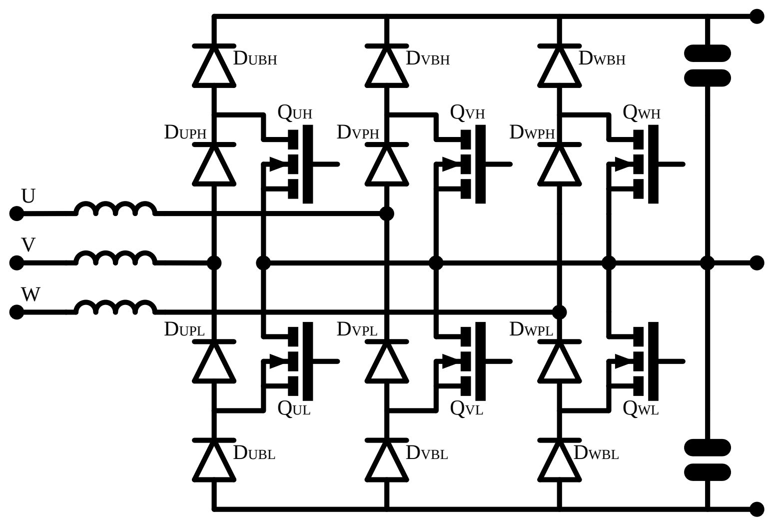

Fig. 12. NPC boost PFC schematic.

Here, three switches are floating and need a floating gate drive. The three other switches are tied to ground. They do not require a floating drive. This could be considered an advantage, but this advantage could disappear for two reasons.

First, depending on power level, a kelvin connection to the switch node might be required to drive the switches and improve efficiency. Secondly, to avoid even current harmonics, symmetrical operation is required between the positive and negative sinewave phases. This means that floating and grounded gate-drive signals should have the same delay. So, for this reason, the same drive schematic is often used for the floating and ground switches.

Depending on sinewave polarity (positive or negative), the corresponding switch needs to be driven. This makes the PWM decoding scheme to drive the correct switch a little bit more complex than with the three-switch Vienna. The current paths for this topology are illustrated in Fig. 13.

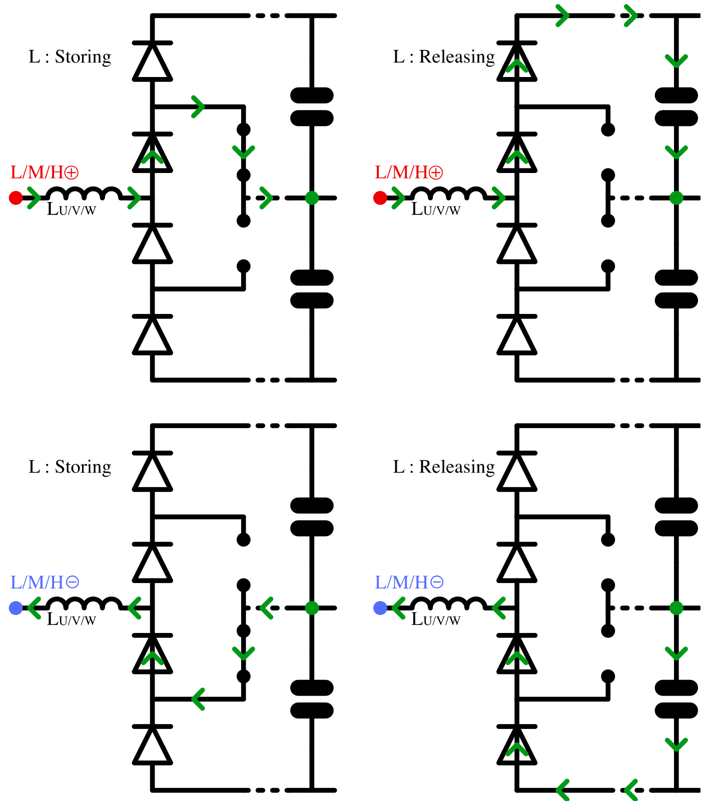

Fig. 13. NPC boost PFC current paths (for energy storing and energy releasing modes) and phase voltage.

As there are no 1200-V diodes, this topology has a clear advantage in losses, with fewer components compared to the original Vienna. But the driver pairing and delay matching is critical and can be seen as a disadvantage.

In this structure, replacing diodes with switches makes the topology bidirectional as in Fig. 14. This version is called A-NPC (for active-neutral point clamp).

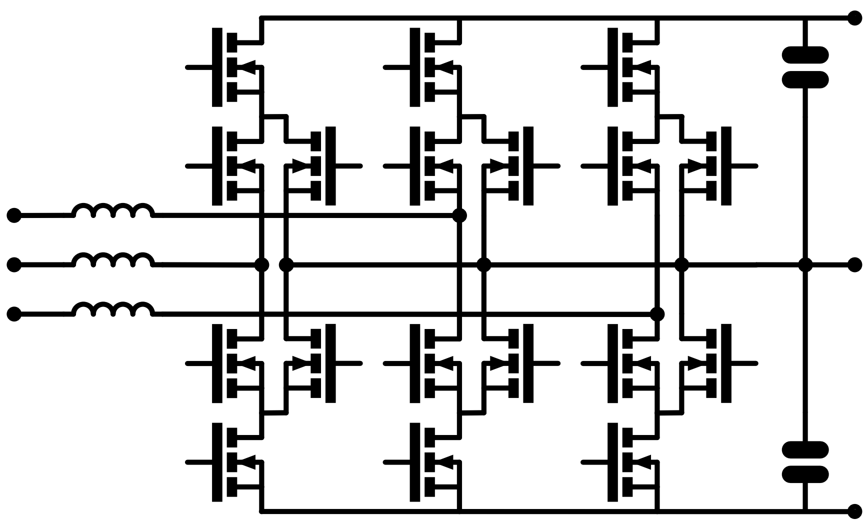

Fig. 14. Bidirectional NPC boost PFC schematic, also called A-NPC boost PFC.

Six-Switch PFC Boost

Six-switch, six-pack or three-phase inverters are widely used to drive motors and in particular BLDC motors. In normal operation, three-phase inverters convert dc voltage from the bus capacitor in a three-phase voltage system to drive the motor windings. When the motor brakes, the energy is extracted from the rotation of the motor and stored in the bus capacitor. This is the same power flow as a PFC stage.

In the braking mode, the power flows from the three-phase source (created by the rotating motor windings) to the dc bus. The motor inductors work as boost inductors in this operating mode. The difference between this motor braking mode and a PFC mode is the control strategy implemented by the control loop. So, six-switch or six-pack PFC has the same schematic as a motor inverter in reverse mode (where the load is the source and vice-versa). It is the simplest topology as can be seen in Fig. 15.

All switches (Q_{xy}) are 1200-V devices. There is only one switch per phase in the power flow at any time. This is an advantage for efficiency that compensates for the higher losses of 1200-V rated devices (versus 650-V devices). It is also a two-level topology. So, the modulation is straight-forward.

Nowadays, some 900-V rated devices are also available and can be used in this topology. Those 900-V devices have better performance than the 1200-V ones. This helps to reduce the drawbacks of having greater than 650-V switching devices.

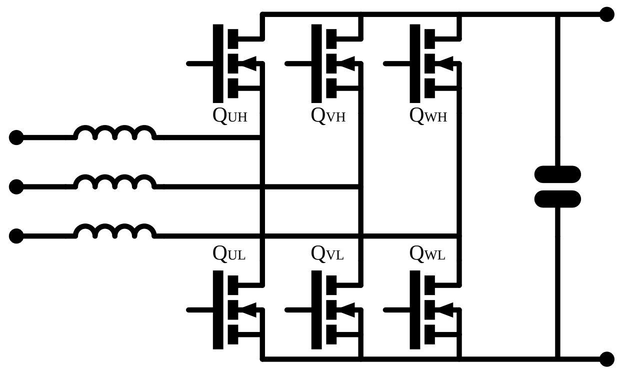

Fig. 15. Six-switch bidirectional two-level boost PFC schematic.

As we have three half-bridges tied to ground, the drivers are much easier to build using half-bridge drivers and techniques like bootstrapping can be used to create a floating supply. This simplifies the schematic using well known and widely used (in motor control applications) techniques. To provide a better understanding of how this topology works, Fig. 16 shows the return and forward paths. As there is no middle point (because it is a two-level topology), the current paths are not so obvious in this case.

Power modules for motor drive are available and can also be used for PFC applications for very high-power applications. This topology is fully bidirectional by nature. The major disadvantages are linked to the fact it is a two-level topology as explained earlier in this article.

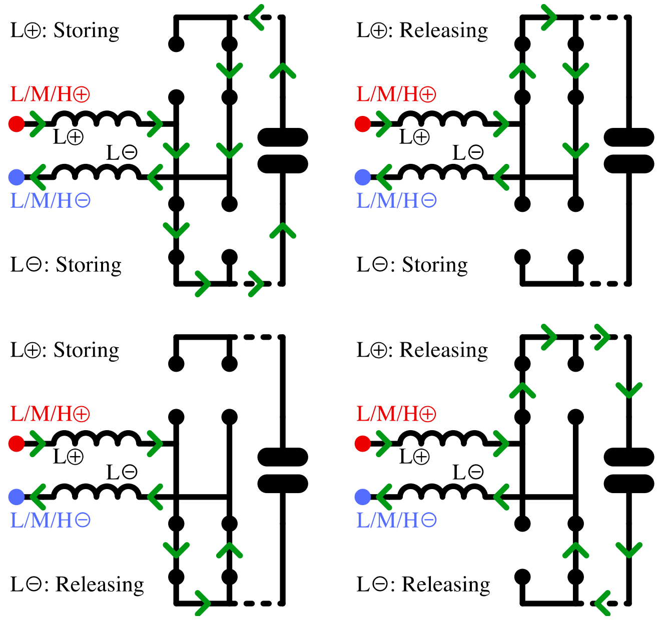

Fig. 16. Six-switch boost PFC current paths for energy storing and energy releasing (boosting) modes and phase voltage.

Three Parallel Single-Phase With Neutral

A simpler alternative to using a dedicated three-phase topology with its complicated control (generally requiring a digital controller) is to use three single-phase PFC stages with a neutral connection as in Fig. 17. In this configuration the neutral is indispensable if the system is unbalanced, even if the three single-phase PFC stages are tied to a load sharing control to split the power equally between the three phases.

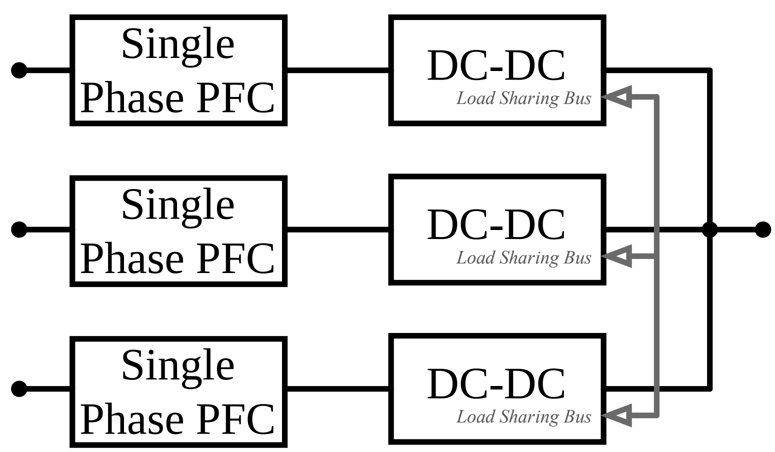

Fig. 17. Three-phase PFC using three single-phase PFC stages.

As single-phase PFC is very popular, it seems easier to proceed this way. People claim the advantage of having three independent converters is that when a failure happens, one fails and two remain available. This is true if the failure doesn't perturb the grid.

This could occur, for example, if the input stage fails shorted and this short-circuit is somehow transmitted to the grid before the fuse blows. If it perturbs the grid and the neutral shifts during this failure, the full phase-to-phase voltage could be applied to the remaining PFC stages. To avoid failing, the remaining stages would have to sustain this transient voltage, which increases the PFC losses, size and cost.

The advantage of this structure is that it is much simpler to design because single-phase PFC converters are well known and widely available. But, the need for a neutral wire makes the distribution network more expensive and not optimum. Also, a single-phase PFC stage cannot handle power above several kilowatts. Beyond that, paralleling is needed.

Summary Of Three-Phase Topologies

The table below summarizes the pros and cons of each topology regarding the design criteria discussed in previous sections.

Table. A comparison of the generic topologies discussed in this article. These values are subject to change in particular applications or actual implementations.
🟢: Very suitable/positive. 🟡: Average 🔴: Not suitable/negative.

	Vienna	*T-NPC*	*A-NPC*	*NPC*	*Six-switch*	*3x single-phase*
Switching levels	3	3	3	3	2	2
Reduced EMI	🔴/🟡	🟡	🟢	🟢	🔴	🟢/🟡
Efficiency	🔴	🟢/🟡	🟢	🟢/🟡	🟡	🟡
Power density	🟡	🟡	🟢	🟡	🟢/🟡	🔴
Overall BOM cost	🟢	🟡	🔴	🟡	🟢	🟡
Control complexity	🟢	🟢	🔴	🟡	🟢	🟢/🟡
Bidirectional	No	Can be	Yes	No (A-NPC)	Yes	No

Conclusion

Three-phase PFC systems are complex, with multiple designs possible to fulfill the same electrical requirements and a broad scope of considerations to address and tradeoffs to make. Finding the optimal solution for each application is a challenge, and it requires expertise both at the system level as well as at the component level.

Device vendors such as ON Semiconductor offer multiple resources to assist you in developing three-phase converters. These include application notes, evaluation boards, simulation models[2] and expert application teams[3] to help demystify three-phase PFC. Application engineers can help you select the right topology based on your application requirements and to find the optimal components for each case.

References

1. "Dreiphasen-Dreipunkt-Pulsgleichrichter" by J. W. Kolar, patent filed Dec. 23, 1993, File No. AT2612/93, European Patent Appl.: EP 94 120 245.9-1242 titled "Vorrichtung und Verfahren zur Umformung von Drehstrom in Gleichstrom".

2. Learn more about three-phase PFC solutions at our website.

3. For questions related to three-phase PFC, reach out to us at support@onsemi.com.

About The Authors

Didier Balocco currently serves as the business marketing engineer for Europe at ON Semiconductor. He came to ON through the company's acquisition of Fairchild Semiconductor, which he joined in 2014 as a field application engineer (FAE) supporting the south of France, Spain and Portugal.

Previously, Didier worked at AEG Power Solutions, formerly Alcatel Converters, as a research engineer for dc-dc and ac-dc converter design in a range of 1 W to 1 kW, mainly for telecom equipment. While at this company, he also managed the research activities. Among his projects, Didier worked on a 15-kW solar inverter module for a 150-kW cabinet in Dallas, Texas, USA. His main interests during this period were switched-mode power supplies, converter stability and modeling as well as high power factor rectifiers. Didier has published more than 10 papers on power electronics and holds one patent.

Didier received his engineering degree from the École Nationale Supérieure d'Électronique et de RadioÉlectricité de Bordeaux, France and his Ph. D. degree in power electronics from the University of Bordeaux.

Oriol Filló serves as a solution marketing engineer for industrial applications at ON Semiconductor. He is responsible for the marketing strategy of industrial solutions, focusing on robotics and energy infrastructure in particular. He has developed his career in the electronics industry with a focus on power and control, and gathered experience in industrial, IoT and automotive applications.

Prior to joining ON Semiconductor in 2019, Oriol worked at Industrial Shields and PRAX Inductive Components in technical sales and business development roles, where among others, he propelled growth of the export business. Oriol received an engineering degree in energy engineering and an M.Sc. in industrial automation systems and industrial electronics from Universitat Politècnica de Catalunya. Oriol also holds a master in management from EADA Business School.

For further reading on designing active power factor correction circuits, see the How2Power Design Guide, locate the Popular Topics category and select "Power Factor Correction".