# Electronic Power Systems – Tradeoffs Between Single-Phase and Three-Phase Power

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**TDI**
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# Executive Summary

Modern Electronic Systems are quite often powered from a three-phase power source. While utilizing power modules that operate directly from three-phase power might seem to provide optimal simplicity and flexibility, the added complexity required to realize three-phase power factor corrected circuitry usually negates any potential savings. This paper compares single-phase and three-phase circuits from the component count, stress level and complexity standpoints. It demonstrates that when these items are taken into account, quite often the best choice is a combination of single-phase modules, configured to balance individual power line phases.

## Introduction

In order to maximize power transfer while minimizing conductor volume, utility power is generally supplied in a three-phase manner, either with or without a neutral connection (Figure 1). Note, when a Neutral is involved, it is generally connected to the installation's safety ground somewhere close to the installation's power entry point.
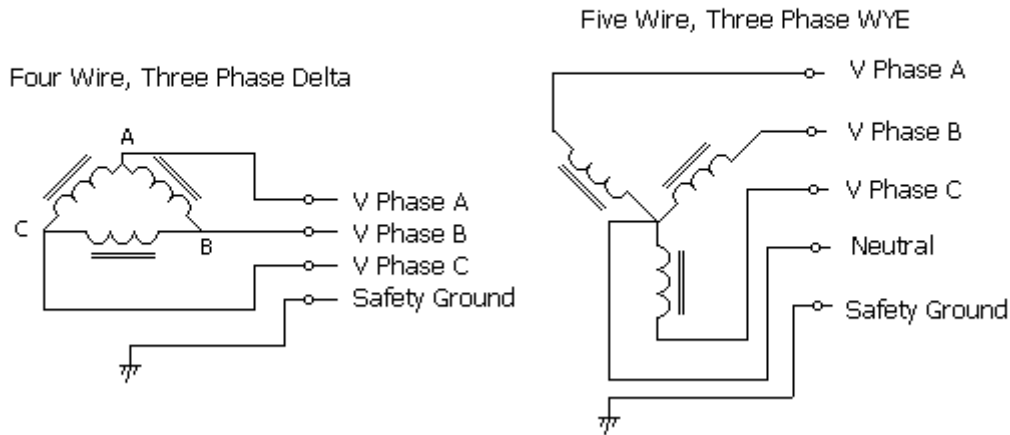


**Figure 1 – Common Three Phase Power Sources**

Common voltages for three phase systems in North America include 4-wire Delta Systems with a phase-to-phase voltage of 208VAC/60Hz, or 480VAC/60Hz. It is also common to see 480VAC/60Hz 5-wire WYE systems with a phase-to-neutral voltage of 277VAC, or 208/60Hz 5-wire WYE systems with a phase-to-neutral voltage of 120VAC. In other parts of the world, typical power line voltages include 50Hz 5-wire WYE systems with a phase to phase voltage of 398VAC and a phase-to-neutral voltage of 230VAC, or a phase-to-phase voltage of 380V with a phase-to-neutral voltage of 220V.

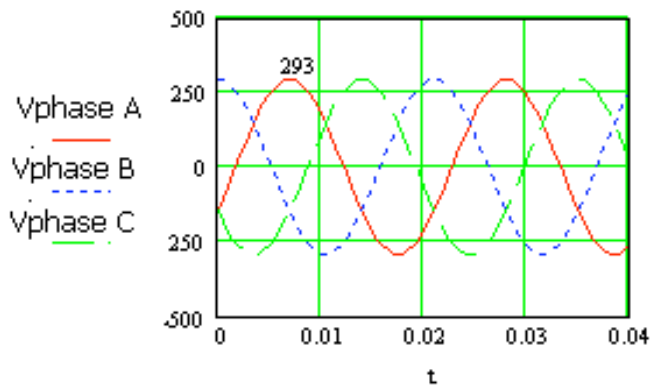Figure 2 presents the phase voltages for a 208VAC Delta System.



**Figure 2 – Individual Phase Voltages versus Time for a 208VAC/60Hz System**

Power conversion systems will typically be designed to draw power evenly from each phase so as not to overload wiring, distribution transformers or circuit breakers. Managing the loading of the three phases can be done by connecting apparatus separately to each phase in such a way that loading is balanced, or

by using power converters that connect to all three phases simultaneously, automatically providing phase balance. Figure 3 illustrates the two alternate methods.
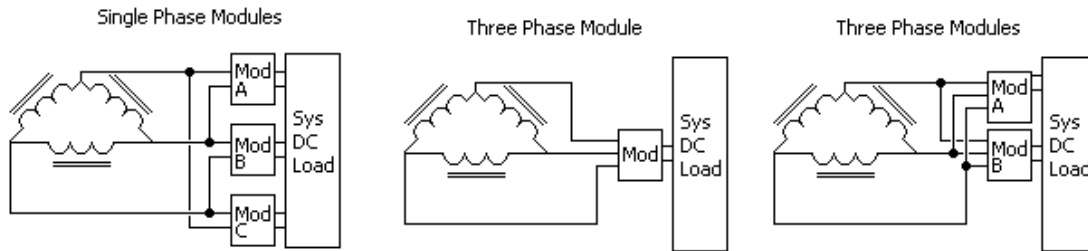


**Figure 3 – Power Conversion Converters with Single-Phase and Three-Phase Input**

**Single-Phase Input Power Modules**

Single-phase modules provide the benefit of simpler and more efficient power conversion circuits, but in order to fully balance line currents, power converters must be implemented in multiples of three. Finding the right fit between individual power module size and overall system load can sometimes be challenging. If the modules are feeding a common load, then power-sharing circuitry must be employed between modules so as to assure equal power drawn from each phase. Power sharing circuits may take the form of a "Droop" share circuit, where small, non-dissipative synthetic impedances are added in series with each module's output. This will force modules to share current as if one unit's current is greater than the others, its output voltage will drop until its load current matches other units in the system. Alternately, single wire, forced current sharing may be employed, where a separate wire is used to exchange information between modules and the modules will reprogram their output voltage to enable current sharing.

**Three Phase Input Modules**

Three-phase input modules provide the benefit of easing phase loading management, where the number of supplies is not important. (If fault tolerant redundancy is required, then the minimum number of modules required is two.) However, three-phase modules come at the cost of added complexity and reduced efficiency and reliability at the power module level. If the modules feed a common load, power-sharing circuitry is still desired so as to assure balanced stresses on modules connected in parallel.

**Comparison of Approaches**

Let us examine some of the reasons that three phase modules are less efficient and reliable. Power conversion efficiency in switching power supplies is a function of the number of switches required to implement the converter, and the voltage and current that these switches must carry. Likewise, converter reliability will be a function of the number of components required, and the stress levels these components must work at.

A typical single-phase converter is presented in Figure 4. The circuit pictured is typical for power levels above 500W and employs two converters – one to provide power factor correction and the other to provide galvanic isolation and load voltage matching. In making its way from input to output, power must pass through six switches: Two input bridge diodes, either the PFC Transistor or Boost diode, two DC-DC converter primary switches, and either of two output rectifiers. For a 277VAC input unit, the voltage rating of all semiconductors on the primary side of the transformer should be at least 600V for reliable operation.
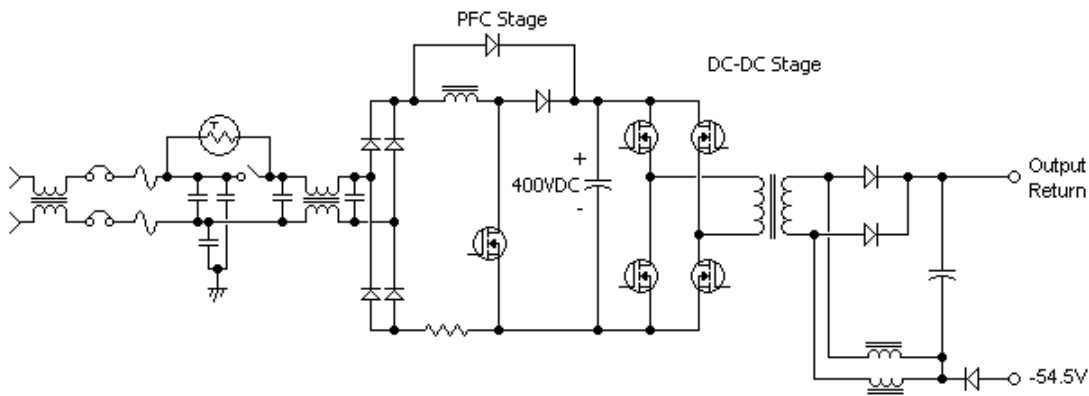
**Figure 4 – Typical Single Phase Module Circuit**

The circuit in Figure 4 utilizes an "inrush limiting" circuit comprised of a resistor and bypass relay. These function to limit maximum current drawn from the power line at initial connection of the module to safe levels. Figure 4 also depicts a typical EMI filter between the PFC circuit and power line. This will help limit electro-magnetic emissions from the unit onto the power line.

When connecting multiple single-phase modules from a three-phase power line, they all share the benefit that their PFC output energy storage capacitors (the capacitor that is labeled to have 400VDC across it in Figure 4) do not share a common return point. This allows unfettered implementation of load-isolating DC-DC converters within the system while not compromising power line phase-to-phase voltage integrity.

One of the challenges in realizing an active power factor correction circuit from a three-phase line is the tradeoff between resultant output voltage and maintaining the integrity of power line phase-to-phase voltages. The realized solution is not a simple as just taking three single-phase PFC circuits and connecting them in parallel, as doing this requires the three PFC circuits not to share a common output connection. Figure 5 illustrates this point.
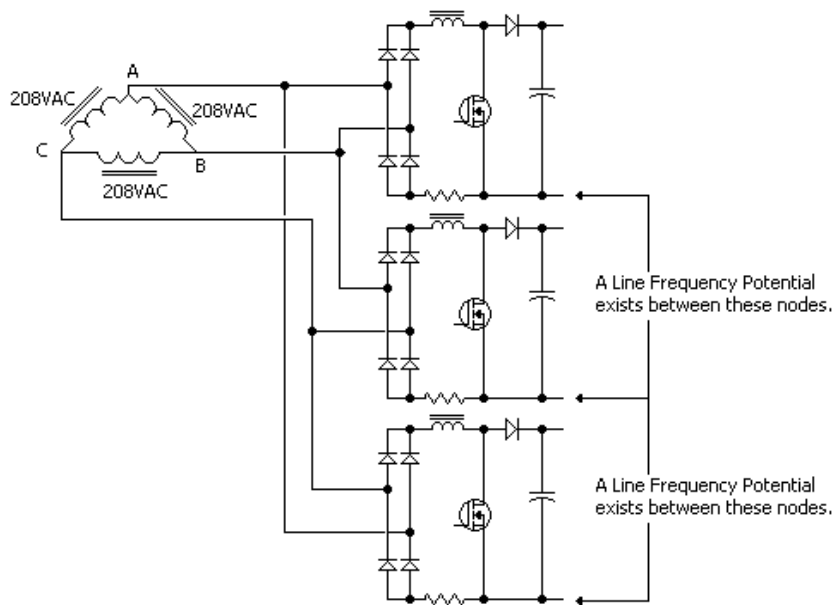


**Figure 5 – Three Single-Phase PFC Circuits connected from a Three-Phase Power Line**

In order to share a common return point, three-phase power factor correction circuits are based on three-phase rectifier principal.  A non power-factor-corrected three-phase input rectifier circuit is depicted in Figure 6.
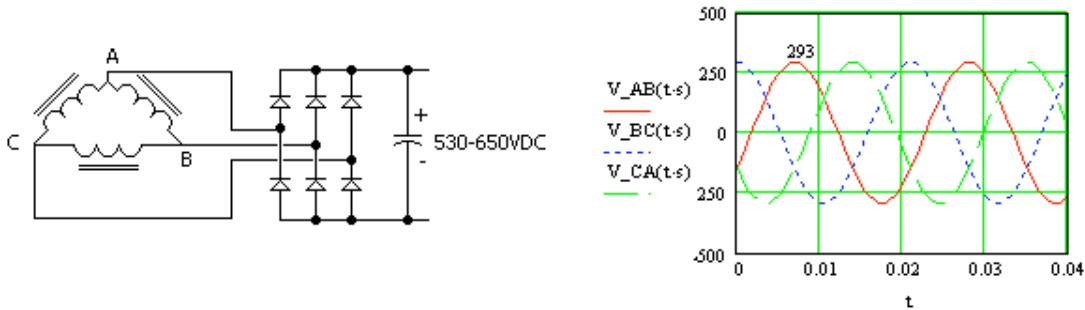


**Figure 6 – Three-Phase Rectifier and Filter Capacitor**

As shown in Figure 6, the resultant output voltage for this type of circuit is approximately twice the peak voltage observed from line to line.  In the case of a 208Vrms line-to-line voltage, this results in a DC output voltage of 208 x square root(2) x 2 = 588VDC.  Power line voltage tolerances will present approximately +/-10% beyond this, or the 530 to 650VDC depicted in the figure.  The significance of this result is that any down stream converter must use components rated at >700V (800-1000V would be the preferred choice), or multiple lower voltage parts must be connected in series.  Insulating space must also be increased to accommodate the increased voltage (over the single phase module case).  The net effect is that a circuit of this nature will require more space, more components and impart greater stresses on the components utilized than what would be encountered in a single phase module.

When a power factor corrected input circuit is employed, the situation gets worse.  As power factor corrector circuits force a sinusoidal input current, the generally require an output voltage that is greater than the peak of the input.  This will result in even higher voltages that have to be managed.

Typical three-phase power factor correction circuits are depicted in Figures 7 and 8.
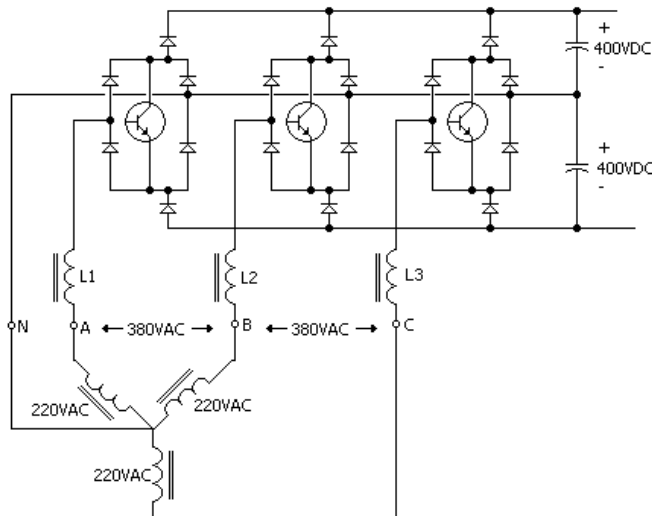


**Figure 7:  Vienna Converter 3-phase PFC**

As shown in Figure 7, the Vienna converter relies on the connection to a 3-phase Neutral to provide two power factor corrected outputs that appear in series. Figure 8 shows a Vienna converter that has been modified to work with or without a Neutral connection.
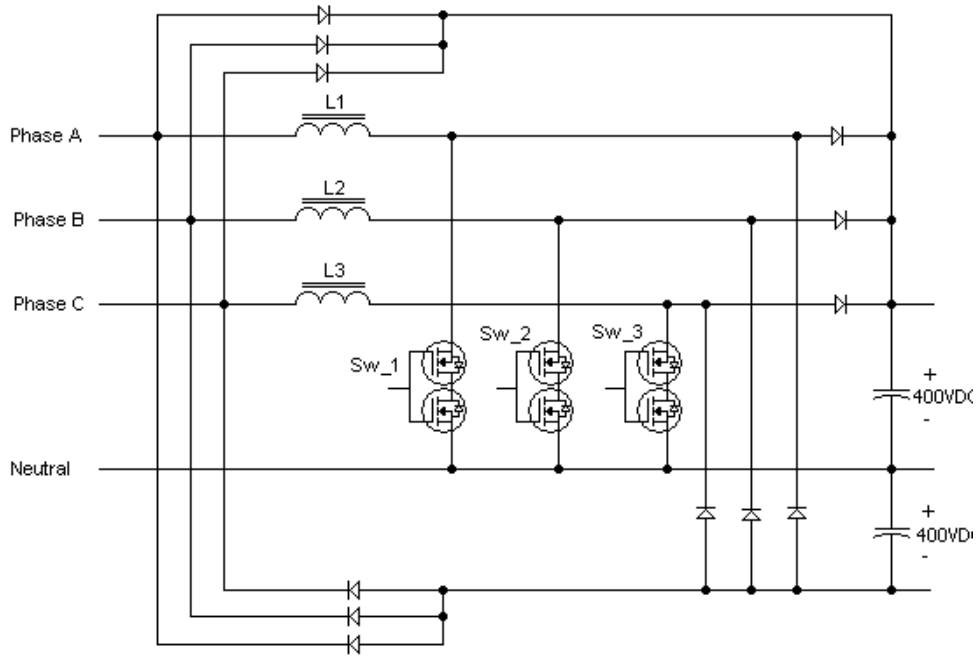


**Figure 6 – Modified Vienna Converter**

In both cases, any down stream converter has to either work from 800VDC, or multiple converters must be connected in series. Figure 7 demonstrates how this is typically accomplished.
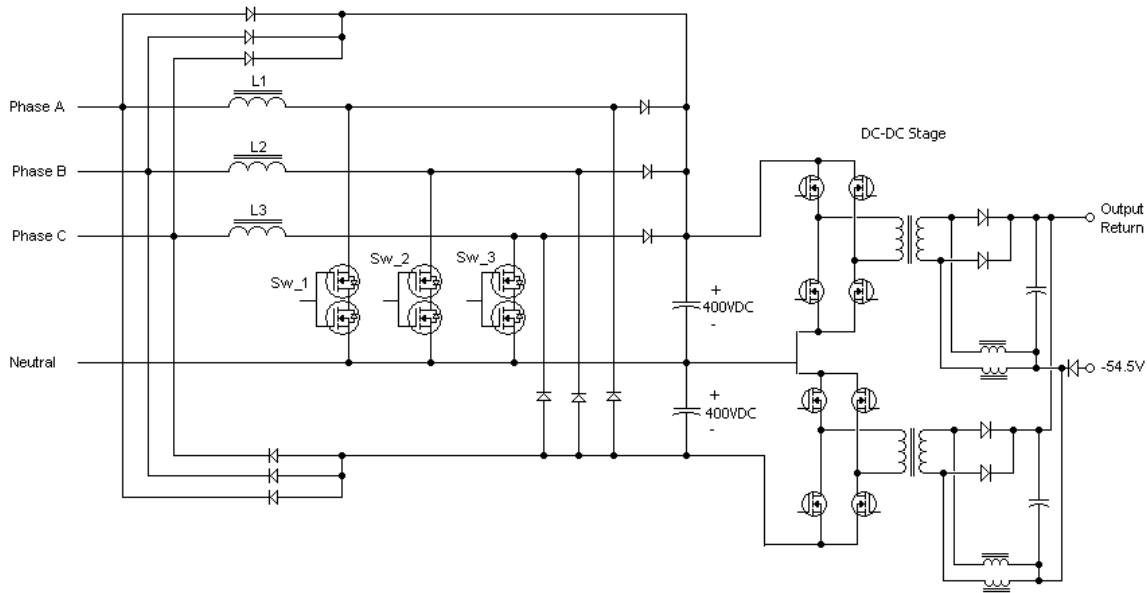


**Figure 7 – Three Phase PFC with Downstream Converters**

A pertinent analysis is to compare the case where three single-phase units are connected in 2+1 redundancy, versus two three-phase units are connected in 1+1 redundancy. Table 1 presents the results of this comparison.

| Topology | 3 Single Phase Converters | 2 Three Phase Converters |
|---|---|---|
| Number of power modules | 3 | 2 |
| Number of PFC Switch Transistors | 3 | 6 (Vienna) 12 (Modified Vienna) |
| Number of PFC Boost Diodes | 3 | 12 |
| Number of Input Rectifier Diodes | 12 | 16 (Vienna) 12 (Modified Vienna) |
| Power rating of PFC Sections | Po/2 | Po/3 |
| Number of 400V Energy Storage Devices | 3 | 4 |
| Number of 600V rated DC-DC Converter Sections | 3 | 4 |
| Power rating of DC-DC sections | Po/2 | Po/2 |
| Number of Inrush Limiting Circuits | 3 | 6 |

**Table 1 – Comparison of Single Phase and Three Phase Approaches**

Table 1 clearly shows that while utilizing a three-phase input module may appear to simplify things from a system approach, it actually adds significant amounts of circuitry. In addition, control circuit realization for Vienna derived converters is more complex than for the single-phase module, resulting in more costly implementation.

In the case of a module failure, unlike with the 3-phase module, the resulting input phase currents will be imbalanced if a single-phase module fails. In a redundant power module installation, the remaining modules' output power will increase to take up the slack of the failed module. Care must be taken in sizing input wiring and circuit breakers to accommodate this scenario, but the overall burden on the system in terms of cost and size is usually minimal.

**Conclusion:**

Through their optimal use of commercially available components and overall reduced component count and complexity, single-phase power modules provide the best solution for electronic systems that are to be powered from three-phase utility power lines.