Technical White Paper How to Meet the Stringent Requirement for Power Factor and iTHD of Three-Phase ac Input system With Vienna PFC

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ABSTRACT

The three-phase AC/DC rectifier is an important interface between the power grid and electrical equipment. Its good operational characteristics can improve the efficiency of the equipment and the quality of electrical energy in the power grid. To meet the stringent requirements of high power factor and low current harmonics in three-phase systems, three-phase Power Factor Correction (PFC) technology is increasingly applied to three-phase equipment. This white paper analyzes the technical trends of three-phase PFC systems, introduces the requirements for current harmonics in international standards such as EN/IEC 61000-3-2, compares and analyzes the advantages and disadvantages of various PFC topologies. Then Vienna PFC system solution, which is characterized by low cost, high performance, high reliability, and high power density, is introduced and simulation results from Matlab[®]/Simulink[®] are provided to verify the effectiveness of the control strategy. Finally, C2000[™] microcontroller units (MCU) code generation function provided by Texas Instruments (TI) based on Matlab/Simulink is introduced, which can significantly shorten the project development cycle and reduce costs.

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1 Introduction

Due to the scarcity of fossil fuels and environmental pollution, coupled with the advancement of power electronics technology, an increasing number of power electronic devices are being connected into the power grid. Traditional rectification devices for AC/DC conversion, such as diode rectifiers and phase-controlled rectifiers, not only result in higher reactive power losses but also introduce a significant amount of harmonics into the grid, which can severely impact the stability and quality of power grid. To ensure electric quality of power grid, global organizations have established a series of standards to regulate the current harmonics and power factor of electrical equipment, including International Electrotechnical Commission (IEC)'s EN/IEC 61000-3-2 and China's GB17625.1.

Large power devices, typically three-phase systems, have a more pronounced impact on harmonic amplitude and power factor of power grid. With the rapid advancement of heat pumps and high-power air conditioners, the number of three-phase devices connected to the grid is increasing. Consequently, to maintain the quality of electric energy and conserve energy, the requirements for the power factor and iTHD of three-phase systems are becoming increasingly stringent.

High-efficiency, high-performance Power Factor Correction (PFC) technologies are extensively implemented in three-phase AC/DC rectification devices to comply with current harmonic standards. The Vienna PFC topology, known for its low cost, high reliability, and high power density, has become prevalent in three-phase AC/DC rectifiers. Texas Instruments (TI) offers a variety of PFC technology reference designs for global customers and provides a comprehensive selection of analog devices and microcontroller units (MCUs), significantly reducing the R&D cycle and associated costs of engineering projects.



Figure 1-1. Diagram of Three-Phase ac Input System

2 Technical Trends of Three-Phase PFC System

The scale of three-phase input equipment is rapidly expanding with the growth of markets for heat pumps, high-power air conditioners, and EV charging stations. For instance, heat pumps are experiencing a global market growth rate of 12%, with the European heat pump market surging at 20%. This promising market outlook is driving research into PFC technologies for three-phase systems and the updating of standard specifications for these systems.

The technological trends in three-phase PFC system include:

- Development of novel PFC topologies to meet diverse application requirements and system performance needs, facilitated by advancements in power electronic devices and embedded processors.
- Utilization of digital control methods, particularly important for devices exceeding 3.3kW in power rating, where the high-power nature demands interference resistance and reliability that analog control schemes may not provide. High-performance, cost-effective MCUs like the C2000 series enhance response speed and control precision, enabling more complex strategies.

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- Integration of Active Power Filters (APF) with PFC in large three-phase systems composed of many subsystems, using centralized active power filters on the grid side for harmonic compensation, offering cost savings and improved stability in systems with currents over 50A.
- Pursuit of high efficiency and power density, with third-generation semiconductors such as GaN helping to increase system efficiency, reduce the size and weight of heat sinks, and allow for higher switching frequencies that minimize the bulk of passive components.
- Compliance with stringent global harmonic standards, influenced by energy crises and grid quality. For Europe, the EN/IEC 61000-3-2: 2019+A1: 2021 standard has been enforced on April 9, 2024. In China, the updated GB 17625.1-2022 comes into effect on July 1, 2024, broadening its scope to encompass more three-phase equipment with strict current harmonic requirements.

TI offers a robust suite of Hall-effect current sensors, isolated operational amplifiers, isolated gate drivers, and the C2000 series of MCUs, along with comprehensive auxiliary power supply solutions. These provide users worldwide with cost-effective, high-performance analog components and MCUs that meet the hardware requirements for implementing three-phase PFC systems. Furthermore, TI supplies mature system scheme reference designs for various PFC topologies and shares software and hardware design resources to foster the application and advancement of PFC technology.

3 Three-Phase PFC to Meet the Stringent Requirement for Power Factor and iTHD

Three-phase PFC system topologies are primarily categorized into two main types: passive PFC and active PFC. Passive PFC systems, composed mainly of inductive filters, operate without the need for control and typically achieve a power factor of 0.9, with current harmonics levels around 30%. Active PFC topologies, on the other hand, incorporate additional semiconductor power switching devices and are controlled by MCUs. These systems can easily increase the power factor to nearly 1 and reduce current harmonics to below 5%. Systems equipped with active PFC topologies can more readily achieve a power factor above 0.99. Consequently, the primary challenge for three-phase PFC topologies is to meet the stringent requirements for current harmonics.



Figure 3-1. Diagram of Three-Phase Passive PFC System



Figure 3-2. Diagram of Three-Phase Active PFC System

Historically, when three-phase system's current harmonic standards were less stringent or undefined, passive filters were utilized for power factor correction and to suppress current harmonics. However, harmonic currents remained significant, and the passive components also had significant size and weight. In recent years, as harmonic standards have become more defined and stringent, especially for equipment with a per-phase rated current not exceeding 16A, there is a growing trend towards the adoption of active PFC topologies. This shift is driven by the need to achieve a high power factor and maintain low levels of current harmonics.

3.1 Current Harmonic Requirements

For instance, the standard EN/IEC 61000-3-2: 2019+A1: 2021 divides equipment into four classes: A, B, C, and D, and specifies the harmonic current limits for each. The balanced three-phase ac input systems discussed here are categorized as Class A devices. The harmonic current limits for Class A devices according to the standard the standard are detailed in Table 3-1.

Harmonic Order hMaximum Permissible Harmonic Xurrent A				
Odd Harmonics				
3	2.30			
5	1.14			
7	0.77			
9	0.40			
11	0.33			
13	0.21			
15≤ <i>h</i> ≤39	0.15 × 15/h			
Even Harmonics				
2	1.08			
4	0.43			
6	0.30			
8≤h≤40	0.23 × 8/h			

Table 3-1. Limits for Class A equipment

The table indicates that IEC primarily sets limits on the amplitudes of harmonics up to the 40th order, with these harmonic amplitudes being considered as absolute values, independent of the fundamental current amplitude. The standard does not specify limits for the total harmonic distortion. However, a typical design target for three-phase active PFC is to achieve an iTHD of less than 5%.

3.2 Three-Phase PFC Topologies

The market currently features mature active PFC topologies such as the two-level PFC, T-type PFC and Vienna PFC. The two-level PFC rectifier topology facilitates control over bidirectional power flow, operating effectively in both inverter and rectifier modes. With a well-established control theory, this topology allows for a controllable and continuous input current, making it easy to achieve a high power factor and low iTHD. However, the switching stress on power devices is significant, equivalent to the output voltage level, which means a voltage rating of at least 1200V is typically required, increasing costs. To prevent shoot-through in the bridge arms, a two-level PFC must incorporate an adequate dead time in its design, which can impact the control performance and reliability of the system. Additionally, the two-level topology exhibits a higher common-mode voltage, posing greater challenges in electromagnetic interference (EMI) mitigation.



Figure 3-3. Two-Level PFC

The T-type PFC topology also facilitates bidirectional power flow and incorporates six additional power switch devices rated for 600/650V based on two-level PFC, allowing the T-type PFC to produce three output voltage levels: 0, +0.5Vbus, and -0.5Vbus. This advancement over the traditional two-level PFC results in reduced current ripple and a smaller power inductor. Furthermore, the three-level topology significantly lowers the common-mode voltage compared to the two-level, which enhances EMI performance. However, issues with reliability and control performance due to dead time still persist. TI provides T type PFC reference designs TIDA-01606 for reference. Additionally, the higher cost associated with this solution makes it less favorable for widespread use in cost-sensitive applications such as heat pumps and air conditioners.





The Vienna PFC topology, a three-level design, replaces six 1200V high-voltage power switching devices in the T-type PFC with low-cost schottky diodes. Although power flow is unidirectional, from the grid to the load, this significantly reduces system costs. The Vienna rectifier is popular due to its operation in continuous conduction mode (CCM), inherent multilevel switching (three level), and reduced voltage stress on the power devices. The bridge arms are replaced with passive diodes, eliminating the need for dead time, which simplifies the control strategy and enhances both control performance and system efficiency. The Vienna PFC's common-mode voltage is comparable to the T-type PFC's, resulting in good EMI performance. TI has already provided 2.4kW Vienna PFC reference design TIDM-1000, and a low-cost 10kW Vienna PFC reference design will also be launched in the near future.



Figure 3-5. Vienna PFC



Also, TI compares and summarizes the passive PFC topology with the three commonly used active PFC topologies as shown in Table 3-2.

	Passive	2-Level	Т-Туре	Vienna
iTHD	Very High	High	Low	Low
Power Factor	Low	High	High	High
Inductor size	Very Large	Large	Low	Low
EMI	Easy	Difficult	Easy	Easy
Control	No need	Complex	Complex	Easy
Bidirectional	No	Yes	Yes	No
Cost	High	High	High	Low

Table 3-2. Pros and Cons of PFC Topologies

In conclusion, Vienna PFC offers the advantages of low cost, high performance, high reliability, and high power density. Given the trend of significantly increasing market size for heat pumps, three-phase air conditioners, and electric vehicle charging stations, along with the increasingly strict requirements for current harmonics, Vienna PFC is expected to be increasingly integrated into three-phase systems.

4 Vienna PFC System Solution and Simulation

To assist global customers in rapidly implementing Vienna PFC to meet the power factor and current harmonic demands of three-phase systems, TI offers a comprehensive hardware and software solution for Vienna PFC. The hardware solution includes components for isolated sampling, isolated driving, the main control MCU, and the auxiliary power supply. The software solution encompasses fully open-source algorithm code. TI has conducted modeling and simulation of Vienna PFC to assist customers in testing and researching the control algorithms. Furthermore, TI's C2000 series MCUs support peripheral configuration and code generation within Matlab/Simulink, enabling the direct compilation of the simulation model into executable code that can be flashed into the MCU for operation.

4.1 Vienna PFC System Solution

TI offers a cost-effective Vienna PFC solution for heat pumps and high-power three-phase air conditioning systems, capable of handling input power up to 10kW. The block diagram is shown in Figure 4-1.



Figure 4-1. Vienna PFC System Solution

Among the system solution, TMS320F280013x is selected as the main MCU, which is a member of the C2000[™] real-time microcontroller family of scalable, ultra-low latency devices designed for efficiency in power electronics applications. The real-time control subsystem is based on TI's 32-bit C28x DSP core, which provides 120 MHz of signal-processing performance for floating- or fixed-point code running from either on-chip flash or SRAM. The C28x CPU is further boosted by the Trigonometric Math Unit (TMU) and Cyclical Redundancy Check (VCRC) extended instruction sets, speeding up common algorithms key to real-time control systems. High-performance analog blocks are integrated on the F280013x real-time microcontroller (MCU) and are closely coupled with the processing and PWM units to provide optimal real-time signal chain performance.

The F280013x series has four internal window comparators, including internal DAC for threshold setting, which can provide hardware protection for overcurrent and overvoltage of three-phase current and output voltage, and directly trigger PWM TZ signals to turn off the PWM signal. It will greatly reduce protection delay and improve system reliability.

The sampling section adopts a fully isolated scheme to ensure system reliability. AMC1350 is selected for voltage sampling, which is a precision, isolated amplifier with an output separated from the input circuitry by an isolation barrier that is highly resistant to magnetic interference. The excellent accuracy and low temperature drift support accurate AC and DC voltage sensing in various applications.



TMCS1101 is selected for current sampling, which is a precision Hall-effect current sensor, featuring a 600-V basic isolation working voltage, < 1.5% full-scale error across temperature, and device options providing both unidirectional and bidirectional current sensing. The device can be used for both AC and DC current measurements and has a bandwidth of 80kHz.

UCC5350 is selected as gate driver to driver two IGBTs. UCC5350 is an isolated, single-channel gate driver with a 5-A source and a 5-A sink peak current. The device is designed to drive MOSFETs, IGBTs, SiC MOSFETs which connects the gate of the transistor to an internal clamp to prevent false turn-on caused by Miller current.

For the convenience of wiring and to meet insulation requirements, the auxiliary power supply adopts a twostage design. The front stage uses UCC28750 to reduce the high-voltage bus voltage to 15V. TPS54202 is used to output 3.3V for MCU power supply, and LM25180 is used to output 5 channels isolated power supplies for sampling and driving circuits in the rear stage.

UCC28750 is a flyback controller which provides high-performance voltage regulation using an optocoupler feedback from the secondary-side. A control law allows a high efficiency across the entire load range, enabling both discontinuous-conduction mode (DCM) and continuous-conduction mode (CCM) designs.

LM25180 is a primary-side regulated (PSR) flyback converter with high efficiency over a wide input voltage range of 4.5 V to 42 V. The isolated output voltage is sampled from the primary-side flyback voltage, eliminating the need for an optocoupler, voltage reference, or third winding from the transformer for output voltage regulation.

TPS54202 is a 28V, 2A synchronous buck converter with two integrated N-channel MOSFETs which are widely used in the appliance industry, typically used to power supply devices such as MCUs, gate drivers or AMPs, and so forth. The optimized internal compensation network minimizes the external component counts and simplifies the control loop design.

TLV74033 low-dropout (LDO) linear regulator is a low quiescent current LDO with excellent line and load transient performance designed for power-sensitive applications. The device has a maximum output current 300mA with fixed output voltage 3.3V.

4.2 Simulation

To gain insights into and affirm the viability and potency of the Vienna PFC control algorithms, TI has crafted a Vienna PFC simulation model based on Matlab/Simulink. This model serves as a tool for R&D staff to conveniently juxtapose simulation outcomes with actual test waveforms, thereby facilitating the resolution of issues encountered during debugging.

The simulation parameters are delineated in Table 4-1.

Parameter	Specifications
Input ac voltage(phase)	220V
Inductor	400uH
Output capacitor	470uF*2+470uF*2
Switching frequency	40kHz
Output dc voltage	650V
Simulation sampling time	50ns

Table 4-1.	Simulation	Parameters
	•	



The simulation results at 10kW are shown in Figure 4-2.











The THD data displayed here calculates a maximum harmonic frequency of 100kHz, while the maximum harmonic frequency used in the THD calculation formula defined by IEC 61000-3-2 is 40 times fundamental frequency, which is 2kHz. Therefore, a table about the power factor and iTHD (up to 2kHz and 100kHz) of the Vienna PFC across various input power lists here.

Input Power/kW	la_rms/A	Output Voltage/V	PF	iTHD/% (up to 2kHz)	iTHD/% (up to 100kHz)
0.5	0.86	650	0.9198	53.4	53.5
1	1.57	650	0.983	7.43	25.49
1.5	2.3	650	0.994	1.23	16.4
2	3.05	650	0.996	0.26	12.29
2.5	3.8	650	0.997	0.26	9.41
3	4.59	650	0.998	0.22	7.85
3.5	5.35	650	0.9989	0.21	6.73
4	6.1	650	0.9992	0.18	5.89
4.5	6.86	650	0.9993	0.18	5.24
5	7.61	650	0.9995	0.17	4.72
6	9	650	0.9996	0.15	3.92
7	10.48	650	0.9997	0.14	3.37
8	11.95	650	0.9998	0.13	2.95
9	13.42	650	0.9998	0.13	2.62
10	14.88	650	0.9999	0.13	2.36

Table 4-2. Simulation Results



Figure 4-4. Vienna PFC Power Factor Simulation Results





Figure 4-5. Vienna PFC iTHD (100kHz) Simulation Results

It should be noted that the simulation model disregards factors such as sampling noise, sampling latency, and the parasitic inductance and capacitance present on the circuit board, which is why the simulation outcomes may slightly exceed the data obtained from actual experimental testing.

4.3 C2000 Code Generation Based on MATLAB/Simulink

The MathWorks model-based approach enables faster development, requires fewer engineering resources, and needs no software expertise. It decouples control algorithm development from firmware development and is portable across C2000 microcontroller product families. The simulation capability enables offline development, tuning and validation of control algorithms.

For instance, in motor control, Figure 4-6 illustrates the simulation model of a Field-Oriented Control (FOC) controller for a permanent magnet synchronous motor (PMSM). It is compatible with the TIDA-010265 hardware platform, enabling the generation of code and its direct programming into the TIDA010265 hardware for execution. Detailed model and hardware information can be located within C:\ti\c2000\C2000Ware_MotorControl_SDK_x_0x_00_00\solutions\tida_010265_wminv.





Figure 4-6. Generate Embedded C Control Code From the Model Using the Embedded Coder Tool

The simulation model allows for the verification of control strategies and the generation of code, with burning capable of being performed without the need for Code Composer Studio[™] (CCS). This compilation and programming process requires the use of the C2000 SDK, C2000 compiler, and CCS software, hence, the appropriate paths must be set during initial use. The model can also directly generate a project readable by CCS, facilitating code modification and optimization.

TI will provide more Matlab/Simulink simulation models and code generation solutions for more reference designs in the future.

5 References

- EN/IEC 61000-3-2 Electromagnetic compatibility (EMC) Part 3-2: Limits Limits for harmonic current emissions (equipment input current≤16A per phase), International Electrotechnical Commission, Edition, Edition 2019+A1:2021, 2021-04
- 2. GB 17625.1-2022 Electromagnetic compatibility Limits Part 1: Limits for harmonic current emissions (equipment input current≤16A per phase), 2022-12
- 3. TIDA-01606
- 4. TIDM-1000

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