POWER ELECTRONICS

Advanced Interleaved One Cycle Control PFC for Electric Vehicle On-Board Chargers: A Technical Deep Dive

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The rapid electrification of the global automotive landscape has catalyzed a paradigm shift in power electronics design. As Electric Vehicles (EVs) transition from niche products to mainstream transport, the demand for highly efficient, compact, and reliable On-Board Chargers (OBCs) has reached an unprecedented peak. At the heart of these systems lies the Power Factor Correction (PFC) stage, a critical component responsible for ensuring that the vehicle draws power from the grid with maximum efficiency and minimal harmonic distortion. Among the various control strategies and topologies available, the **Two-Phase Interleaved One Cycle Control (OCC) PFC**has emerged as a superior solution for meeting the stringent requirements of automotive applications.

This article provides a comprehensive technical exploration of interleaved OCC PFC systems, detailing their theoretical foundations, mechanical advantages over traditional multiplier-based controls, and their specific implementation in high-power automotive battery chargers. By analyzing the intersection of interleaving benefits and the simplicity of OCC, we will uncover why this specific architecture is becoming the industry standard for 3.3 kW and higher power density OBC designs.

Fundamental Challenges in On-Board Charger Design

An On-Board Charger (OBC) serves as the interface between the AC power grid and the high-voltage DC battery pack within an EV. Engineering an OBC presents unique challenges that differ significantly from consumer electronics or industrial power supplies:

- Thermal Constraints: Automotive environments are characterized by high ambient temperatures and limited cooling space.
- Power Density: Weight and volume directly impact vehicle range; thus, magnetic components must be minimized.
- Electromagnetic Interference (EMI): Strict automotive EMC standards (such as CISPR 25) require sophisticated filtering and noise mitigation.
- Grid Compliance: Regulations such as IEC 61000-3-2 mandate low Total Harmonic Distortion (THD) and a Power Factor (PF) close to unity.

Traditional single-phase PFC converters, while simple, often struggle to meet these requirements at higher power levels due to the physical size of the inductors and the high current stress on individual semiconductor switches. This is where interleaving and advanced control methodologies like OCC provide a technological leap.

The Mechanics of One Cycle Control (OCC)

One Cycle Control (OCC), also known as Integration Reset Control, is a non-linear control technique that forces the average value of a switched variable to follow a control reference within each switching cycle. Unlike traditional pulse-width modulation (PWM) schemes that rely on a multiplier to shape the input current, OCC uses a resettable integrator to maintain the control law.

The Control Law and Mathematical Framework

In a standard boost PFC, the goal is to make the input impedance appear purely resistive. The traditional approach involves sensing the rectified input voltage, multiplying it by the error signal from the output voltage loop, and using that as a reference for the current loop. This requires complex analog multipliers or high-speed digital processing.

The OCC technique simplifies this by satisfying the following equation:

$$V_m * d = V_{rs}$$

Where:

- V_m: The control voltage derived from the voltage error amplifier.
- d: The duty cycle of the switch.
- V_{rs}: The voltage across the current sensing resistor, representing the input current.

In the OCC architecture, a constant frequency clock initiates the switching cycle by turning on the MOSFET. Simultaneously, an integrator starts integrating the control voltage (V_m). When the output of the integrator reaches a threshold related to the sensed current, the switch is turned off, and the integrator is reset for the next cycle. This inherently ensures that the average current follows the input voltage without the need for a dedicated voltage sensing multiplier, significantly reducing component count and improving transient response.

Comparison: OCC vs. Multiplier-Based PFC

Feature	Multiplier-Based PFC (Traditional)	One Cycle Control (OCC) PFC
Input Voltage Sensing	Required for current reference generation.	Not required for current loop.
Circuit Complexity	High (requires analog multiplier or DSP).	Low (uses integrator and comparators).
Bandwidth	Limited by multiplier and sensing delays.	Very high; responds within a single cycle.
Dynamic Response	Slower due to multi-stage filtering.	Fast and robust against line/load steps.
Component Count	Higher.	Lower, facilitating higher power density.

The Power of Interleaving in PFC Topologies

Interleaving involves paralleling two or more boost converters (phases) and operating them with a specific phase shift. For a two-phase system, the switches are operated 180 degrees out of phase. This technique offers transformative benefits for automotive OBCs.

1. Current Ripple Cancellation

The primary advantage of interleaving is the reduction of input and output current ripples. Since the two phases are 180 degrees apart, the peak of the ripple in Phase A coincides with the trough of the ripple in Phase B. This cancellation effect results in a significantly smoother total input current. This reduction in ripple allows for the use of much smaller EMI filters and reduces the stress on the input capacitors.

2. Thermal Management and Component Sizing

By splitting the total power (e.g., 3.3 kW) between two phases, each inductor and MOSFET only handles half the current. This distribution reduces I^2R losses, which are the dominant source of heat in high-power converters. Furthermore, smaller inductors can be used because the effective frequency seen by the input and output filters is doubled (2x switching frequency), while the individual switches continue to operate at a lower, more efficient frequency.

3. Redundancy and Reliability

In high-reliability automotive systems, interleaving can provide a degree of fault tolerance. Depending on the control implementation, the system may continue to operate at reduced power if one phase fails, though this requires sophisticated monitoring and protection logic.

Technical Analysis: Implementing a Two-Phase Interleaved OCC PFC

To implement an effective two-phase interleaved OCC PFC for an automotive OBC, several critical subsystems must be integrated: the OCC controller, the synchronization logic, and the current sensing network.

Synchronization and Phase Shifting

In a two-phase system, a master clock or a specialized IC (like the UCC28070) is used to generate two PWM signals. The first phase triggers at the clock's rising edge, while the second phase triggers with a delay equivalent to half the switching period (T/2). This 180-degree phase shift is essential for the ripple cancellation effect. In OCC-based systems, this synchronization must also handle the resetting of the integrators for each phase accurately.

Current Sensing Strategies

Accurate current sensing is vital for OCC. There are three common methods used in automotive PFCs:

- Shunt Resistors: Placed in the source path of the MOSFETs. They provide high accuracy but introduce conduction losses.
- Current Transformers (CT): These provide galvanic isolation and are more efficient at high currents but are bulkier and can suffer from magnetic saturation.
- Hall-Effect Sensors: These offer non-contact sensing and isolation but are generally more expensive and may have slower response times than shunts for high-frequency OCC.

For a 3.3 kW OBC, current transformers or high-precision shunt resistors with Kelvin sensing are typically preferred to maintain the accuracy required for high power factor.

Bridgeless Topologies: The SEPIC Alternative

While the standard interleaved boost PFC is common, researchers are increasingly exploring **Bridgeless SEPIC (Single-Ended Primary-Inductor Converter)**topologies. A bridgeless design eliminates the input diode bridge rectifier, which is often the largest source of conduction loss in a PFC stage.

In a two-stage interleaved bridgeless SEPIC based PFC:

1. The input bridge is replaced by switches and diodes that conduct only during specific halves of the AC cycle.
2. The SEPIC topology allows the output voltage to be either higher or lower than the input voltage, providing flexibility in battery voltage matching.
3. Interleaving these SEPIC stages further reduces the ripple, making it an attractive choice for "Level 2" chargers where efficiency is paramount.

Case Study: 3.3 kW Automotive PFC Design Choice

Consider a design requirement for a 3.3 kW OBC with an input range of 85V AC to 265V AC and a DC output of 400V. The designer must choose between a standard Continuous Conduction Mode (CCM) PFC and an Interleaved OCC PFC.

Design Comparison Matrix

Metric	Single-Phase CCM PFC	Two-Phase Interleaved OCC PFC
Max Power	Typically < 2 kW for optimal efficiency.	Scalable to 3.3 kW, 6.6 kW, and beyond.
Inductor Volume	Large (must handle full peak current).	Small (2x smaller inductors).
MOSFET Stress	High (Full RMS current through one switch).	Low (Current shared between two switches).
Input Filter Size	Large due to high current ripple.	Small due to ripple cancellation.
Efficiency at 3.3 kW	~94% - 95%	~97% - 98%

The analysis clearly shows that for a 3.3 kW application, the Interleaved OCC PFC is the superior choice. The reduction in inductor size alone often offsets the cost of the additional MOSFET and diode, while the improved efficiency reduces the cooling requirements of the vehicle.

Practical Implementation and Troubleshooting

Designing an interleaved OCC PFC is not without its hurdles. Engineers must pay close attention to several operational challenges during the prototyping and validation phases.

Addressing Current Imbalance

One common issue in interleaved systems is current imbalance between the phases. If one phase carries more current than the other, it will experience higher thermal stress, leading to premature failure. This is often caused by mismatches in inductor values or gate drive delays. Modern OCC controllers like the **UCC28070**include active current balancing circuits that adjust the duty cycle of each phase to ensure equal current distribution.

Managing Light-Load Efficiency

At light loads, the switching losses of two phases can outweigh the conduction losses, reducing efficiency. To solve this, "Phase Shedding" is often employed. The controller monitors the load and shuts down one of the phases when the power demand falls below a certain threshold, effectively operating as a single-phase PFC to maintain high efficiency across the entire load range.

Handling Floating Ground Issues

In bridgeless and some two-stage topologies, the DC ground may float with respect to the input AC line. This creates challenges for current sensing and EMI. Implementing an input filter with proper common-mode and differential-mode chokes, along with isolated sensing, is critical for addressing these "floating ground" problems and ensuring automotive safety standards are met.

The Future of PFC in EV Infrastructure

As EV battery voltages move from 400V toward 800V architectures (to support ultra-fast charging), the PFC stage must also evolve. We are seeing a transition from Silicon (Si) MOSFETs to **Silicon Carbide (SiC)** and **Gallium Nitride (GaN)**devices. These wide-bandgap (WBG) semiconductors allow for even higher switching frequencies, further reducing the size of the interleaved inductors in OCC designs.

Furthermore, the integration of OCC into digital controllers (DSP/MCU) is becoming more common. While traditional OCC was analog-centric, digital implementations allow for more sophisticated phase-shedding algorithms, real-time telemetry, and adaptive control laws that can compensate for component aging over the vehicle's lifespan.

The Two-Phase Interleaved One Cycle Control PFC represents a masterclass in power electronics optimization. By combining the ripple-reducing benefits of interleaving with the high-speed, simplified control logic of OCC, automotive engineers can deliver on-board chargers that are not only smaller and lighter but also significantly more efficient. As the industry moves toward Level 2 and Level 3 charging as standard features, the principles of interleaved OCC will remain a cornerstone of robust EV infrastructure. The ability to handle high power levels while maintaining a near-unity power factor ensures that the EVs of tomorrow will be as gentle on the electrical grid as they are on the environment. For designers and manufacturers, mastering these topologies is no longer optional—it is the key to staying competitive in the electrified future.

Baca Juga (Artikel Terkait)

- **The Engineering Blueprint of 1000W Power Inverters: From Circuit Topology to System Integration**
  URL: http://123caramba.com/1000w-power-inverter-circuit-design-engineering-guide.pdf
- **Comprehensive Engineering Guide to Ultralow-Noise High-PSRR LDO Regulators: ADM7150, ADM7151, and TPS795 Series**
  URL: http://123caramba.com/ultralow-noise-high-psrr-ldo-regulators-technical-guide.pdf
- **Designing High-Efficiency Solar Charging Systems: A Deep Dive into Boost-Topology and Power Electronics**
  URL: http://123caramba.com/solar-boost-topology-battery-charger-guide.pdf
- **Advanced Analysis of Transformerless Buck–Boost Converters with Positive Output Voltage and Quadratic Gain**
  URL: http://123caramba.com/transformerless-buck-boost-converter-positive-output.pdf

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