Technical White Paper

Optimize Traction System Efficiency with Texas Instruments' New Modulation Technique

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1 Executive Summary

Vehicle electrification continues to accelerate globally as automakers pursue aggressive electrification targets. However, lowering EV costs by improving efficiency remains a key challenge and focus for OEMs and Tier-1 suppliers.

In the current state-of-the-art traction inverter systems, variations of the Space-Vector Pulse-Width-Modulation (SVPWM) technique are used. While SVPWM is simple, effective and well understood, synchronous optimal pulse pattern (OPP) based modulation promises increased efficiency. The concept of optimal pulse patterns is well known since the days of the thyristor when converter switching frequencies were highly limited. However, applying OPP modulation to EV traction systems needs to account for several fundamental challenges that existing MCUs' processing and peripheral capabilities struggle to overcome. In introducing its Optimal Pulse Pattern (OPP) implementation, TI is addressing these fundamental challenges by leveraging the unique peripheral capabilities and unrivaled processing power of its F29x MCUs. Preliminary high power test results show a 0.8% improvement in traction system efficiency, enabling more than $100 in savings per battery pack for EV makers.

This paper highlights the importance of traction inverter optimization, how OPP can unlock meaningful system-level benefits, and how TI's F29x MCUs address practical challenges in implementing OPP.

2 Why Traction System Efficiency Matters

Because traction systems are the major consumers of the EV battery's energy and the EV battery is the costliest component of an EV, improving traction system efficiency is the most effective way to address these major OEM goals:

Table 2-1. OEM goals and common design challenge

OEM Goals	Technical Design Challenge to Reach Goals
Reduce battery size and vehicle cost	Improve traction system efficiency
Increase driving range to meet consumer expectations	

The two components which impact traction system efficiency that can be influenced by OPP are:

- **Switching losses** in power semiconductors
- Motor conduction and **harmonic losses**

TI's unique OPP design finds the *sweet spot* in minimizing both switching and motor harmonic losses, resulting in optimized traction system efficiency.

3 Optimal Pulse Positioning: A New Modulation Strategy

Modulation is the process of creating an AC waveform from a DC battery by precisely turning switches on and off. Faster switching enables a cleaner sine waveform but increases switching losses, as there is loss in the FET every time it is switched. Slower switching introduces motor harmonic losses due to a distorted sine waveform. A well-designed modulation technique optimizes both switching losses and motor harmonic losses across the entire drive cycle without compromising vehicle performance or driver experience.

The traditional modulation technique mentioned earlier, SVPWM, has a fixed period / frequency and uses a predetermined number of edges within a PWM period. OPP uses a variable switching frequency and can have multiple switching events and edges within a PWM period. This is fundamentally what unlocks the potential for meaningful efficiency gains with OPP. Figure 3-1 compares an OPP waveform against an SVPWM waveform, highlighting the difference in modulation and complexity.

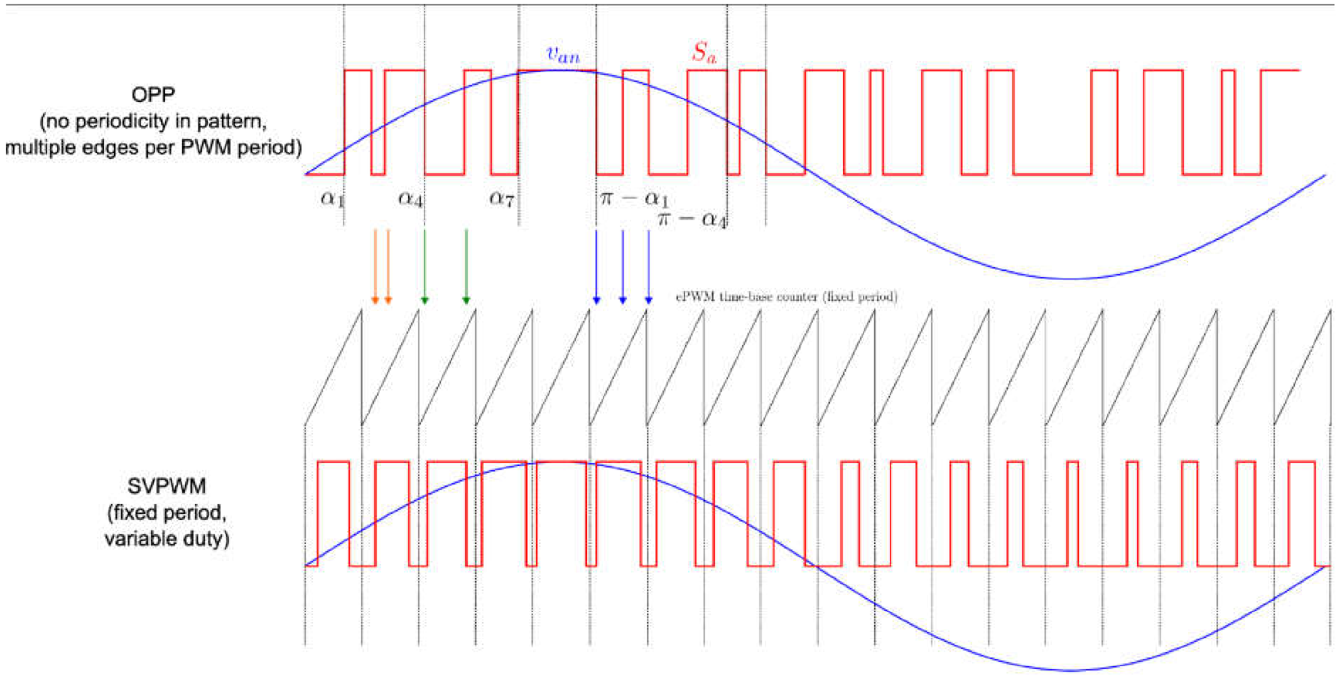


Figure 3-1. Optimal Pulse Pattern waveform vs. Space-Vector Modulated Waveform

OPP enables operation at lower switching frequencies while minimizing motor harmonics. OPP also enables more efficient utilization of the EV battery, resulting in fewer copper losses (a component of motor losses). Both allow optimization of total system losses. The figure below reflects this.

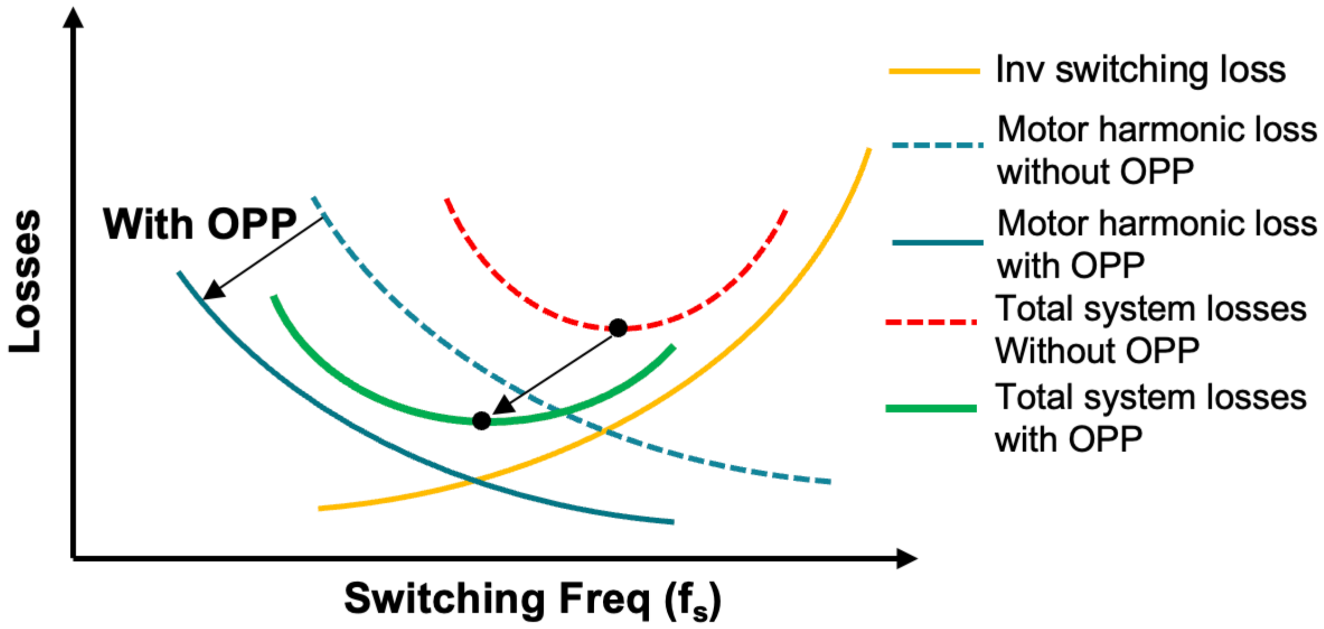


Figure 3-2. Total system losses reduced with OPP

4 Key Challenges to Implement OPP and How TI Has Solved Them

Implementing a robust OPP solution introduces three complex challenges:

1. Synchronous PWM pulse generation
2. SVPWM to OPP transition
3. Dynamic response and robust closed loop control

These challenges demand differentiated MCUs that support industry-leading real-time control performance and unique features. TI's OPP design solved these challenges with F29x real-time microcontrollers. Key F29x MCU features that enable this are:

- High-performance C29 CPU core optimized for real-time motor control
- Type 5 ePWM enabling accurate edge placement, multiple edges within a PWM period, and active and shadow register capabilities
- Tightly coupled CPU-PWM minimizing CPU overhead

5 Synchronous PWM Pulse Generation

As mentioned earlier, an OPP waveform can require a higher of compare events, or edges, within a PWM period. F29 MCU's Type 5 ePWM module with its XCMP feature enables OPP by supporting multiple compare events per PWM period. Figure 5-1 demonstrates 4 XCMP events, or 4 edges, within a single PWM period. Without this feature, competitor MCUs are limited to fewer independent edges within a PWM period, limiting their ability to run OPP especially at lower speeds – leaving efficiency gains on the table.

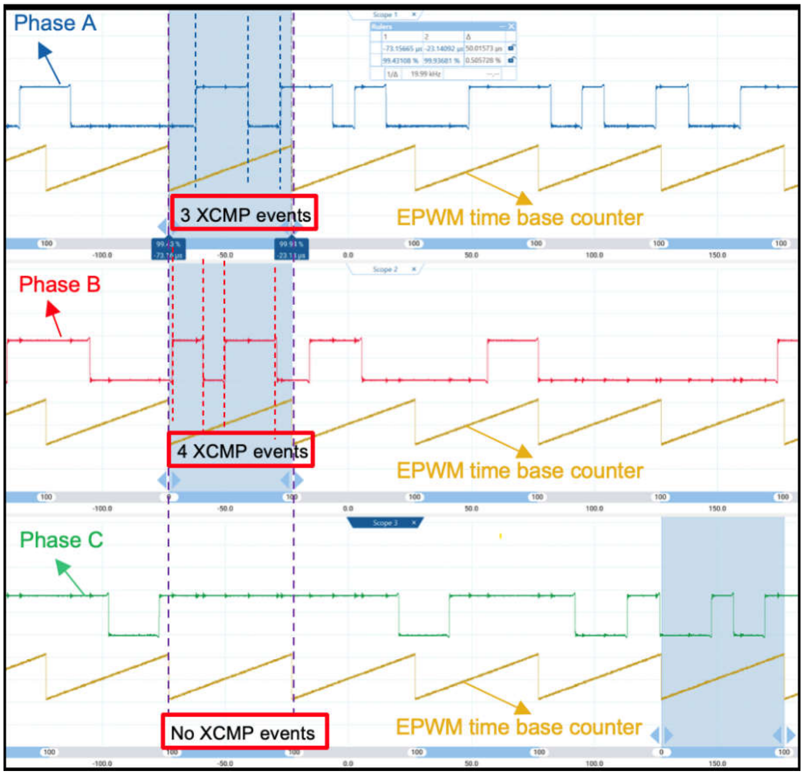


Figure 5-1. Multiple XCMP Events or Edges Within Single PWM period

Accurate edge placement is also a critical factor for Synchronous PWM pulse generation. The slightest error on PWM edge placement results in motor harmonic losses. The key differentiators on F29 MCUs that solve this problem are twofold:

- C29 performance which addresses the high demand for calculations on how many edges need to be placed, and exactly when.
- Tight CPU to PWM interconnect: with minimal CPU cycles needed to update PWM

Because the CPU must write to the PWM register at every compare event, it can take significant CPU bandwidth if there are multiple edges in a single PWM period. But thanks to the ultra-low latency of the C29 CPU to the PWM interconnect, there are minimal CPU cycles needed to keep up with the demand of PWM compare events. This effectively resolves the concern of CPU bandwidth loss due to several PWM register writes.

6 SVPWM to OPP Transition

A transition from Space Vector Pulse-Width Modulation (SVPWM) to OPP is highly complex. This transition is needed in the first place because at low speeds (start-up), the system must be operating in SVPWM mode to maximize efficiency. However, as motor speeds increase, transition to OPP is needed to maintain efficiency. A smooth and seamless transition from one mode (SVPWM) to another (OPP) is enabled by yet another Type 5 ePWM feature on F29: shadow and active registers. Shadow and active registers allow SVPWM and OPP configurations to coexist simultaneously and enable and on-the-fly PWM reconfiguration. The image below highlights TI's implementation of Type 5 ePWM to solve the problem of SVPWM to OPP transition.

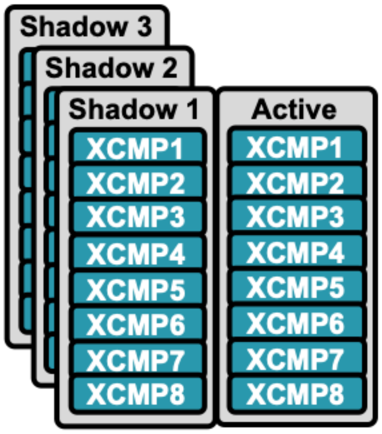


Figure 6-1. Shadow and Active Registers Visualization

7 Dynamic Response and Robust Closed-Loop Control

While one can hope for good conditions, real-world systems always introduces periodic anomalies or disturbances. The motor current can be disturbed any of the following:

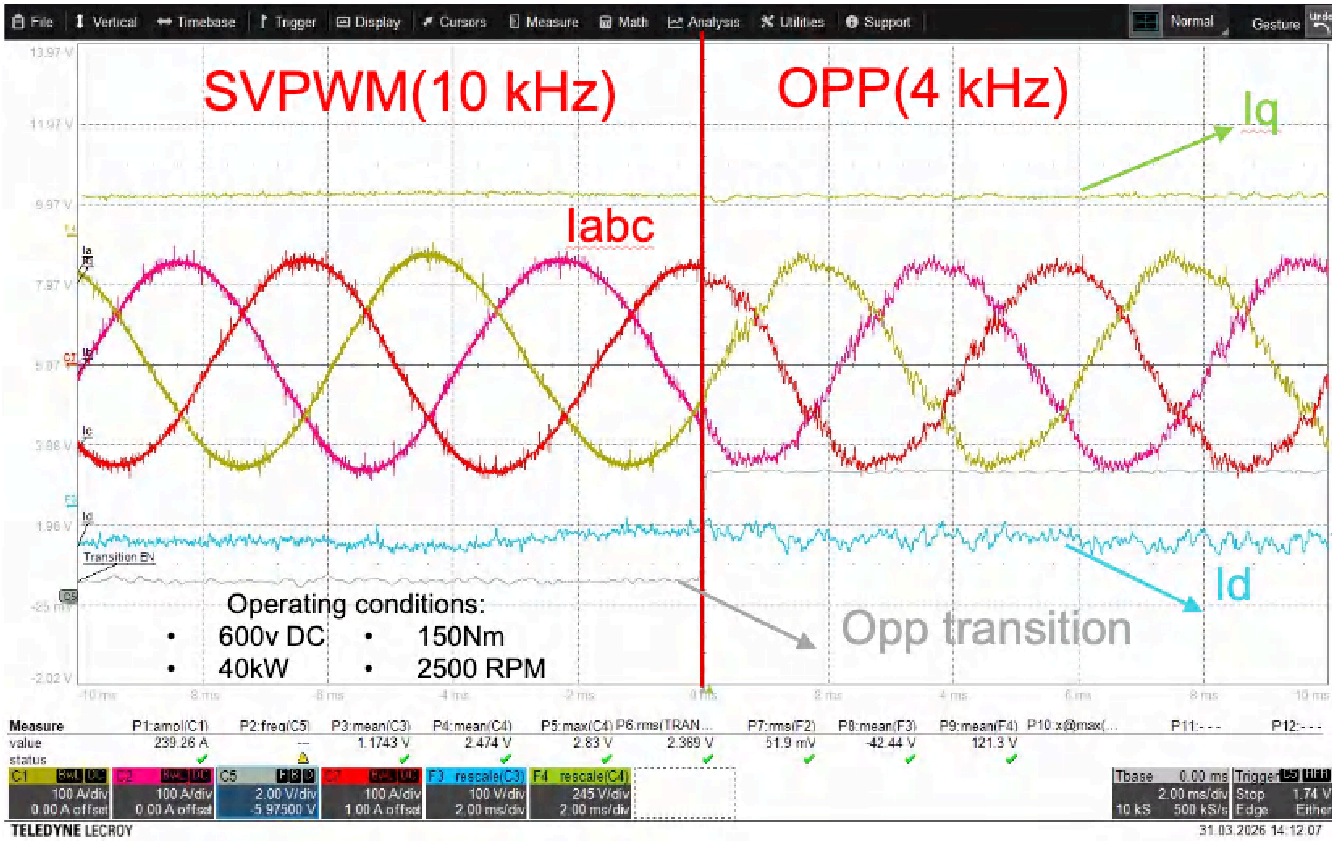
- SVPWM to OPP transition
- Changing number of OPP pulses
- Torque request change (driver input)

Closed loop and active control that address each of these cases are critical in realizing a complete and robust OPP design.

Because active control cannot be done by traditional FOC (Field-Oriented Control) alone, flux control is necessary. Flux control is highly complex and introduces three sub-challenges:

- Flux reference: what flux must be.
- Flux observer: actual flux. This is difficult because flux cannot be measured.
- Flux controller: corrective action and calculations to minimize flux error

TI has designed a flux controller to achieve robust, closed-loop control – which is highly computation-intensive and complex. C29 CPU addresses this with industry-leading real-time performance, showing more than 2.5x better performance versus other competitor MCUs in the traction inverter market (benchmarked by leading Automotive TIER1). The hardware-based TMU (Trigonometric Math Unit) feature significantly offloads specific math functions from the C29 CPU, helping further improve performance. The figure below showcases TI's OPP design validated for stable closed-loop control.



Measure	P1:ampl(C1)	P2:freq(C5)	P3:mean(C3)	P4:mean(C4)	P5:max(C4)	P6:rms(TRAN...	P7:rms(F2)	P8:mean(F3)	P9:mean(F4)	P10:x@max(...	P11:---	P12:---
value	239.26 A	---	1.1743 V	2.474 V	2.83 V	2.369 V	51.9 mV	-42.44 V	121.3 V			
status	✓	⚠	✓	✓	✓	✓	✓	✓	✓			

C1 BWL DC	C2 BWL DC	C5 F B D	C7 BWL DC	F3 rescale(C3)	F4 rescale(C4)	Tbase 0.00 ms	Trigger C5 HFR
100 A/div	100 A/div	2.00 V/div	100 A/div	100 V/div	245 V/div	2.00 ms/div	Stop 1.74 V
0.00 A offset	0.00 A offset	-5.97500 V	1.00 A offset	2.00 ms/div	2.00 ms/div	10 kS 500 kS/s	Edge Either

Figure 7-1. Stable Closed-Loop Control

8 Conclusion

As EV/HEV adoption continues to grow, lowering vehicle cost by optimizing EV efficiency remains a key priority for automakers. The traction inverter is the most impactful area for optimization.

TI's Optimal Pulse Positioning (OPP) design introduces a new modulation technique that dynamically minimizes inverter switching and motor harmonic losses. While initial test results are promising, enabling more than $100 in savings for a single battery pack, TI’s OPP solution continues to refine with more features and capability to improve ease of use and efficiency. Enabled by the high-performance F29x MCU and its differentiated features, OPP can deliver meaningful system-level benefits including reduced battery size and/or longer drive range. For automotive OEMs and Tier-1 suppliers seeking to maximize EV efficiency, TI's OPP solution represents a compelling next step in traction inverter innovation

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