Doing More with Less

Maximizing Performance: Enhancing Horsepower, Torque, Speed, and Efficiency with the RAJ306102 16-bit MCU Motor Control IC

Jun Oie, Minoru Kurosawa, and Miguel Mendoza, Renesas Electronics Corporation

Summary

This white paper delves into enhancing performance aspects—specifically, horsepower, torque, speed, and power efficiency—within cordless power tool applications. Through dynamometer testing, we illuminate the contrasting outcomes achieved by employing traditional 120-Degree (Trapezoidal) commutation versus 150-Degree commutation. The results, obtained with the same power supply and motor but differing algorithms, offer a direct head-to-head comparison. Additionally, practical examples showcase the real-world performance of these algorithms, providing valuable insights into user experiences.

Background

The Motor Control IC is a semiconductor solution comprising a processor or state machine and an analog front end (AFE). Specifically, the RAJ306102 utilizes an RL78/G1F MCU and AFE to form a comprehensive inverter, excluding the MOSFETs. The AFE encompasses regulators, charge pump, LDOs, MOSFET driver, differential OP Amps, and comparators, along with fault monitoring circuitry to ensure safety and reliability. Housed in a single 8mm x 8mm QFN package, this dual-die configuration offers compact integration.

Figure 1 provides a visual representation of the RAJ306102 device, accompanied by functional block diagram descriptions. Notably, the MOSFETs are external, affording users the flexibility to adapt to varying input voltage and peak current requirements.

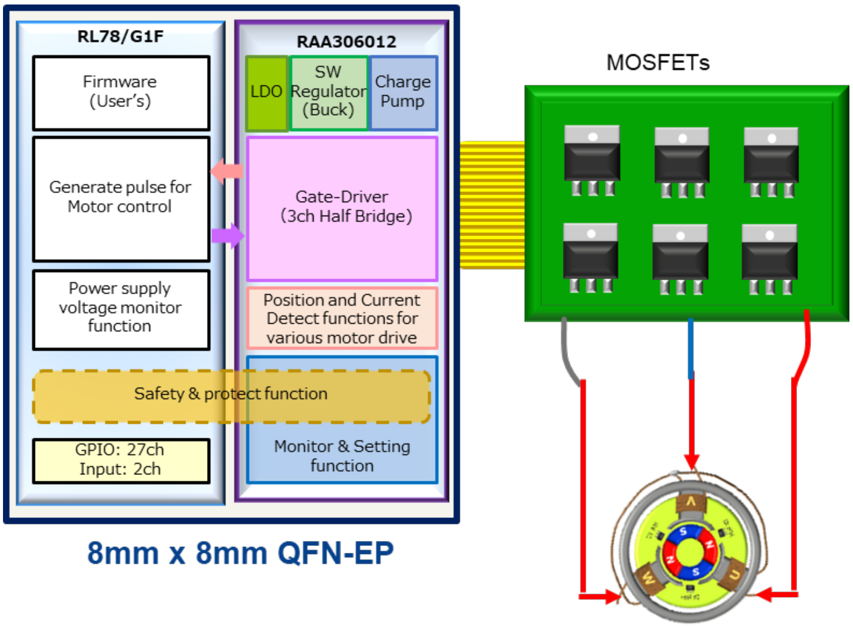


Figure 1: RAJ306102 Simple Representation

The RAJ306102 excels in driving sensorless 120-Degree and 150-Degree commutation without necessitating hardware modifications. In our experimentation, a prototyping board featuring 12 MOSFETs, with two in parallel configuration, was developed to handle peak currents of up to 300A for 50ms. Figure 2 showcases these prototyping boards, incorporating 12 x IRF7480 Direct FETs to align with the stock drill specifications. To mitigate MOSFET heat during stall conditions, a heatsink was employed, ensuring reliable performance.

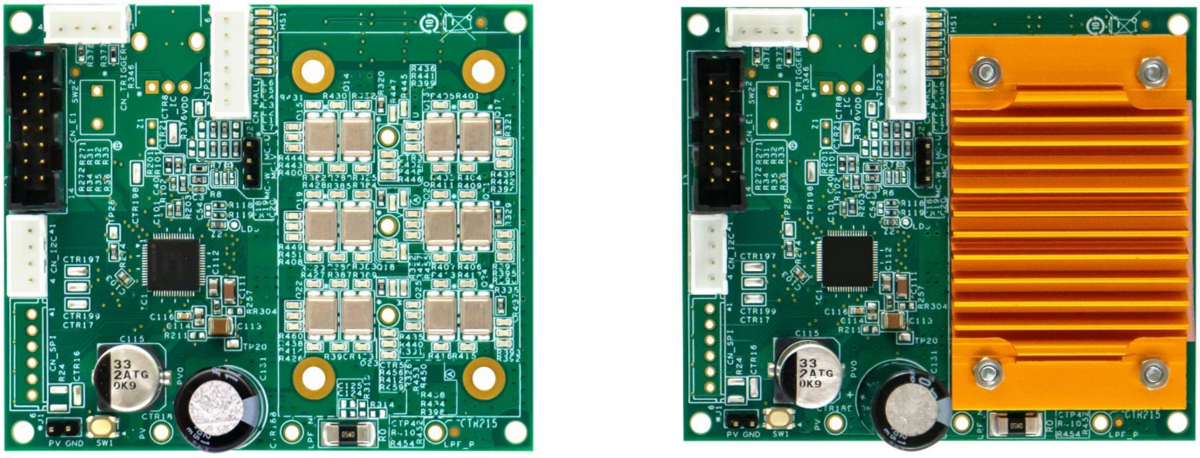


Figure 2: Prototyping board for Power Drill Application (Using RAJ306010)

120-Degree vs. 150-Degree commutation

To achieve the rotation of a BLDC motor, precise control of the current's direction and timing into the stator coils is essential. The rotor, equipped with permanent magnets, obediently aligns itself with the revolving magnetic field flux. Among motor control algorithms, the 120-Degree commutation method stands out as the simplest and finds widespread use in consumer applications. This method excels in simplicity by energizing only two of the stator's phase coils at any given time. The non-energized phase coil serves a crucial role in detecting the Back ElectroMotive Force (BEMF) voltage, enabling sensorless control by identifying zero crossings.

Sustaining rotation involves a continuous interchange of flux, ensuring the perpetual pursuit of the permanent magnet by the rotating magnetic field generated by the coils. This dynamic process mandates the constant switching of the U, V, and W stator coils' energization, propelling a moving flux that consistently exerts force on the rotor magnet. The MOSFET inverter directs the current, with each phase linked to a half-bridge connecting to the switch node. This arrangement forms a 3-phase inverter, facilitating the current's directional switch in six different directions, as illustrated in Figure 3.

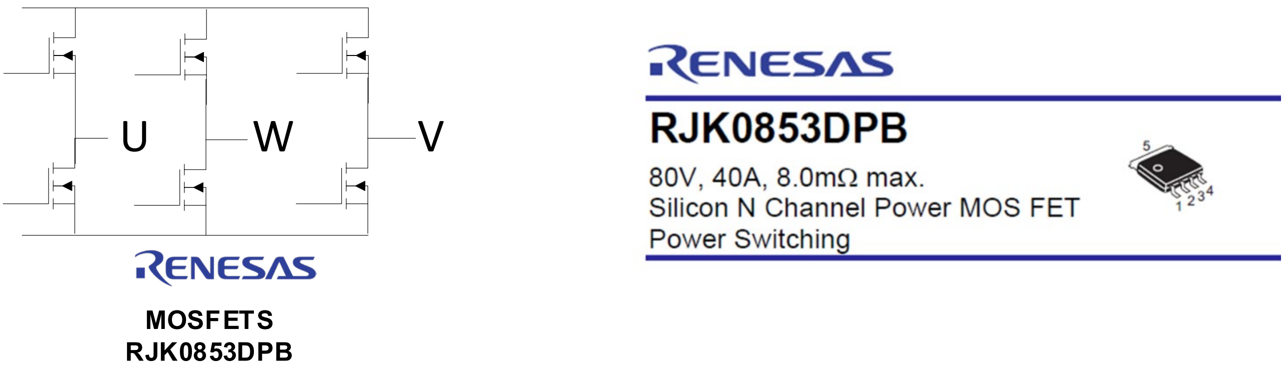
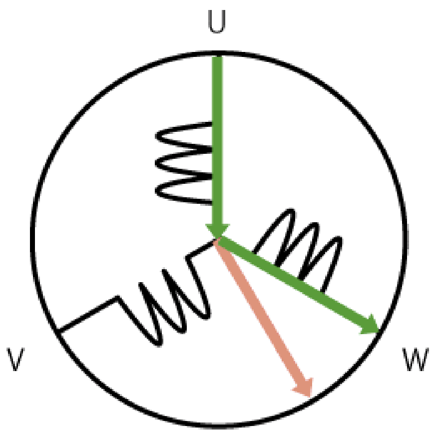


Figure 3: Typical 3 Phase MOSFET Bridge Inverter Using RJK0853DPB MOSFETs

In Figure 4, the interplay between energized phases and flux is depicted. Sequentially switching the current through modes 1 to 6 induces clockwise rotation of the rotor through one complete revolution. The rotational speed is finely tuned by managing the rate of phase transitions. This control method is commonly referred to as "120-degree commutation."



Energizing Mode	Energized Phase	Resultant Flux
1	U→W	
2	U→V	
3	W→V	
4	W→U	
5	V→U	
6	V→W	

Figure 4: The changing resultant flux continually pulls the rotor magnet, causing the rotor to turn.

With 120-degree commutation, the motor is steered by only six resultant flux directions. For instance, transitioning from Mode 1 to 2 (refer to Fig. 4) adjusts the resultant flux direction by 60°, compelling the rotor to follow suit. The shift from Mode 2 to 3 introduces another 60° shift in the flux direction, once again influencing the rotor's movement. Replicating this sequence generates continuous rotation, albeit with a non-smooth flux, resulting in a distinctive trapezoidal appearance in the phase current.

Illustrated in Figure 5 is an exemplary representation of 120-degree commutation, also commonly known as "trapezoidal." This nomenclature is derived from the trapezoidal shape of the phase current, depicted in light blue on the oscilloscope. While not renowned for being the most power-efficient motor control algorithm, 120-degree commutation is highly practical. Its practicality stems from its minimal demand for processing power from the microcontroller, making it versatile enough to operate a wide range of BLDC motors concerning power and speed. This motor control scheme is extensively utilized in BLDC power tools and appliances like stick vacuums.

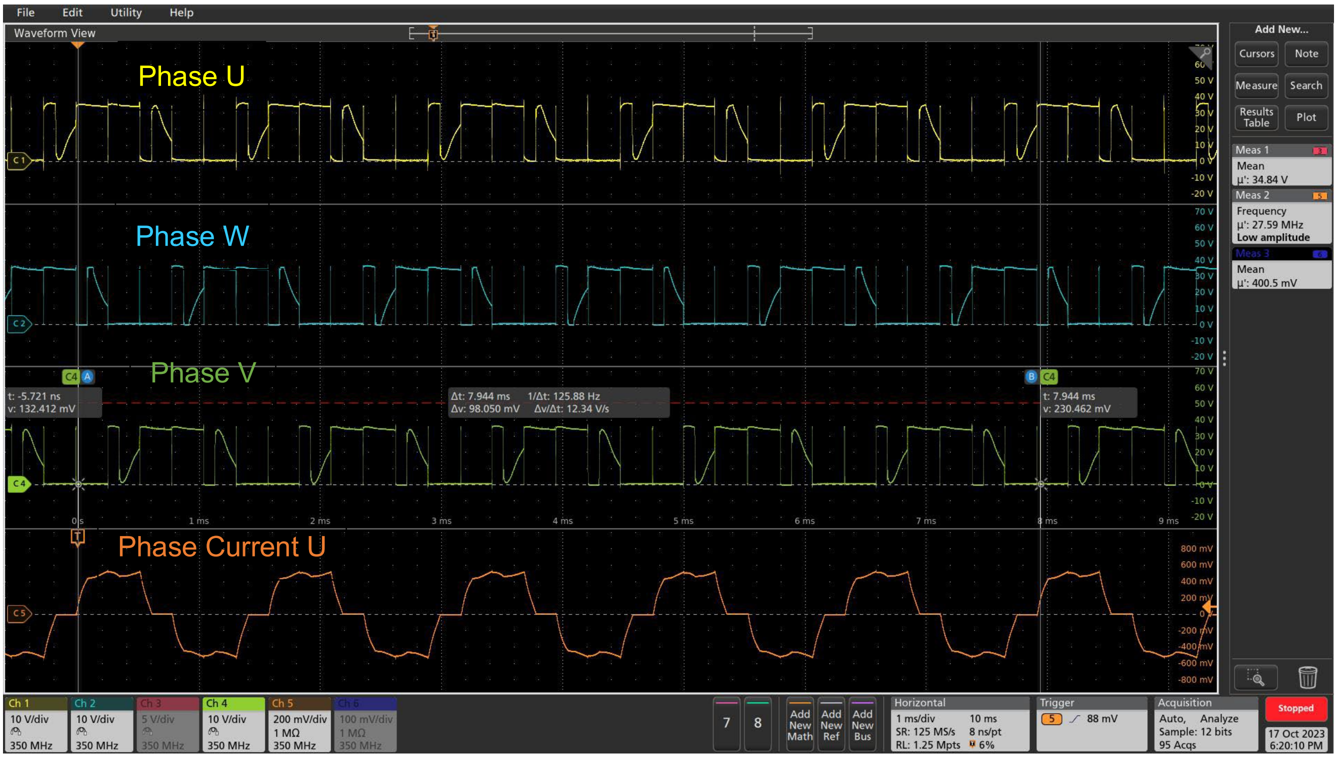


Figure 5: Example of 120 Degree (Trapezoidal) commutation

Theoretically, the most power-efficient BLDC motor control scheme is sinusoidal control, achievable through the widely adopted Vector control or Field Orientated Control (FOC). This control scheme crafts a sinusoidal phase current that closely aligns with the characteristics of a BLDC motor by meticulously adjusting the current flow into each of the three phases. This precise adjustment facilitates a more continuous change in resultant flux, resulting in smoother motor rotation, as evidenced in Figure 6. Figure 7 provides a scope shot illustrating the remarkably smooth sinusoidal phase current, accompanied by three other waveforms demonstrating phase voltages continuously energized to appropriate levels for creating a smoother rotating flux.

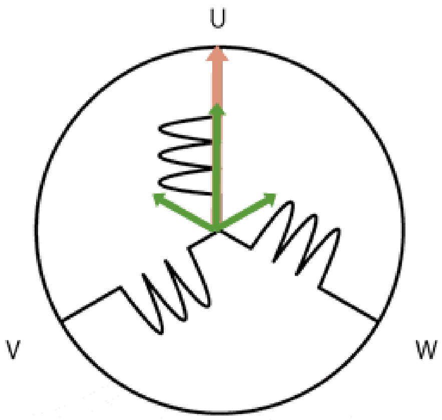


Figure 6: Sinusoidal Control

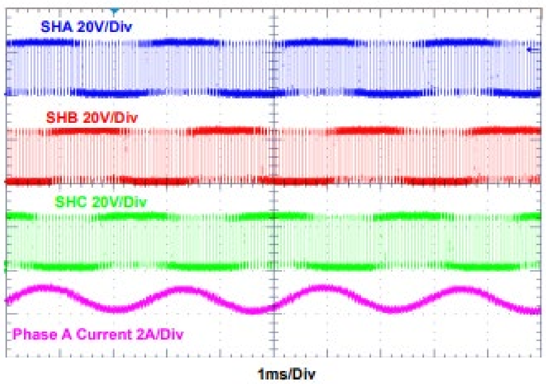


Figure 7: BLDC Motor Commutation with FOC, VM = 24V

However, the Vector control scheme has a notable drawback—it demands substantially more processing power to accurately calculate rotor position by measuring the current in each phase. This necessitates the use of more expensive microcontrollers like RX23T or RA4T1 when compared to the RL78/G1F, which efficiently handles motor control schemes without overwhelming the microprocessor's headroom capability.

An alternative motor control scheme, often overlooked, is the 150-degree commutation, boasting power efficiency comparable to sinusoidal control. This scheme builds upon the 120-degree commutation but introduces a 30-degree advance angle to approximate sinusoidal waveforms. The resulting phase current exhibits a more sinusoidal shape compared to the 120-degree approach, as showcased in the scope shot example in Figure 8. The remaining 30-degree unenergized phase is employed to detect zero cross generated by the Back ElectroMotive Force (BEMF) for sensorless control. Implementing this scheme requires no hardware changes from the 120-degree commutation setup, presenting a more cost-effective solution compared to sinusoidal alternatives.

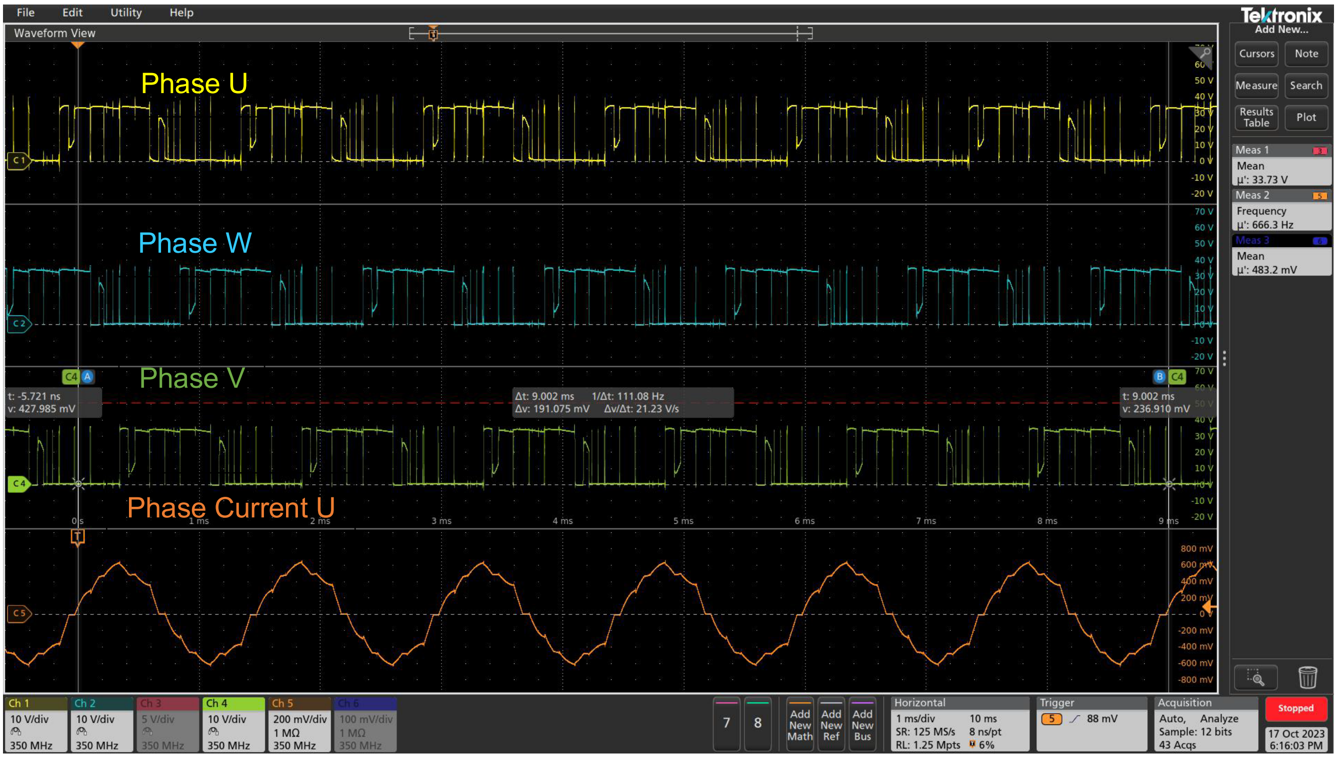


Figure 8: 150-degree Commutation

Test Case

To compare the performance of 120-degree and 150-degree commutation, we chose a typical application: a cordless power tool, specifically a widely available BLDC drill found in local home improvement stores. For our testing, we retrofitted the stock cordless drill using our dedicated prototyping board, as depicted in

Figure 9. This ensures a standardized testing environment, allowing us to evaluate 120-degree and 150-degree commutation using the same tool and eliminating any discrepancies in the device under test.

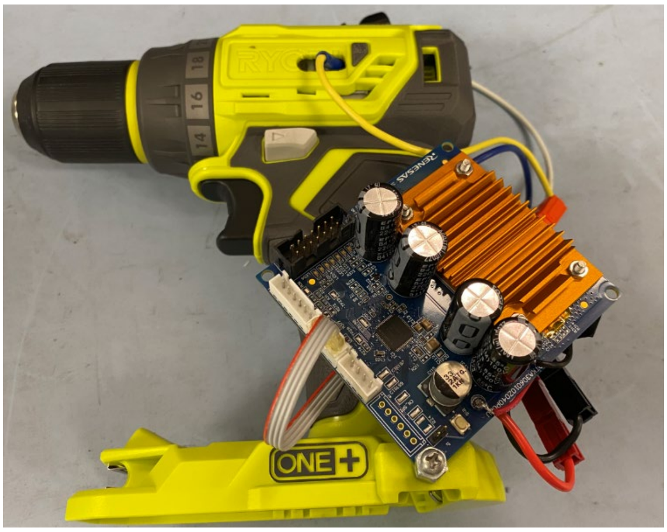


Figure 9: BLDC Cordless Power Tool Under Test

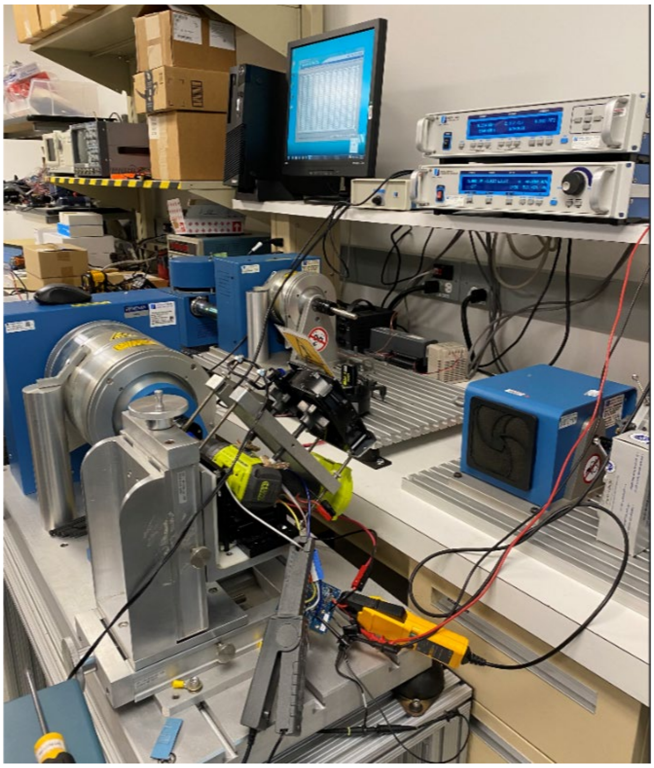


Figure 10: Magtrol Test Setup

Our test configuration involved the use of a Magtrol 6530 Three-Phase Power Analyzer, DSP6001 Dynamometer Controller, and an HD-815-5C1-0200 Dynamometer, as illustrated in Figure 10. This comprehensive setup enables precise measurements of horsepower, power efficiency, and the relationship between speed and torque. With this arrangement, we established a direct and reproducible comparison, with the sole variable being the motor control algorithm.

Initially, we conducted measurements with the dynamometer running under 120-Degree commutation to capture baseline data for comparison. Subsequently, we replaced the hardware with 150-degree firmware and repeated the same test. Fine-tuning the advance angle within a range from -2° to 6° per RPM steps was necessary to optimize power efficiency. The graph in Figure 11 illustrates a comparison between 150-Degree and 120-Degree commutation. Notably, there is a noteworthy 25% improvement in horsepower using 150-Degree (0.829hp) compared to 120-Degree (0.663hp). Additionally, speed, efficiency, and torque have all shown improvements with 150-degree commutation, affirming its enhanced efficiency and superior results compared to the traditional 120-Degree commutation.

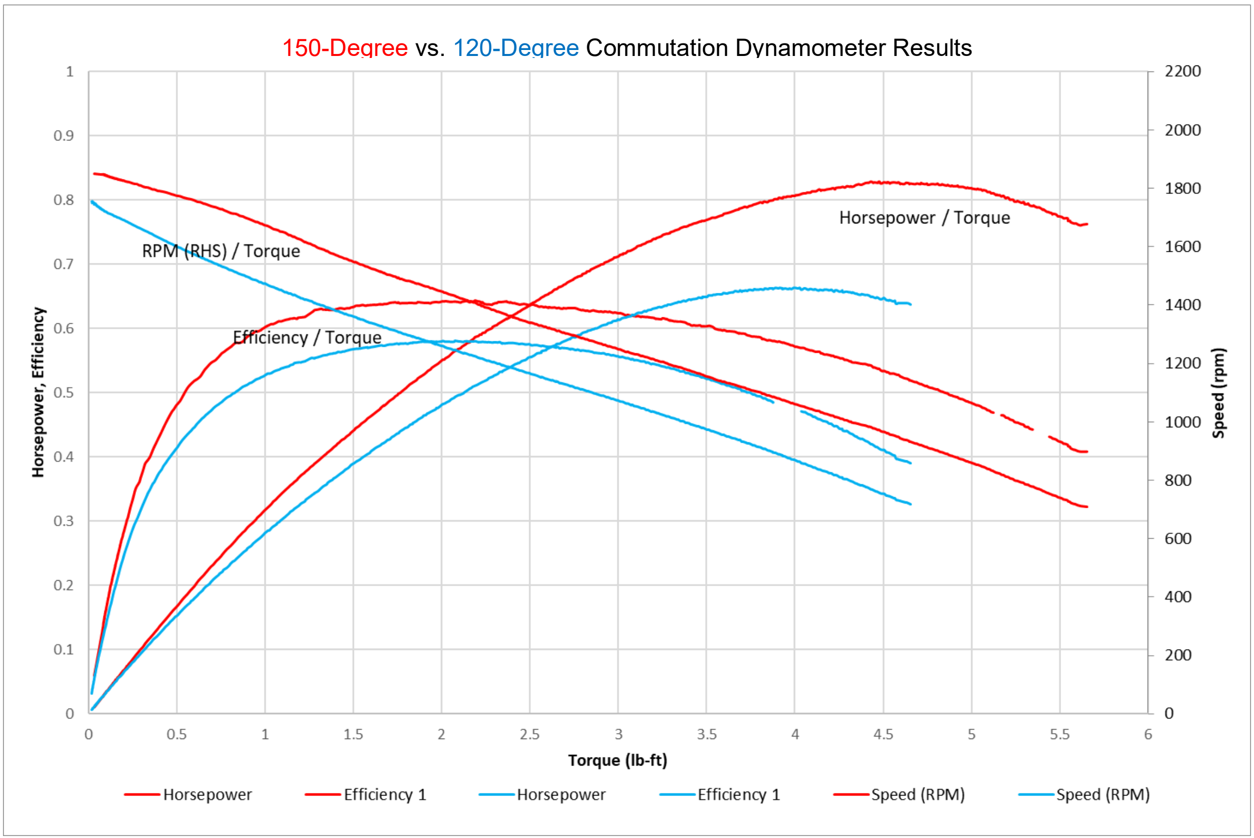
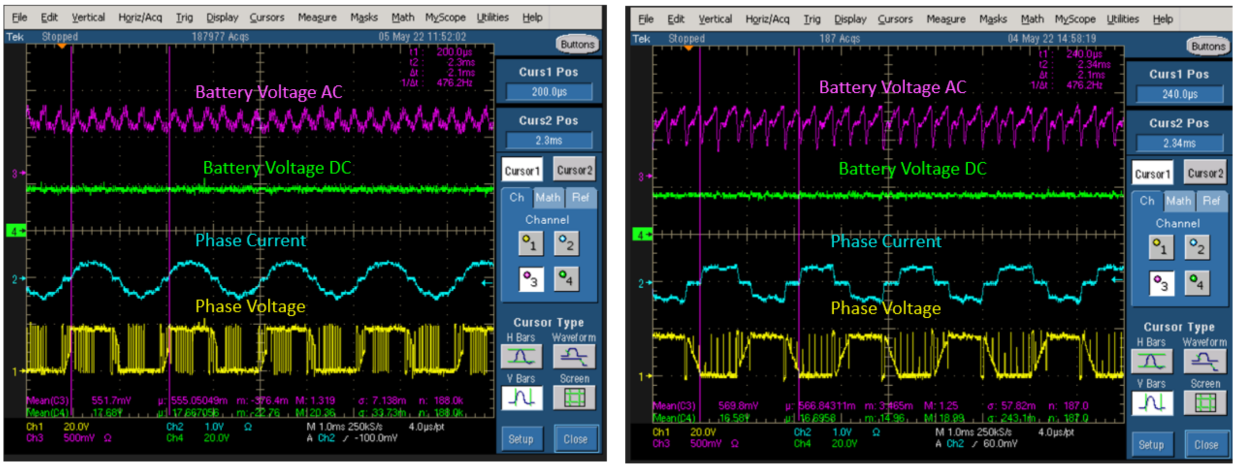


Figure 11: Dynamometer Results for 150-Degree vs. 120-Degree Commutation

Additional enhancements, such as reduced voltage ripple and lower current consumption for the same mechanical work or energy output, have been consistently observed. In a practical application, specifically testing a leaf blower, we compared the impact of 120-Degree and 150-Degree commutation. The 120-Degree drive consumed 522.5 Watts, while the 150-Degree drive consumed a notably lower 495.7 Watts for the same RPM. This translates to a substantial 1.48 Amps less current consumption for the 150-Degree commutation, resulting in extended run time with a single charge and an overall more positive user experience.

Furthermore, the 150-Degree commutation exhibited less ripple on the battery voltage compared to the 120-Degree commutation, as illustrated in Figure 12. This reduction in supply ripple is crucial, as significant supply ripple can adversely impact battery life and performance due to increased power loss and higher operating temperatures. Hence, the observed improvements in current consumption and voltage ripple underscore the practical advantages of employing the 150-Degree commutation scheme.

150-Degree Commutation | 120-Degree Commutation



Power Consumption = 495.72W
Current Consumption 27.54A @ current probe was 50A/1V

Power Consumption = 522.54W
Current Consumption = 29.03A @ current probe was 50A/1V

Figure 12: Scope shot comparison for 150-Degree and 120-Degree in Leaf Blower application.

Conclusion

The test case detailed in this document unequivocally establishes that 150-Degree commutation stands out as an enhanced motor control scheme without incurring additional costs compared to 120-Degree commutation, utilizing the same hardware and solution. Demonstrating superior performance across various metrics, including power efficiency, horsepower, torque, and speed, 150-Degree commutation proves to be a noteworthy advancement. Additionally, our observations revealed reduced ripple on the supply line, a critical factor contributing to enhanced battery pack lifetime and performance.

In power-intensive applications like cordless power drills, the benefits of improved horsepower and torque become evident, particularly when driving heavy loads. For devices such as leaf blowers, the reduced power consumption associated with 150-Degree commutation translates into extended run times, significantly enhancing the overall user experience. Importantly, implementing 150-Degree commutation represents a straightforward enhancement for existing applications, requiring no modifications to the tool's motor, housing, or battery, making it a pragmatic and accessible upgrade.

Resources

- RAJ306102 Application Note
- Controlling BLDC Motors

Corporate Headquarters

TOYOSU FORESIA, 3-2-24 Toyosu, Koto-ku, Tokyo 135-0061, Japan
https://www.renesas.com

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Doc Number: R16WP0007EU0100