Design Example Report

<table>
<thead>
<tr>
<th>Title</th>
<th>3-Phase Inverter Using BridgeSwitch™ BRD1260C and LinkSwitch™-TN2 LNK3202D in Sinusoidal Control Scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specification</td>
<td>310 VDC Input, 40 W Inverter Output, 0.2 A Motor RMS Current, 1500 RPM for 8-Pole Brushless DC Motors</td>
</tr>
<tr>
<td>Application</td>
<td>High-Voltage Brushless DC (BLDC) Motor for Fan Application</td>
</tr>
<tr>
<td>Author</td>
<td>Applications Engineering Department</td>
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<td>1.0</td>
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</table>

Summary and Features

- BridgeSwitch – High-voltage half-bridge motor driver
- Integrated 600 V FREDFETs with ultra-soft, fast recovery diodes
- Hall sensor based sinusoidal control scheme using Princeton Technology Corp. IC (PT2505)
- +24 V motor control chip aux supply circuit using LinkSwitch-TN2 in buck configuration
- Fully self-biased operation - no auxiliary power supply needed on the BridgeSwitch devices
- Lossless over-current protection using BridgeSwitch instantaneous phase current output
- Integrated high-side and low-side cycle-by-cycle current limit on each BridgeSwitch devices
- Device over-temperature protection
- Fault protection mechanisms (overvoltage and undervoltage protection, over-current protection, system over-temperature and motor lock protection)
- On-board programming interface for parameter setting and one-time programming (OTP)
- Voltage controlled speed input and pulse output signal for speed information
- PCB size customized for a 40 W inverter fan design
- No external heat sink

PATENT INFORMATION

The products and applications illustrated herein (including transformer construction and circuits external to the products) may be covered by one or more U.S. and foreign patents, or potentially by pending U.S. and foreign patent applications assigned to Power Integrations. A complete list of Power Integrations' patents may be found at www.power.com. Power Integrations grants its customers a license under certain patent rights as set forth at https://www.power.com/company/intellectual-property-licensing/.
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Important Note:
During operation, the design example board is subject to hazards including high voltages, rotating parts, bare wires, and hot surfaces. Energized DC bus capacitors require time to discharge after DC input disconnection.

All testing should use an isolation transformer to provide the DC input to the board.
1 Introduction

This document is an engineering report describing a 40 W, >93% efficiency sinusoidal control 3-phase inverter for a high-voltage brushless DC (BLDC) motor drive. The design incorporates a complete inverter stage and a control stage to drive a 3-phase BLDC motor for fan applications.

The inverter stage is implemented using three fully integrated BridgeSwitch (BRD1260C) devices in a small footprint surface mount InSOP-24C package with exposed pads that enable heat sinking through PCB.

The control part uses a hall sensor based sine wave driving scheme control chip from Princeton Technology Corp. (PT2505) in SSOP28 package. Sinusoidal commutation allows electrical audible noise reduction in motor phase commutation. The PT2505 operates at 20 kHz PWM frequency and comes with a BLDC user interface kit that allows parameter settings and one-time programming directly on the inverter board.

This document contains the inverter and motor specifications, schematic, bill of materials, printed circuit board layout, the inverter performance, fault protections, parameter settings and test setup.

Figure 1 – Populated Circuit Board Photograph.
## Specifications

The table below provides the electrical specification of the 3-phase inverter design. The results section provides actual performance data.

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Units</th>
<th>Comment</th>
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<tr>
<td><strong>Input</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage</td>
<td>$V_{IN}$</td>
<td>280</td>
<td>310</td>
<td>340</td>
<td>V</td>
<td>High-Voltage DC Bus.</td>
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<td>Power</td>
<td>$P_{IN}$</td>
<td>43</td>
<td></td>
<td></td>
<td>W</td>
<td></td>
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<tr>
<td>Speed Control Voltage</td>
<td>$V_{SP}$</td>
<td>2.1</td>
<td></td>
<td>5.4</td>
<td>V</td>
<td></td>
</tr>
<tr>
<td><strong>Output</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuous Power</td>
<td>$P_{OUT}$</td>
<td>40</td>
<td></td>
<td></td>
<td>W</td>
<td>Inverter Output Tested At 0.2 N-m 1500 RPM.</td>
</tr>
<tr>
<td>Peak Power(^1)</td>
<td>$P_{OUT-PK}$</td>
<td>60</td>
<td></td>
<td></td>
<td>W</td>
<td>Inverter Output Tested At 0.2 N-m 2400 RPM.</td>
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<tr>
<td>Motor Current</td>
<td>$I_{MOTOR}$</td>
<td>0.2</td>
<td></td>
<td></td>
<td>Arms</td>
<td>At 0.2 N-m Torque.</td>
</tr>
<tr>
<td>Output Speed</td>
<td>$\omega$</td>
<td>1500</td>
<td></td>
<td>2400</td>
<td>RPM</td>
<td></td>
</tr>
<tr>
<td>PWM Carrier Frequency</td>
<td>$F_{PWM}$</td>
<td>20</td>
<td></td>
<td></td>
<td>kHz</td>
<td>Self-Supplied Operation.</td>
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<tr>
<td>Speed Pulse Output(^2)</td>
<td>FG</td>
<td>300</td>
<td></td>
<td></td>
<td>Hz</td>
<td>FG Terminal Output.</td>
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<tr>
<td><strong>Efficiency</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full load</td>
<td>$\zeta$</td>
<td></td>
<td>93</td>
<td></td>
<td>%</td>
<td>Inverter Efficiency at 0.2 N-m Torque at 1500 RPM.</td>
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<tr>
<td><strong>Motor Specifications</strong></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Poles</td>
<td>$N_{POLES}$</td>
<td>8</td>
<td></td>
<td></td>
<td>P</td>
<td></td>
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<td>Rated Power</td>
<td>$P_{MOTOR}$</td>
<td>40</td>
<td></td>
<td></td>
<td>W</td>
<td></td>
</tr>
<tr>
<td>Rated Speed</td>
<td>$\omega_{MOTOR}$</td>
<td>1500</td>
<td></td>
<td></td>
<td>RPM</td>
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<tr>
<td><strong>Environmental</strong></td>
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<td>Ambient Temperature</td>
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<td>25</td>
<td>40</td>
<td>°C</td>
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<tr>
<td>Undervoltage Threshold</td>
<td>$V_{UV}$</td>
<td>240</td>
<td></td>
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<td>V</td>
<td></td>
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<td>Overvoltage Threshold</td>
<td>$V_{OV}$</td>
<td>390</td>
<td></td>
<td></td>
<td>V</td>
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<tr>
<td>Internal HS/LS FREDFET Over-current Threshold(^3)</td>
<td>$I_{OC}$</td>
<td>0.7</td>
<td></td>
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<td>A</td>
<td>BridgeSwitch Integrated Feature.</td>
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<td>System Over-current</td>
<td>$I_{SYS-OC}$</td>
<td>0.5</td>
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<td></td>
<td>A</td>
<td>Motor Current Sensed Through JPH Pin.</td>
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<td>System Over-temperature(^4)</td>
<td>$T_{SYS}$</td>
<td>95</td>
<td></td>
<td></td>
<td>°C</td>
<td>Hysteretic – Operation Restarts at 45 °C Ambient Temperature.</td>
</tr>
</tbody>
</table>

Notes:
\(^1\) Peak power duration depends on the application consideration of the motor case temperature - needs verification in the actual application
\(^2\) Speed pulse output frequency relation: 5 pulses per mechanical revolution – FG terminal pulled up to external supply (5 V to 15 V)
\(^3\) Externally programmable through XL/XH pin resistors (44.2 kΩ default at 0.7 A)
\(^4\) Temperature sensed through external NTC thermistor - needs verification in the actual application

**Table 1** – Inverter Specification.
Figure 2 – BridgeSwitch 3-Phase Inverter Input Stage and Controller Schematic.
Figure 3 – BridgeSwitch 3-Phase Power Stage Schematic.
4 Circuit Description

The schematic in Figure 2 and 3 shows a 3-phase inverter employing three BRD1260C devices driven by a hall sensor based motor control chip (PT2505) in a sinusoidal commutation scheme. The circuit enables driving a high-voltage, 3-phase brushless DC (BLDC) motor from a rectified AC input voltage ideal for a fan application. BridgeSwitch combines two N-channel 600 V rated power FREDFETs, gate drivers and controllers into a low profile surface mount package. The power FREDFETs feature ultra-soft, fast recovery diodes ideally suited for hard switched inverter drives. Both drivers are fully self-supplied eliminating the need for an external power supply for the design. Integrated on the board is the LinkSwitch-TN2 (LNK3202D) in a buck converter configuration used to provide power to the motor control chip. The inverter board operates without using external heat sinks.

4.1 Input and Output Terminals

The high-voltage DC input connects to the input terminals J1 and the power ground to J2 terminal. Terminal J3 provides the input for the voltage control speed input. Output pulse signal proportional to the motor speed is provided through J4 terminal.

4.2 Decoupling Capacitors and Input Protection

The input stage provides local decoupling of the rectified AC mains through capacitor C23. A film capacitor was chosen because it offers high temperature capacity, excellent stability and higher reliability against mechanical vibrations from the motor operation. Resistor R10 provides a low cost protection mechanism for any occurring abnormal high current faults in the inverter board.

4.3 LinkSwitch-TN2 (LNK3202D) IC Supply Stage

The LNK3202D IC tapped to the high-voltage input in a non-isolated buck configuration powers the motor control chip PT2505 at +24 V. LinkSwitch-TN2 integrates a 725 V power MOSFET and control circuitry into a single low cost IC. The device is self-starting from the DRAIN (D) pin with local supply decoupling provided by capacitor C3 connected to the BYPASS (BP) pin. During normal operation, the device is powered from output via a current limiting resistor R1. Output rectification is provided by L1 and C4 with D2 as freewheeling diode. The voltage across L1 is rectified and smoothed by D1 and C2. Feedback is provided by R1 and R2 and connected to the FB pin to provide the nominal output voltage of 24 V. Resistor R26 is placed across the output as a pre-load resistor.

4.4 PT2505 Controller Stage

4.4.1 Power Supply and Decoupling Capacitors

The power is provided to the motor control chip from the output of LNK3202D buck circuit. Bypass capacitor C10 is placed close to the VDD pin for decoupling to improve chip performance. C9 and C19 provides decoupling to the +5 V LDO output pin (VREG) and +7.5 V OTP programming pin (VPP) respectively.
4.4.2 Speed Control Interface
IC PT2505 has I^2C, external DC and PWM control input to change the motor speed via VSP pin. In this application DC voltage input (V_\text{SP}) is used. The control parameter setting and V_\text{SP} range (V_{\text{SP_MAX}} and V_{\text{SP_MIN}}) are controlled via register settings. Diodes D3 and D4 in series are optional which is used to achieve a 2.1 V V_{\text{SP_MIN}}. VR1 provides the clamping action when V_\text{SP} exceeds maximum setting with R23 as the current limiting resistor.

4.4.3 Hall Sensor Interface
IC PT2505 supports two hall configurations (hall element or hall sensor IC) at 60 degrees or 120 degrees electrical spacing. This application example uses three hall elements (U5, U6, U7) at 120 degrees electrical spacing selected through a register internal setting. Capacitor C12 provides decoupling of the hall bias supply (HB) while C13, C14, and C15 provide high frequency bypass for each hall element output to the IC input pins respectively.

4.4.4 Pulse Output for Speed Information
Output pin FG provides revolution pulse output proportional to the motor speed. Q1, C18, and R17 provide an interface to the FG terminal output, which is to be connected to an external pull up supply. Resistor R17 limits the sinking current to the FG pin <5 mA. Acceptable pullup voltage range is 5 V to 15 V. Pulse output and speed relation can be set through registers internal setting.

4.4.5 PWM Output
The respective high-side and low-side PWM outputs UH, VH, WH, UL, VL, WL connect to each BridgeSwitch devices INH and INL pins controlling the high-side and low-side FREDFET switching state to commutate the motor.

4.4.6 System Overvoltage and Undervoltage Protection
The system over/under voltage protection is achieved through voltage sensing of the ROVP pin. Any voltage over the OV and under UV threshold will stop the motor operation. OC PT2505 supports multi-level undervoltage thresholds to achieve different operation range through register internal settings.

4.4.7 System and Internal Over-current Protection
The PT2505 has a two-level current protection function via sensed voltage on the RF pin (V_{RF}). In this design example, the instantaneous phase current information (IPH) - internal feature of each BridgeSwitch device was used to provide a reference voltage V_{RF} - that represents the instantaneous motor current. Resistor R19 provides the IPH output voltage scaling with its output fed to a low pass filter through R18 and C17. V_{OCPL} threshold will result to a PWM duty cycle reduction until V_{RF} is less that V_{OCPL} while V_{OCPH} threshold will result to PWM turnoff and the motor will go in lock on protection. These threshold settings can be configured via controller register settings.
Internal programmable overcurrent protection on both high-side and low-side FREDFET of BridgeSwitch provides an independent, hardware based level over-current protection in case of any abnormal condition such a motor winding short, stalled motor and phase disconnection.

4.4.8 System Over-temperature Protection
The PT2505 supports external or internal over-temperature protection through register internal settings. This application utilizes the external over-temperature protection using an NTC thermistor (RT1) in a resistor divider configuration with R14.

4.4.9 PTC BLDC UI Kit Interface
The on-board terminals SDA, SCL, VPP, FG’ and GND provide the interface to the PTC BLDC UI Kit connected to PC via USB interface enabling the use PTC Graphical User Interface (GUI). It allows performing various actions such as registers parameter modification, registers parameter reading, OTP parameter reading and burning, motor instant control and status display. This capability offers the control flexibility for different application requirement using the same type of motor.

4.5 Three-phase Inverter Stage
The three BridgeSwitch devices U1, U3, and U8 form the 3-phase inverter. The outputs of the inverter connect to each phase of the motor respectively.

4.5.1 Self-Supply Operation
Capacitors C5, C11, and C22 provide self-supply decoupling for the integrated low-side controller and gate driver. Internal high-voltage current sources recharge them as soon as the voltage level starts to dip. Capacitors C1, C6, and C16 provide self-supply decoupling for the integrated high-side controller and gate driver. Internal high-voltage current sources recharge them whenever the half-bridge point of the respective device drops to the low-side Source voltage level (i.e. the low-side FREDFET turns on).

4.5.2 PWM Input
Input signals UH, UL, VH, VL, WH, and WL control the switching state of the integrated high side and low side power FREDFETs. Series gate resistors R5, R6, R13, R15, R21 and R22 are placed to maintain the PWM outputs signal integrity.

4.5.3 Local Decoupling Capacitor
Capacitor C7 provide decoupling of the high-voltage DC bus local to BridgeSwitch devices U1, U3, and U8. Capacitor C7 provides a local decoupling on the inverter circuit to help reducing the induced negative voltage spikes on the half-bridge due to parasitic inductances.
4.5.4 Cycle-by-Cycle Current Limit
Resistors R7, R16, R24, R4, R12, and R20 set the cycle-by-cycle current limit level for the integrated low-side and high-side power FREDFETs. The selected value of 44.2 kΩ sets it to 100% of the default level or 0.7 A.

4.5.5 Instantaneous Phase Current Information
Each BRD1260C provides instantaneous phase current information through its IPH output tied together across resistor R19. The voltage across R19 is fed to a low pass filter then to the controller current limit voltage sense (RF) pin to provide the over-current protection mechanism. The device IPH current gain is 400 μA/A.
5 Printed Circuit Board Layout

Figure 4 – Printed Circuit Board Layout Top and Bottom View.
# 6 Bill of Materials

<table>
<thead>
<tr>
<th>Item</th>
<th>Qty</th>
<th>Ref Des</th>
<th>Description</th>
<th>Mfg Part Number</th>
<th>Mfg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>R10</td>
<td>RES, 0.22 Ω, 5%, 1/4 W, Thick Film, 1206</td>
<td>EJ88QR1J22U</td>
<td>Panasonic</td>
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<tr>
<td>2</td>
<td>1</td>
<td>R8</td>
<td>RES, 1 MΩ, 5%, 1/4 W, Thick Film, 1206</td>
<td>ERJ-8GEYJ105 V</td>
<td>Panasonic</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>R9</td>
<td>RES, 1 MΩ, 5%, 1/4 W, Thick Film, 1206</td>
<td>ERJ-8GEYJ105 V</td>
<td>Panasonic</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>C13, C14, C15</td>
<td>1 nF, 25 V, Ceramic, X7R, 0603</td>
<td>GRM188R71E010K010D</td>
<td>Murata</td>
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<tr>
<td>5</td>
<td>5</td>
<td>C5, C10, C11, C17, C22</td>
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<td>C1608X7R1V105M</td>
<td>TDK</td>
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<td>6</td>
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<td>C18</td>
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<td>10 μF, 10%, 50V, Ceramic, X7R, 1206</td>
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<td>R17</td>
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<td>Panasonic</td>
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<td>11</td>
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<td>RT1</td>
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<td>Murata</td>
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<td>C3, C9, C12, C19, C20</td>
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<td>Nippon Chemi-Con</td>
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<td>D3, D4</td>
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<td>I1H418W RHG</td>
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<td>Yageo</td>
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<td>RES, 2.49 kΩ, 1%, 1/8 W, Thick Film, 0805</td>
<td>ERJ-6NF2491V</td>
<td>Panasonic</td>
</tr>
<tr>
<td>22</td>
<td>1</td>
<td>C7</td>
<td>220 nF, 500 V, Ceramic, X7R, 1812</td>
<td>CI812C24KCRACTU</td>
<td>Kemet</td>
</tr>
<tr>
<td>23</td>
<td>1</td>
<td>R2</td>
<td>RES, 25.5 kΩ, 1%, 1/16 W, Thick Film, 0603</td>
<td>ERJ-3KF2552V</td>
<td>Panasonic</td>
</tr>
<tr>
<td>24</td>
<td>1</td>
<td>R14</td>
<td>RES, 32.4 kΩ, 1%, 1/8 W, Thick Film, 0805</td>
<td>ERJ-6NF3242V</td>
<td>Panasonic</td>
</tr>
<tr>
<td>25</td>
<td>1</td>
<td>R18</td>
<td>RES, 4.7 kΩ, 5%, 1/10 W, Thick Film, 0603</td>
<td>ERJ-3GEYJ4R7V</td>
<td>Panasonic</td>
</tr>
<tr>
<td>26</td>
<td>3</td>
<td>C1, C6, C16</td>
<td>4.7 μF, ±10%, 25 V, Ceramic, X7R, 1206</td>
<td>GCM31CR71E475KA55L</td>
<td>Murata</td>
</tr>
<tr>
<td>27</td>
<td>6</td>
<td>R4, R7, R12, R16, R20, R24</td>
<td>RES, 44.2 kΩ, 1%, 1/16 W, Thick Film, 0603</td>
<td>ERJ-3KF4422V</td>
<td>Panasonic</td>
</tr>
<tr>
<td>28</td>
<td>1</td>
<td>L1</td>
<td>680 μH, ±20%, Shielded, Wire wound, 165 mA, 3.77  Ω</td>
<td>PA4300.684NLT</td>
<td>Pulse</td>
</tr>
<tr>
<td>29</td>
<td>1</td>
<td>R26</td>
<td>RES, 8.06 kΩ, 1%, 1/8 W, Thick Film, 0805</td>
<td>ERJ-6ENF8061V</td>
<td>Panasonic</td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>R1</td>
<td>RES, 91 kΩ, 5%, 1/8 W, Thick Film, 0805</td>
<td>ERJ-6GEYJ913V</td>
<td>Panasonic</td>
</tr>
<tr>
<td>31</td>
<td>5</td>
<td>TP1, TP2, TP3, TP4, TP5</td>
<td>Test Point, BLK, Miniature THRU-HOLE MOUNT</td>
<td>5001</td>
<td>Keystone</td>
</tr>
<tr>
<td>32</td>
<td>3</td>
<td>U1, U3, U8</td>
<td>BridgeSwitch, Full Featured, Max. BLDC Motor Current 0.7 A (RMS)</td>
<td>BRD1260C</td>
<td>Power Integrations</td>
</tr>
<tr>
<td>33</td>
<td>1</td>
<td>D2</td>
<td>600 V, 1 A, Glass Passivated, DO-214AC</td>
<td>CD214A-F1600</td>
<td>Bourns</td>
</tr>
<tr>
<td>34</td>
<td>4</td>
<td>J1, J2, J3, J4</td>
<td>Flying Lead, Hole size 70mils</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>35</td>
<td>3</td>
<td>U5, U6, U7</td>
<td>IC, Hall Effect Sensor, Single Axis, Linear, Analog 4-409</td>
<td>HW101A</td>
<td>AKM Semi</td>
</tr>
<tr>
<td>36</td>
<td>1</td>
<td>U2</td>
<td>LinkSwitch-TN2, LNK3202D, SO-8C</td>
<td>LNK3202D</td>
<td>Power Integrations</td>
</tr>
<tr>
<td>37</td>
<td>1</td>
<td>Q1</td>
<td>NPN, Small Signal BJT, GP, 40V, 600 mA, 250 MHz, 300 mW, SOT-23</td>
<td>MMBT4401L3G</td>
<td>On Semi</td>
</tr>
<tr>
<td>38</td>
<td>1</td>
<td>VR1</td>
<td>DIODE ZENER 5.6V 500MW SOD123</td>
<td>MMSZ5232B-7-F</td>
<td>Diodes, Inc.</td>
</tr>
<tr>
<td>39</td>
<td>1</td>
<td>U4</td>
<td>IC, DC motor control, 3 phase, hall sensor, sinusoidal, brushless DC</td>
<td>PT2505</td>
<td>Princeton</td>
</tr>
<tr>
<td>40</td>
<td>1</td>
<td>D1</td>
<td>600 V, 1 A, Standard Recovery, SMA</td>
<td>S1J13-F</td>
<td>Diodes, Inc.</td>
</tr>
</tbody>
</table>

**Table 2 – Bill of Materials.**
7  **Performance Data**

This section presents waveform plots and performance data gathered on the DER-749. The HV bus voltage level is 310 VDC unless stated otherwise. A 400V 120 µF bulk capacitor is placed at the HV bus input. All measurements were performed at room ambient temperature.

7.1  **Start-up Operation**

Figure 5 and 6 shows the motor start-up waveforms at no load and 0.1 N-m load respectively. Proper power up sequence follows applying a high-voltage dc input first then the speed input voltage (V\(_{SP}\)). Typically, motor will start at 2.1 V \(V_{SP}\) voltage.

At motor start-up, the initial position is known according to the Hall sensors outputs. The controller uses 6-step control commutation before entering normal state with sinusoidal commutation as depicted in the following waveform plots.

The maximum start-up torque can be changed by modifying the start-up maximum duty to suit different motor application. The profile can be set from the PTC GUI parameter settings. In this design example, the driver is configured to allow the motor to start up to 0.1 N-m load.

![Waveform plots](image)

**Figure 5** – Start-Up at No Load.
First: \(I_{MOTOR (PHASE U)}\), 500 mA / div.
Second: \(V_{INL (PHASE U)}\), 5 V / div.
Third: \(V_{INH (PHASE U)}\), 5 V / div.
Fourth: \(V_{DS-LS (PHASE U)}\), 200 V / div., 20 ms / div.
Figure 6 — Start-Up at 0.1 N-m Load.
First: $I_{\text{MOTOR (PHASE U)}}$, 500 mA / div.
Second: $V_{\text{INL (PHASE U)}}$, 5 V / div.
Third: $V_{\text{UNH (PHASE U)}}$, 5 V / div.
Fourth: $V_{\text{DS-LS (PHASE U)}}$, 200 V / div., 20 ms / div.
7.2 **Steady-State Operation**

7.2.1 Steady-State Waveforms at 0.1 N-m Load

![Steady-State Waveforms at 0.1 N-m Load, 1500 RPM.](image)

**Figure 7** — Steady-State Waveforms at 0.1 N-m Load, 1500 RPM.

- First: $I_{MOTOR}$ (PHASE V), 500 mA / div.
- Second: $V_{INL}$ (PHASE V), 5 V / div.
- Third: $V_{INH}$ (PHASE V), 5 V / div.
- Fourth: $V_{DS-LS}$ (PHASE V), 200 V / div., 5 ms / div.
Figure 8 – Steady State Waveforms at 0.1 N-m load, 2000 RPM.
First: $I_{\text{MOTOR (PHASE V)}}$, 500 mA / div.
Second: $V_{\text{INL (PHASE V)}}$, 5 V / div.
Third: $V_{\text{INH (PHASE V)}}$, 5 V / div.
Fourth: $V_{\text{DS-LS (PHASE V)}}$, 200 V / div., 5 ms / div.

7.2.2 Steady-State Waveforms at 0.2 N-m Load

Figure 9 – Steady-State Waveforms at 0.2 N-m Load, 1500 RPM.
First: $I_{\text{MOTOR (PHASE V)}}$, 500 mA / div.
Second: $V_{\text{INL (PHASE V)}}$, 5 V / div.
Third: $V_{\text{INH (PHASE V)}}$, 5 V / div.
Fourth: $V_{\text{DS-LS (PHASE V)}}$, 200 V / div., 5 ms / div.
Figure 10 – Steady-State Waveforms at 0.1 N-m Load, 2000 RPM.

First: $I_{MOTOR} (PHASE \ V)$, 500 mA / div.
Second: $V_{INL} (PHASE \ V)$, 5 V / div.
Third: $V_{INH} (PHASE \ V)$, 5 V / div.
Fourth: $V_{DS-LS} (PHASE \ V)$, 200 V / div., 5 ms / div.
7.2.3 Speed Pulse Output
The motor speed monitor is provided from the FG output terminal (J4) as a logic level pulse frequency. FG should connect to an external pull-up supply with range from 5 V to 15 V. In this design example, FG output frequency is set from the register to be 3 times the electrical speed/frequency (FG = 3* F Hz). Motor actual speed can be calculated given FG output frequency as speed (RPM) = FG Hz * 5.

Figure 11 to 13 depicts the FG output at 1500 RPM and 2000 RPM for 0.1 N-m and 0.2 N-load torque respectively. FG terminal is connected to +5 V external pull-up with 10 kΩ resistor.

Figure 11 – Speed Pulse Output at 0.1 N-m Load, 1500 RPM.
First: VFG, 2 V / div.
Second: IMOTOR (PHASE V), 500 mA / div.
Third: IMOTOR (PHASE W), 500 mA / div., 5 ms / div.
FG Output Frequency: 301.8 Hz.
Figure 12 – Speed Pulse Output at 0.1 N·m Load, 2000 RPM.
First: $V_{FG}$, 2V / div.
Second: $I_{MOTOR (PHASE V)}$, 500 mA / div.
Third: $I_{MOTOR (PHASE W)}$, 500 mA / div., 5 ms / div.
FG Output Frequency: 402.2 Hz.

Figure 13 – Speed Pulse Output at 0.2 N·m Load, 1500 RPM.
First: $V_{FG}$, 2V / div.
Second: $I_{MOTOR (PHASE V)}$, 500 mA / div.
Third: $I_{MOTOR (PHASE W)}$, 500 mA / div., 5 ms / div.
FG Output Frequency: 302.3 Hz.
Figure 14 – Speed Pulse Output at 0.1 N-m Load, 2000 RPM.
First: V_{FG}, 2V / div.
Second: I_{MOTOR (PHASE V)}, 500 mA / div.
Third: I_{MOTOR (PHASE W)}, 500 mA / div., 5 ms / div.
FG Output Frequency: 401.5 Hz.
7.2.4 Motor Speed Profile

PT2505 offers I²C, external DC and PWM input control to change the motor speed. In this design example, the motor speed is controlled through external DC input on the VSP terminal input (J3). For external DC input speed control, VSP range can be set through register settings as well as the maximum speed setting. In this design example, the motor speed is limited to ~2400 RPM.

Figure 15 depicts the motor speed profile vs. VSP voltage \(V_{SP}\) at 0.1 N-m and 0.2 N-m load respectively.

![Motor Speed Profile](image)

**Figure 15** – Motor Speed Profile.
7.3 Thermal Performance

Figure 16 and Figure 17 depict the open case on-board thermal scan of BridgeSwitch devices (U1, U3, U8) and the motor control chip (U1) after 30 minutes of operation running at 1500 RPM at 0.1 N-m and 0.2 N-m load respectively at ~26 ºC ambient temperature.

Figure 16 – Thermal Scan at 0.1 N-m Load.

Figure 17 – Thermal Scan at 0.2 N-m Load.
7.4  **No-Load Power Consumption**

Figure 18 depicts the BridgeSwitch inverter and the system (inverter including the LinkSwitch-TN2 auxiliary and PT2505 controller circuit) no-load input power consumption measured across the input line voltage.

![Graph of No-Load Input Power](image)

*Figure 18 – No-Load Input Power.*
7.5 Efficiency

Figure 19 and Figure 20 depict the inverter efficiency at 310 V input voltage at torque loads of 0.1 N-m and 0.2 N-m versus motor speed and output power respectively.

The inverter efficiency denotes inverter stage efficiency only. It does not include the power consumption from the LinkSwitch-TN2 auxiliary supply circuit.

![Inverter Efficiency vs. Speed](chart.png)

**Figure 19** – Inverter Efficiency vs. Speed.
Figure 20 – Inverter Efficiency vs Output Power
Table 3 and 4 shows the data from the efficiency graph described.

<table>
<thead>
<tr>
<th>Input DC Voltage (V)</th>
<th>Speed (RPM)</th>
<th>DC Input Power (W)</th>
<th>Motor RMS Current Phase U (A)</th>
<th>Motor RMS Current Phase V (A)</th>
<th>Motor RMS Current Phase W (A)</th>
<th>Inverter Output Power (W)</th>
<th>Inverter Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>311</td>
<td>1500</td>
<td>0.1457</td>
<td>0.1470</td>
<td>0.1451</td>
<td>0.1457</td>
<td>18.28</td>
<td>89.5</td>
</tr>
<tr>
<td>311</td>
<td>2000</td>
<td>0.1556</td>
<td>0.1571</td>
<td>0.1551</td>
<td>0.1556</td>
<td>23.75</td>
<td>91.3</td>
</tr>
<tr>
<td>311</td>
<td>2250</td>
<td>0.1599</td>
<td>0.1619</td>
<td>0.1595</td>
<td>0.1599</td>
<td>26.23</td>
<td>91.9</td>
</tr>
<tr>
<td>311</td>
<td>2400</td>
<td>0.1624</td>
<td>0.1644</td>
<td>0.1619</td>
<td>0.1624</td>
<td>27.56</td>
<td>92.2</td>
</tr>
</tbody>
</table>

Table 3 – Efficiency Table at 0.1 m load.

<table>
<thead>
<tr>
<th>Input DC Voltage (V)</th>
<th>Speed (RPM)</th>
<th>DC Input Power (W)</th>
<th>Motor RMS Current Phase U (A)</th>
<th>Motor RMS Current Phase V (A)</th>
<th>Motor RMS Current Phase W (A)</th>
<th>Inverter Output Power (W)</th>
<th>Inverter Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>311</td>
<td>1500</td>
<td>44.4390</td>
<td>0.2110</td>
<td>0.2120</td>
<td>0.2100</td>
<td>41.39</td>
<td>93.1</td>
</tr>
<tr>
<td>311</td>
<td>2000</td>
<td>55.0640</td>
<td>0.2064</td>
<td>0.2080</td>
<td>0.2054</td>
<td>52.05</td>
<td>94.5</td>
</tr>
<tr>
<td>311</td>
<td>2250</td>
<td>59.6040</td>
<td>0.2044</td>
<td>0.2059</td>
<td>0.2034</td>
<td>56.60</td>
<td>95.0</td>
</tr>
<tr>
<td>311</td>
<td>2400</td>
<td>63.1350</td>
<td>0.2049</td>
<td>0.2069</td>
<td>0.2039</td>
<td>60.11</td>
<td>95.2</td>
</tr>
</tbody>
</table>

Table 4 – Efficiency Table at 0.2 m load.
7.6 **System Level Protection**
This section demonstrates the system-level protection features on the inverter driver. Protection related parameters described can be configured using the PTC GUI software.

7.6.1 Over-current Protection
The system-level over-current protection is achieved using PT2505 two-stage over-current protection (OCPL and OCPH). The motor current information is sensed from the composite IPH signal provided by the three BridgeSwitch devices via R19. When the voltage \( V_{RF} \) on the sense resistor reaches \( V_{OCPL} \), OCPL condition will be triggered. At this time, the controller will reduce the PWM duty cycle until \( V_{RF} \) is less than \( V_{OCPL} \). The driver is configured by reducing PWM duty cycle by 25% when the current reaches ~0.47 A. Figure 21 depicts the OCPL condition.

![OCPL Condition PWM Duty Reduced to 25%](image)

**Figure 21** – OCPL Condition PWM Duty Reduced to 25%.
First: \( V_{INL} \), 5 V / div.
Second: \( V_{INH} \), 5 V / div.
Third: \( I_{MOTOR} \) (PHASE V), 500 mA / div.
Fourth: \( V_{RF} \), 200 mV / div., 10 ms / div.
When $V_{RF}$ exceeds the $V_{OCPH}$, OCPH condition will be triggered and the PWM will turn off immediately and will go into lock mode. Lock mode protection means the controller will wait a certain period and re-start again (period and re-start times are set through register internal parameters) and the exception number counter will plus one. If the motor remained to be locked and the counter exceeds the max exception setting, it would cause system to go into deadlock status. The system will no longer start at this state and a power cycle is required to restart the system. Figure 22 and Figure 23 shows the PWM turn off and restart condition during OCPH condition ~0.5 A motor current.

**Figure 22 – OCPH Condition PWM Turn Off**

First: $V_{INL}$, 5 V / div.
Second: $V_{UNH}$, 5 V / div.
Third: $I_{MOTOR}$ (PHASE V), 500 mA / div.
Fourth: $V_{RF}$, 200 mV / div., 10 ms / div.
Figure 23 – Retry during OCPH Condition.
First: \( V_{\text{INL}} \), 5 V / div.
Second: \( V_{\text{INH}} \), 5 V / div.
Third: \( I_{\text{MOTOR (PHASE V)}} \), 500 mA / div.
Fourth: \( V_{RF} \), 200 mV / div., 10 ms / div.
7.6.2 Over/Undervoltage Protection

The system overvoltage and undervoltage protection is achieved using external voltage divider (R8, R9, R11) connected to the chip ROVP pin of PT2505. When ROVP voltage is greater than $V_{\text{PRTH}}$ (3.5 V - overvoltage threshold) or less than $V_{\text{PRTL}}$ (undervoltage threshold – set through register internal settings) it will enter over/undervoltage protection and the PWM will turn off until the fault is removed.

Figure 24 depicts the overvoltage condition at ~390 V.

![Figure 24 – Overvoltage Condition PWM Turn Off.](image)

- First: $V_{\text{HV BUS}}$, 50 V / div.
- Second: $V_{\text{ROVP}}$, 500 mV / div.
- Third: $V_{\text{INL}}$, 5 V / div.
- Fourth: $V_{\text{VINL}}$, 5 V / div.
- Fifth: $I_{\text{MOTOR (PHASE U)}}$, 500 mA / div., 1 s / div.
Figure 25 depicts the restart after the overvoltage condition is removed. Figure 26 and 27 depicts the undervoltage protection and restart respectively. Undervoltage protection is set at ~240 V.

**Figure 25 — Restart after Overvoltage Condition is Removed.**
- First: $V_{HV\ BUS}$, 50 V / div.
- Second: $V_{ROVP}$, 500 mV / div.
- Third: $V_{INL}$, 5 V / div.
- Fourth: $V_{INL}$, 5 V / div.
- Fifth: $I_{MOTOR}$ (PHASE U), 500 mA / div., 1 s / div.

**Figure 26 — Undervoltage Condition PWM Turn Off.**
- First: $V_{HV\ BUS}$, 50 V / div.
- Second: $V_{ROVP}$, 500 mV / div.
- Third: $V_{INL}$, 5 V / div.
- Fourth: $V_{INL}$, 5 V / div.
- Fifth: $I_{MOTOR}$ (PHASE U), 500 mA / div., 1 s / div.
Figure 27 – Restart after Undervoltage Condition is Removed.
First: $V_{HV\ BUS}$, 50 V / div.
Second: $V_{ROVP}$, 500 mV / div.
Third: $V_{INL}$, 5 V / div.
Fourth: $V_{UNL}$, 5 V / div.
Fifth: $I_{MOTOR\ (PHASE\ U)}$, 500 mA / div., 1 s / div.
7.6.3 System Over-temperature Protection

The system over-temperature is achieved by using an external NTC temperature-sensing resistor (RT1) connected to RTSD pin of PT2505 in series with R14. Over-temperature protection will be triggered when the $V_{\text{RTSD}}$ drops to the lower reference ($V_{\text{REFL}}$) voltage 1.2 V then it will be released once $V_{\text{RTSD}}$ is greater than the higher reference ($V_{\text{REFH}}$) 2.6 V.

In this design example, the inverter board will trigger over-temperature protection around 95 ºC and will restart around 45 ºC ambient temperature.

Figure 28 and 29 depicts the over-temperature condition and restart after the over-temperature condition respectively.

![Figure 28 – Over-temperature Condition PWM Turn Off.](image)

First: $V_{\text{INL}}$, 5 V / div
Second: $V_{\text{INL}}$, 5 V / div.
Third: $I_{\text{MOTOR (PHASE U)}}$, 500 mA / div.
Fourth: $V_{\text{RTSD}}$, 1 V / div., 1 s / div.
Figure 29 – Restart after Over-temperature Condition

First: $V_{INL}$, 5 V / div
Second: $V_{UNL}$, 5 V / div.
Third: $I_{MOTOR (PHASE U)}$, 500 mA / div.
Fourth: $V_{RTSD}$, 1 V / div., 1 s / div.
8 Appendix

8.1 Inverter Circuit Board Manual

Figure 30 shows locations and functions of all connectors to and from the inverter board.

Figure 30 – DER-749 Connections (Top View).
The high-voltage DC bus connects to the inverter through two through-hole mount terminal points, J1 and J2. The positive input terminal should connect to J1, and the negative input terminal should connect to J2.

Speed control input signal (VSP) connects to terminal J3 and speed output monitor (FG) connect to the terminal J4. Programming interface to the PTC BLDC UI Kit connects to TP1, TP2, TP3, TP4 and TP5 respectively. Motor phase winding connects to Phase U, Phase V and Phase W terminals. See Table 5 for each pin connection description.

Table 5 lists the input and output signals and programming interface connections on the inverter board.

<table>
<thead>
<tr>
<th>Pin No.</th>
<th>Signal</th>
<th>Type</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HV*</td>
<td>Input</td>
<td>High-voltage bus input supply (310Vdc typical)</td>
</tr>
<tr>
<td>2</td>
<td>GND</td>
<td>n/a</td>
<td>Power ground connection</td>
</tr>
<tr>
<td>3</td>
<td>VSP</td>
<td>Input</td>
<td>DC input speed control voltage (2.1 V – 5.4 V)</td>
</tr>
<tr>
<td>4</td>
<td>FG</td>
<td>Output</td>
<td>Pulse output monitor for rotation speed information. Should pull-up to external supply (5 V – 15 V)</td>
</tr>
<tr>
<td>5</td>
<td>GND</td>
<td>n/a</td>
<td>Signal ground connection</td>
</tr>
<tr>
<td>6</td>
<td>SDA</td>
<td>Input/Output</td>
<td>Serial data I²C control interface</td>
</tr>
<tr>
<td>7</td>
<td>FG’</td>
<td>Input</td>
<td>Input for system clock trimming</td>
</tr>
<tr>
<td>8</td>
<td>SCL</td>
<td>Input</td>
<td>Serial clock input I²C interface</td>
</tr>
<tr>
<td>9</td>
<td>VPP</td>
<td>Input</td>
<td>+7.5 V for OTP programming, provided internally from PTC BLDC UI Kit</td>
</tr>
</tbody>
</table>

Table 5 – Input/Output, and Programming Interface Connector Pinout.
8.2 **Test Bench Set-up**

Figure 31 depicts the test bench used to gather the performance data presented in this report. It consists of:

- 3-phase inverter using BRD1260C with PT2505 in sinusoidal commutation logic
- 310VDC, 8 poles BLDC motor (Foshan Lepuda PLD-39-8-1)
  - Alternate motor: WZDK-38G-2 30W 310VDC 8P BLDC motor
- Electro-mechanics hysteresis brake (HB-103)
- Programmable DC input source
- Bench power supply
- Motor brake controller (ICS-2000)
8.3 **PTC BLDC UI Kit**

The PT2505 provides a BLDC User Interface (UI) Kit to work with their Graphical User Interface (GUI) software for OTP parameter settings. For complete instruction of how to use the UI Kit and parameter settings using GUI, PTC provides a detailed instruction documented in the application note. To obtain the PTC BLDC UI Kit and software, please contact PTC sales or their customer contact window.

8.3.1 **BLDC UI (I2C-to-USB) Kit**

The PTC BLDC UI Kit needs to be connected to the PC/NB via the USB interface. With the GUI software, the following actions can be performed on the PT2501/PT2502/PT2505/PT2511 and other ICs:

- Temporary parameter modification
- Register parameter reading
- OTP parameter burning
- OTP parameter reading
- Motor instant control
- Motor status display

![PTC BLDC UI Kit Connection Diagram](image)

**Figure 32** – PTC BLDC UI Kit Connection Diagram.

![PTC BLDC (USB-to-I2C) UI Kit](image)

**Figure 33** – PTC BLDC (USB-to-I2C) UI Kit.
The programming interface on the inverter connects to pin 1-to-5 respectively (SCL, SDA, VPP, GND and FCON) to achieve clock trimming, parameter write/read, motor instant control and display and one-time programming. Detailed instruction is provided in the application note.

**Figure 34 -- PTC BLDC UI Kit Pin Description.**

<table>
<thead>
<tr>
<th>Pin Name</th>
<th>Description</th>
<th>Pin No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCL</td>
<td>I2C serial frequency (internal pull-up resistor 4.7KΩ)</td>
<td>1</td>
</tr>
<tr>
<td>SDA</td>
<td>I2C serial data (internal pull-up resistor 4.7KΩ)</td>
<td>2</td>
</tr>
<tr>
<td>VPP</td>
<td>OTP recording voltage is 7.5V, Normal is 5V</td>
<td>3</td>
</tr>
<tr>
<td>GND</td>
<td>Ground</td>
<td>4</td>
</tr>
<tr>
<td>FCON</td>
<td>Connect to the “FG” pin on the motor control board</td>
<td>5</td>
</tr>
<tr>
<td>VCON</td>
<td>Calibrate VREG voltage output to +5V</td>
<td>6</td>
</tr>
<tr>
<td>3.3V</td>
<td>3.3V power supply</td>
<td>7</td>
</tr>
<tr>
<td>5V</td>
<td>5V power supply</td>
<td>8</td>
</tr>
<tr>
<td>GND</td>
<td>Ground</td>
<td>9</td>
</tr>
<tr>
<td>Button</td>
<td>Offline burn button (production use)</td>
<td>10</td>
</tr>
<tr>
<td>BTN</td>
<td>Offline burn button extension contact, external button</td>
<td>10</td>
</tr>
<tr>
<td>USB</td>
<td>USB port</td>
<td>11</td>
</tr>
<tr>
<td>LED1</td>
<td>Offline burning &quot;Failed&quot; The light is on red, the buzzer is one second long sound.</td>
<td>12</td>
</tr>
<tr>
<td>LED2</td>
<td>Offline burning &quot;success&quot; The light is on green, the buzzer sounds short.</td>
<td>13</td>
</tr>
</tbody>
</table>
8.3.2 PTC Graphical User Interface (GUI)

Figure 35 depicts the overview of PTC GUI used together with the PTC BLDC (I2C to USB) kit for control parameter settings to suit different motor applications and performance optimization. PTC provides a detailed instruction how to use the GUI documented in the application note. The parameter settings used in this design example is available and can be obtained from the applications engineering group.

![Figure 35 – PTC BLDC Graphical User Interface.](image-url)
8.4 **Inverter Output Power Measurement**

3-phase inverter output power \( P_{\text{OUT}} \) and efficiency measurements apply the “two wattmeter” method illustrated in Figure 36 below.

\[
P_{\text{OUT}} = P_{\text{CH1}} + P_{\text{CH2}}
\]

![Diagram of BridgeSwitch Inverter Drive and 3-Phase BLDC Motor](image)

**Figure 36** – Inverter Output Power Measurement.
Notes
## Revision History

<table>
<thead>
<tr>
<th>Date</th>
<th>Author</th>
<th>Revision</th>
<th>Description &amp; Changes</th>
<th>Reviewed</th>
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<tr>
<td>13-Nov-18</td>
<td>JHP</td>
<td>1.0</td>
<td>Initial Release.</td>
<td>Apps &amp; Mktg</td>
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<tr>
<td>20-Dec-18</td>
<td>JHP</td>
<td>1.1</td>
<td>Updated Schematic Figure 2 and Text.</td>
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<tr>
<td>09-Jan-19</td>
<td>JHP</td>
<td>1.2</td>
<td>Updated PCB Images.</td>
<td></td>
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</tbody>
</table>
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