

Demonstration System EPC9128 Quick Start Guide

*6.78 MHz, ZVS Class-D, 16 W Class 3
Wireless Power System*

Revision 1.0



DESCRIPTION

The EPC9128 wireless power demonstration system is a high efficiency, AirFuel™ Alliance compatible, Zero Voltage Switching (ZVS), Voltage Mode class-D wireless power transfer demonstration kit capable of delivering up to 16 W into a DC load while operating at 6.78 MHz (Lowest ISM band). The purpose of this demonstration system is to simplify the evaluation process of wireless power technology using eGaN® FETs.

The EPC9128 wireless power system is comprised of three boards (shown in figure 1):

- 1) A Source Board (Transmitter or Power Amplifier) EPC9509
- 2) A Class 3 AirFuel Alliance compliant Source Coil (Transmit Coil)
- 3) A Category 3 AirFuel Alliance compliant Receive Device EPC9513
- 4) A Category 4 AirFuel Alliance compliant Receive Device EPC9515

The amplifier board features the enhancement-mode half-bridge field effect transistor (FET), the 60 V rated EPC2108 eGaN FET with integrated synchronous bootstrap FET. The amplifier is configured for single-ended operation and includes the gate driver(s), oscillator, and feedback controller for the pre-regulator that ensures operation for wireless power control based on the AirFuel Alliance standard. This allows for testing compliant to the AirFuel class 3 standard over the entire load range of $\pm 50j \Omega$. The pre-regulator features the 100 V rated, 73 m Ω EPC2036 as the main switching device for a SEPIC converter.

The amplifier is equipped with a pre-regulator controller that adjusts the voltage supplied to the ZVS class-D amplifier based on the limits of three parameters; coil current, DC power delivered and maximum voltage. The coil current has the lowest priority followed by the power delivered with the amplifier supply voltage having the highest priority. Changes in the device load power demand, physical placement of the device on the source coil and other factors, such as metal objects in proximity to the source coil, all contribute to variations in coil current, DC power and amplifier voltage requirements. Under any conditions, the controller will ensure the correct operating conditions for the ZVS class-D amplifier based on the AirFuel Alliance standard.

The pre-regulator can be bypassed to allow testing with custom control hardware. The board further allows easy access to critical measurement nodes that allow accurate power measurement instrumentation hookup. A simplified diagram of the amplifier board is given in figure 2.

The Source and Device Coils are AirFuel Alliance compliant and have been pre-tuned to operate at 6.78 MHz with the EPC9509 amplifier. The source coil is Class 3 and the device coils are Category 3 and Category 4 compliant.

The EPC9513 (Category 3) and EPC9515 (Category 4) device boards include a high frequency Schottky diode based full-bridge rectifier, DC smoothing capacitor and 5 V regulator. The regulator is based on a SEPIC converter that features a 200 V EPC2019 eGaN FET. The power circuit is attached to the backside of the coil which is provided with a ferrite shield that prevents the circuit from shunting the coil's magnetic field.

For more information on the EPC2108, EPC2036, and EPC2019 eGaN FETs and ICs please refer to the datasheets available from EPC at www.epc-co.com. The datasheets should be read in conjunction with this quick start guide.

MECHANICAL ASSEMBLY

The assembly of the EPC9128 Wireless Demonstration kit is simple and shown in figure 1. The source coil and amplifier have been equipped with SMA connectors. The source coil is simply connected to the amplifier. The device board does not need to be mechanically attached to the source coil.

DETAILED DESCRIPTION

The Amplifier Board (EPC9509)

Figure 2 shows the system block diagram of the EPC9509 ZVS class-D amplifier with pre-regulator and figure 3 shows the details of the ZVS class-D amplifier section. The pre-regulator is used to control the ZVS class-D wireless power amplifier based on three feedback parameters 1) the magnitude of the coil current indicated by the green LED, 2) the DC power drawn by the amplifier indicated by the yellow LED and 3) a maximum supply voltage to the amplifier indicated by the red LED. Only one parameter at any time is used to control the pre-regulator with the highest priority being the maximum voltage supplied to the amplifier followed by the power delivered to the amplifier and lastly the magnitude of the coil current. The maximum amplifier supply voltage is pre-set to 52 V and the maximum power drawn by the amplifier is pre-set to 16 W. The coil current magnitude is pre-set to 8000 mA_{RMS}, but can be made adjustable using P25. The pre-regulator comprises a SEPIC converter that can operate at full power from 17 V through 24 V.

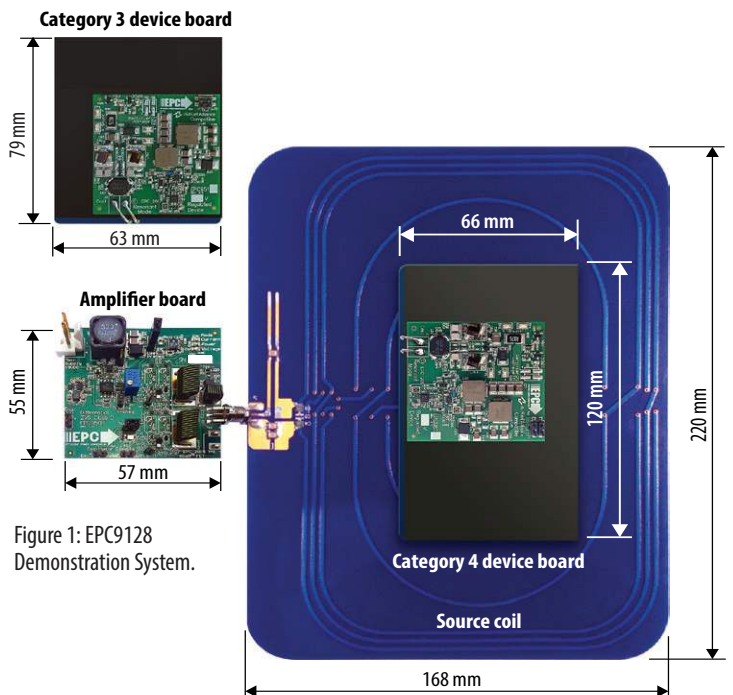


Figure 1: EPC9128 Demonstration System.

Table 1: Performance Summary (T_A = 25°C) EPC9509

| Symbol | Parameter | Conditions | Min | Max | Units |
|--------------------------|--|---|------|-----|-------|
| V _{IN} | Bus Input Voltage Range – Pre-Regulator Mode | Also used in bypass mode for logic supply | 17 | 24 | V |
| V _{IN} | Amp Input Voltage Range – Bypass Mode | | 0 | 52 | V |
| V _{OUT} | Switch Node Output Voltage | | | 52 | V |
| I _{OUT} | Switch Node Output Current (each) | | | 1* | A |
| V _{extosc} | External Oscillator Input Threshold | Input 'Low' | -0.3 | 0.8 | V |
| | | Input 'High' | 2.4 | 5 | V |
| V _{Pre_Disable} | Pre-regulator Disable Voltage Range | Floating | -0.3 | 5.5 | V |
| I _{Pre_Disable} | Pre-regulator Disable Current | Floating | -10 | 10 | mA |
| V _{Osc_Disable} | Oscillator Disable Voltage Range | Open Drain/Collector | -0.3 | 5 | V |
| I _{Osc_Disable} | Oscillator Disable Current | Open Drain/Collector | -25 | 25 | mA |
| V _{SgnDiff} | Differential or Single Select Voltage | Open Drain/Collector | -0.3 | 5.5 | V |
| I _{SgnDiff} | Differential or Single Select Current | Open Drain/Collector | -1 | 1 | mA |

*Maximum current depends on die temperature – actual maximum current will be subject to switching frequency, bus voltage and thermals.

Table 2a: Performance Summary (T_A = 25°C) EPC9513 - Category 3 Device Board

| Symbol | Parameter | Conditions | Min | Max | Units |
|--------------------------|-----------------------------|--------------------------------|------|-------|-------|
| V _{Unreg} | Un-regulated output voltage | | | 38 | V |
| I _{Unreg} | Un-regulated output current | | | 1.5* | A |
| V _{Unreg_UVLOR} | UVLO Enable | Un-regulated voltage rising | | 10.96 | V |
| V _{Unreg_UVLOF} | UVLO Disable | Un-regulated voltage falling | 5.96 | | V |
| V _{OUT} | Output Voltage Range | V _{Unreg_min} = 8.3 V | 4.8 | 5.1 | V |
| I _{OUT} | Output Current Range | V _{Unreg_min} = 8.3 V | 0 | 1* | A |

Actual maximum current subject to operating temperature limits

Table 2b: Performance Summary (T_A = 25°C) EPC9515 - Category 4 Device Board

| Symbol | Parameter | Conditions | Min | Max | Units |
|--------------------------|-----------------------------|--------------------------------|------|-------|-------|
| V _{Unreg} | Un-regulated output voltage | | | 38 | V |
| I _{Unreg} | Un-regulated output current | | | 2* | A |
| V _{Unreg_UVLOR} | UVLO Enable | Un-regulated voltage rising | | 10.96 | V |
| V _{Unreg_UVLOF} | UVLO Disable | Un-regulated voltage falling | 5.96 | | V |
| V _{OUT} | Output Voltage Range | V _{Unreg_min} = 8.3 V | 4.8 | 5.1 | V |
| I _{OUT} | Output Current Range | V _{Unreg_min} = 8.3 V | 0 | 1* | A |

Actual maximum current subject to operating temperature limits

The pre-regulator can be bypassed by connecting the positive supply directly to the ZVS class-D amplifier supply after removing the jumper at location JP1 and connecting the main positive supply to the bottom pin. JP1 can also be removed and replaced with a DC ammeter to directly measure the current drawn by the amplifier. When doing this, observe a low impedance connection to ensure continued stable operation of the controller. Together with the Kelvin voltage probes (TP1 and TP2) connected to the amplifier supply, an accurate measurement of the power drawn by the amplifier can be made.

The EPC9509 is also provided with a miniature high efficiency switch-mode 5V supply to power the logic circuits on board such as the gate drivers and oscillator.

The amplifier comes with its own low supply current oscillator that is pre-programmed to 6.78 MHz ± 678 Hz. It can be disabled by placing a jumper into JP70 or can be externally shutdown using an externally controlled open collector / drain transistor on the terminals of JP70 (note which is the ground connection). The switch needs to be capable of sinking at least 25 mA. An external oscillator can be used instead of the internal oscillator when connected to J70 (note which is the ground connection) and the jumper (JP71) is removed.

The pre-regulator can also be disabled in a similar manner as the oscillator using JP50. However, note that this connection is floating with respect to the ground so removing the jumper for external connection requires a floating switch to correctly control this function. Refer to the datasheet of the controller IC and the schematic in this QSG for specific details.

The EPC9509 is provided with three LED's that indicate the mode of operation of the system. If the system is operating in coil current limit mode, then the green LED will illuminate. For power limit mode, the yellow LED will illuminate. Finally, when the pre-regulator reaches maximum output voltage the red LED will illuminate indicating that the system is no longer AirFuel compliant as the load impedance is too high for the amplifier to drive. When the load impedance is too high to reach power limit or voltage limit mode, then the current limit LED will illuminate incorrectly indicating current limit mode. This mode also falls outside the AirFuel standard and by measuring the amplifier supply voltage across TP1 and TP2 will show that it has nearly reach the maximum value limit.

ZVS Timing Adjustment

Setting the correct time to establish ZVS transitions is critical to achieving high efficiency with the EPC9509 amplifier. This can be done by selecting the values for R71 and R72 or P71 and P72 respectively. This procedure is best performed using a potentiometer installed at the appropriate locations that is used to determine the fixed resistor values. The timing MUST initially be set WITHOUT the source coil connected to the amplifier. The timing diagrams are given in figure 10 and should be referenced when following this procedure. Only perform these steps if changes have been made to the board, as it is shipped preset. The steps are:

1. With power off, remove the jumper in JP1 and install it into JP50 to place the EPC9509 amplifier into Bypass mode. Connect the main input power supply (+) to JP1 (bottom pin – for bypass mode) with ground connected to J1 ground (-) connection.
2. With power off, connect the control input power supply bus (19V) to (+) connector J1. Note the polarity of the supply connector.
3. Connect a LOW capacitance oscilloscope probe to the probe-hole and ground post indicated in figure 9.
4. Turn on the control supply – make sure the supply is approximately 19V.
5. Turn on the main supply voltage starting at 0 V and increasing to the required predominant operating value (such as 24 V but NEVER exceed the absolute maximum voltage of 52 V).

6. While observing the oscilloscope adjust the applicable potentiometers to achieve the green waveform of figure 10.
7. Replace the potentiometers with fixed value resistors if required. Remove the jumper from JP50 and install it back into JP1 to revert the EPC9509 back to pre-regulator mode.

Determining component values for L_{ZVS}

The ZVS tank circuit is not operated at resonance, and only provides the necessary negative device current for self-commutation of the output voltage at turn off. The capacitor C_{ZVS1} is chosen to have a very small ripple voltage component and is typically around 1 μF. The amplifier supply voltage, switch-node transition time will determine the value of inductances for L_{ZVS1} and L_{ZVS2} which needs to be sufficient to maintain ZVS operation over the DC device load resistance range and coupling between the device and source coil range and can be calculated using the following equation:

$$L_{ZVS} = \frac{\Delta t_{vt}}{8 \cdot f_{sw} \cdot (C_{OSSQ} + C_{well})} \quad (1)$$

Where:

- Δt_{vt} = Voltage transition time [s]
- f_{sw} = Operating frequency [Hz]
- C_{OSSQ} = Charge equivalent device output capacitance [F].
- C_{well} = Gate driver well capacitance [F]. Use 20 pF for the LM5113

NOTE. The amplifier supply voltage V_{AMP} is absent from the equation as it is accounted for by the voltage transition time. The C_{OSS} of the EPC2108 eGaN FETs is very low and lower than the gate driver well capacitance C_{well} which as a result must be now be included in the ZVS timing calculation. The charge equivalent capacitance can be determined using the following equation:

$$C_{OSSQ} = \frac{1}{V_{AMP}} \cdot \int_0^{V_{AMP}} C_{OSS}(v) \cdot dv \quad (2)$$

To add additional immunity margin for shifts in coil impedance, the value of L_{ZVS} can be decreased to increase the current at turn off of the devices (which will increase device losses). Typical voltage transition times range from 2 ns through 12 ns.

The Source Coil

Figure 4 shows the schematic for the source coil which is Class 3 AirFuel compliant. The matching network includes both series and shunt tuning. The matching network series tuning is differential to allow balanced connection and voltage reduction for the capacitors.

The Device Boards - EPC9513 and EPC9515

Figure 5 shows the basic schematic diagram of the EPC9513 and EPC9515 device boards which comprises a tuning circuit for the device coil with a common-mode choke for EMI suppression, a high frequency rectifier and SEPIC converter based output regulator. The EPC9513 is powered using a Category 3 AirFuel Alliance compliant device coil and the EPC9515 is powered using a Category 4 AirFuel Alliance compliant device coil. Both are by default tuned to 6.78 MHz for the specific coil provided with it. The tuning circuit comprises both parallel and series tuning which is also differential to allow balanced connection and voltage reduction for the capacitors.

Two LEDs have been provided to indicate that the board is receiving power with an un-regulated voltage greater than 4 V (green LED) and the red LED will illuminate when the un-regulated voltage exceeds 36 V.

The EPC9513 and EPC9515 have limited over-voltage protection using a TVS diode that clamps the un-regulated voltage to 38 V. This can occur when the receive coil is placed above a high power transmitter with insufficient distance to the transmit coil and there is little or no load connected. During an over-voltage event, the TVS diode will dissipate a large amount of power and the red LED will illuminate indicating an over-voltage. The receiver should be removed from the transmitter as soon as possible to prevent the TVS diode from over-heating.

The EPC9513 and EPC9515 can be operated with or without the regulator. The regulator can be disabled by inserting a jumper into position JP50 and connecting the load to the unregulated output terminals. In regulated mode, the design of the EPC9513 and EPC9515 controller will ensure stable operation in a wireless power system. The regulator operates at 280 kHz and the controller features over current protection that limits the load current to 1 A for the EPC9513 and 2 A for the EPC9515.

The EPC9513 and EPC9515 device boards come equipped with Kelvin connections for easy and accurate measurement of the un-regulated and regulated output voltages. The rectified voltage current can also be measured using the included shunt resistor. In addition, the EPC9513 and EPC9515 have been provided with a switch-node measurement connection for low inductance connection to an oscilloscope probe to yield reliable waveforms.

The EPC9513 is designed to operate in conjunction with EPC9127 (10 W EPC9510), EPC9128 (16 W EPC9509), EPC9120 (33 W EPC9512) and EPC9121 (10 W EPC9511) transmitter units. The EPC9515 is designed to operate in conjunction with EPC9128 (16 W EPC9509), and EPC9120 (33 W EPC9512) transmitter units.

QUICK START PROCEDURE

The EPC9128 demonstration system is easy to set up and evaluate the performance of eGaN FETs and ICs in a wireless power transfer application. Refer to figure 1 to assemble the system and figures 6 through 8 for proper connection and measurement setup before following the testing procedures.

The EPC9509 can be operated using any one of two alternative methods:

- a. Using the pre-regulator.
- b. By-passing the pre-regulator.

a. Operation using the pre-regulator

The pre-regulator is used to supply power to the amplifier in this mode and will limit the coil current, power delivered or maximum supply voltage to the amplifier based on the pre-determined settings.

The main 19 V supply must be capable of delivering 2 A_{DC}. DO NOT turn up the voltage of this supply when instructed to power up the board, instead simply turn on the supply. The EPC9509 board includes a pre-regulator to ensure proper operation of the board including start up.

1. Make sure the entire system is fully assembled prior to making electrical connections and make sure jumper JP1 is installed. Also make sure the source coil and device coil with load are connected.
2. With power off, connect the main input power supply bus to J1 as shown in figure 6. Note the polarity of the supply connector.
3. Make sure all instrumentation is connected to the system.
4. Turn on the main supply voltage to the required value (19 V).
5. Once operation has been confirmed, observe the output voltage, efficiency and other parameters on both the amplifier and device boards.
6. For shutdown, please follow steps in the reverse order.

b. Operation bypassing the pre-regulator

In this mode, the pre-regulator is bypassed and the main power is connected directly to the amplifier. This allows the amplifier to be operated using an external regulator. In this mode there is no protection for ensuring the correct operating conditions for the eGaN FETs.

1. Make sure the entire system is fully assembled prior to making electrical connections and make sure jumper JP1 has been removed and installed in JP50 to disable the pre-regulator and place the EPC9509 in bypass mode. Also make sure the source coil and device coil with load are connected.
2. With power off, connect the main input power supply bus to the bottom pin of JP1 and the ground to the ground connection of J1 as shown in figure 6.
3. With power off, connect the control input power supply bus to J1. Note the polarity of the supply connector. This is used to power the gate drivers and logic circuits.
4. Make sure all instrumentation is connected to the system.
5. Turn on the control supply – make sure the supply is 19 V range.
6. Turn on the main supply voltage to the required value (it is recommended to start at 0 V and do not exceed the absolute maximum voltage of 52 V).

7. Once operation has been confirmed, adjust the main supply voltage within the operating range and observe the output voltage, efficiency and other parameters on both the amplifier and device boards.

8. For shutdown, please follow steps in the reverse order. Start by reducing the main supply voltage to 0 V followed by steps 6 through 2.

NOTE.

1. When measuring the high frequency content switch-node (Source Coil Voltage), care must be taken to avoid long ground leads. An oscilloscope probe connection (preferred method) has been built into the board to simplify the measurement of the Source Coil voltage (shown in figure 9).
2. AVOID using a Lab Benchtop programmable DC as the load for the category 3 device when connected to the unregulated output. These loads have low control bandwidth and will cause the EPC9128 system to oscillate at a low frequency and may lead to failure. It is recommended to use a fixed low inductance resistor as an initial load.

THERMAL CONSIDERATIONS

The EPC9128 demonstration system showcases the EPC2108, EPC2037 and EPC2019 eGaN FETs and ICs in a wireless energy transfer application. Although the electrical performance surpasses that of traditional silicon devices, their relatively smaller size does magnify the thermal management requirements. The operator must observe the temperature of the gate driver and eGaN FETs to ensure that both are operating within the thermal limits as per the datasheets.

NOTE. The EPC9128 demonstration system has limited current protection only when operating off the Pre-Regulator. When bypassing the pre-regulator there is no current protection on board and care must be exercised not to over-current or over-temperature the devices. Excessively wide coil coupling and load range variations can lead to increased losses in the devices.

Pre-Cautions

The EPC9128 demonstration system has no enhanced protection systems and therefore should be operated with caution. Some specific precautions are:

1. Never operate the EPC9128 system with a device board that is AirFuel Alliance compliant as this system does not communicate with the device to correctly setup the required operating conditions, and doing so, can lead to failure of the device board. Contact EPC should operating the system with an AirFuel compliant device be required to obtain instructions on how to do this. Please contact EPC at info@epc-co.com should the tuning of the coil be required to change to suit specific conditions so that it can be correctly adjusted for use with the ZVS class-D amplifier.
2. There is no heat sink on the devices and during experimental evaluation it is possible present conditions to the amplifier that may cause the devices to overheat. Always check operating conditions and monitor the temperature of the EPC devices using an IR camera.
3. Never connect the EPC9509 amplifier board into your VNA in an attempt to measure the output impedance of the amplifier. Doing so will severely damage the VNA

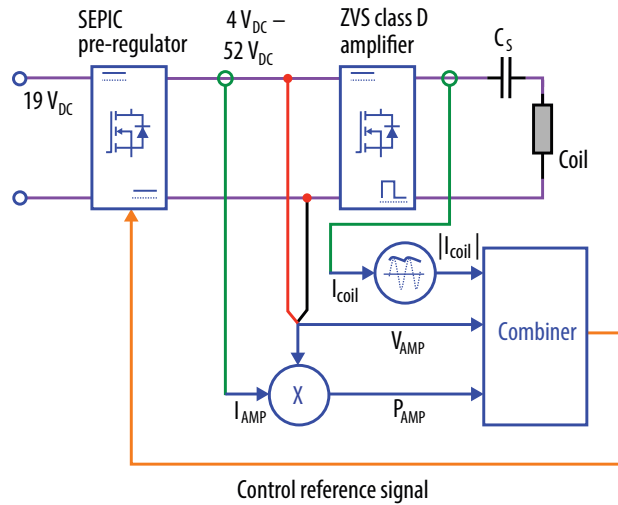


Figure 2: Block diagram of the EPC9509 wireless power amplifier.

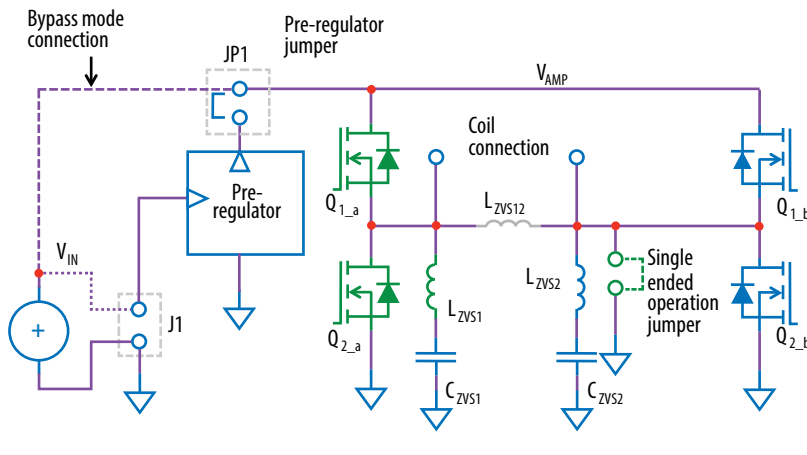


Figure 3: Diagram of EPC9509 amplifier circuit.

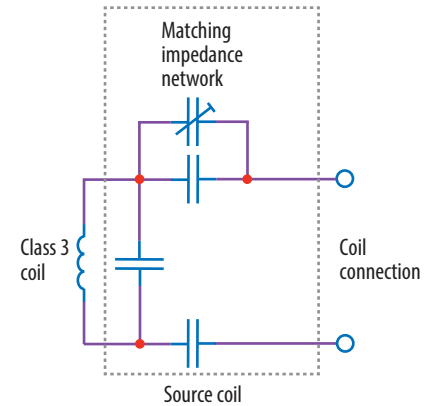


Figure 4: Basic schematic of the AirFuel Alliance Class 3 source coil.

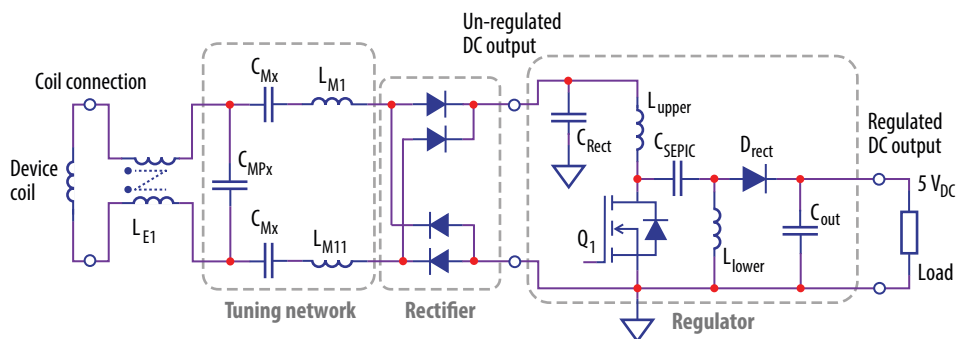


Figure 5: Schematic diagram of the EPC9513 (Category 3) and EPC9515 (Category 4), AirFuel Alliance device boards.

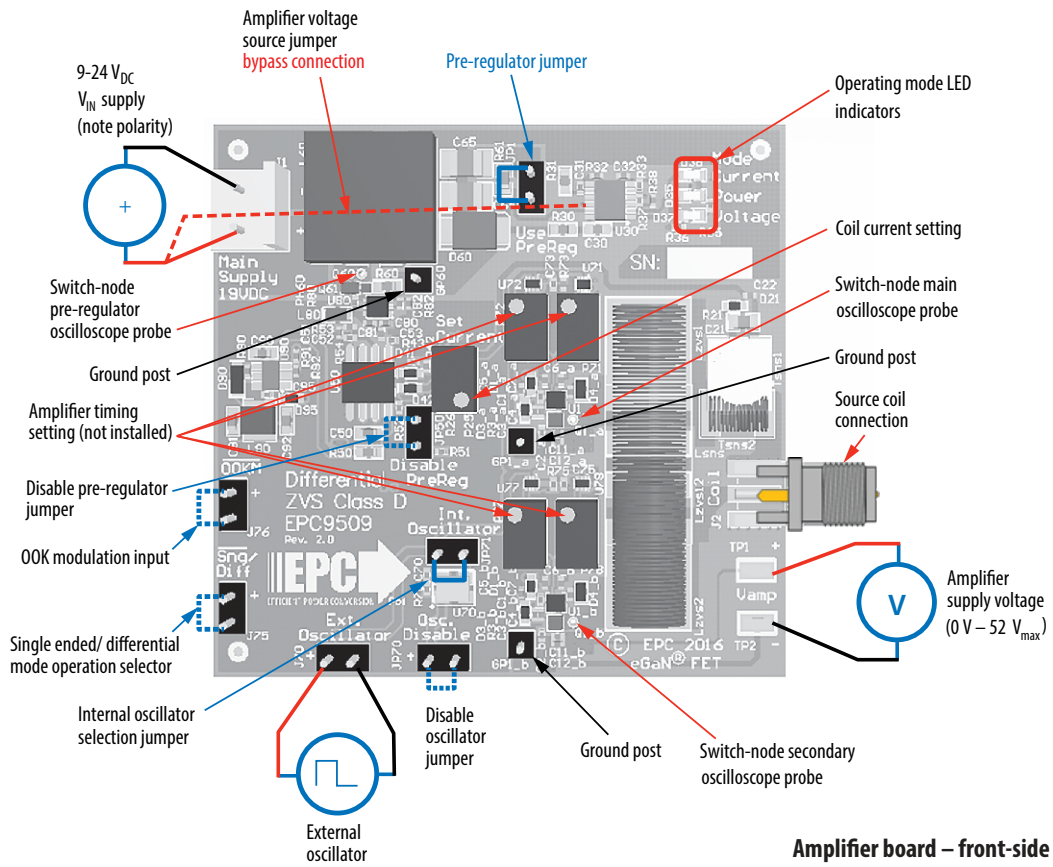


Figure 6: Proper connection and measurement setup for the amplifier board.

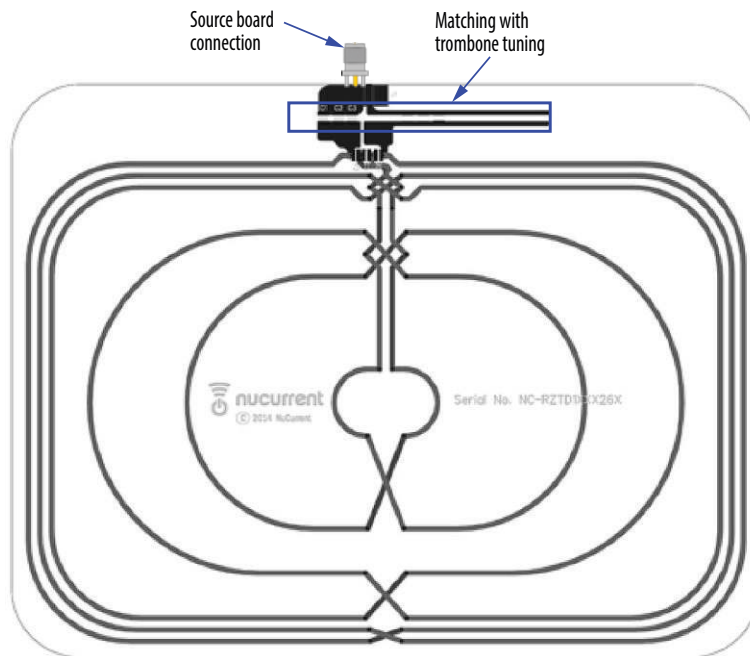


Figure 7: Proper connection for the source coil.

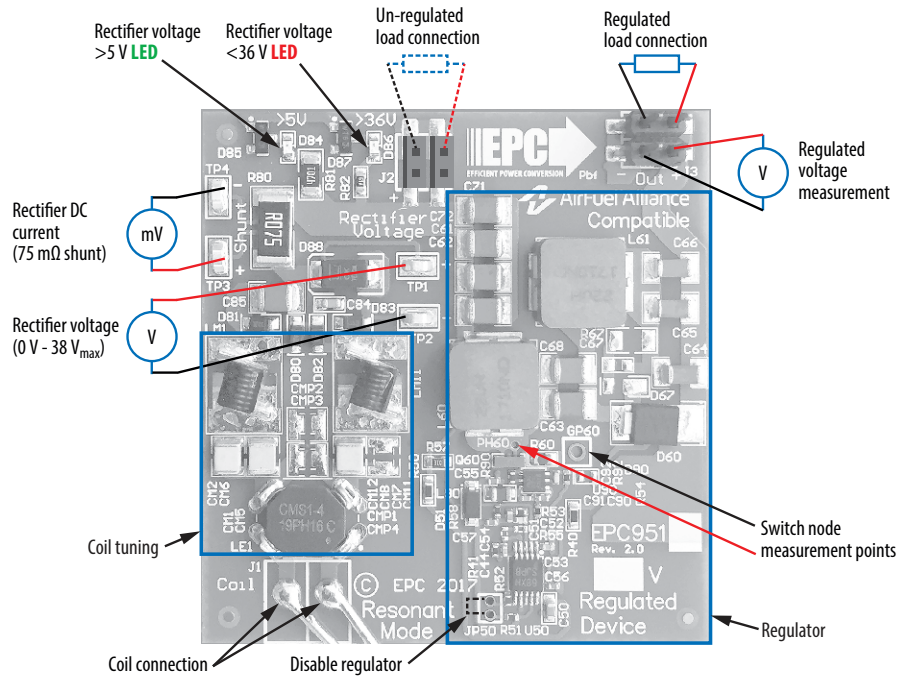


Figure 8: Proper connection and measurement setup for the receiver board.

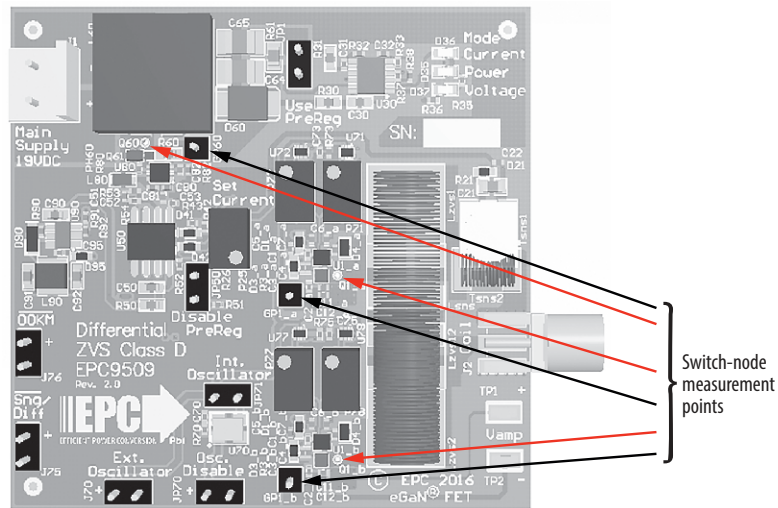


Figure 9: Proper measurement of the switch nodes using the hole and ground post.

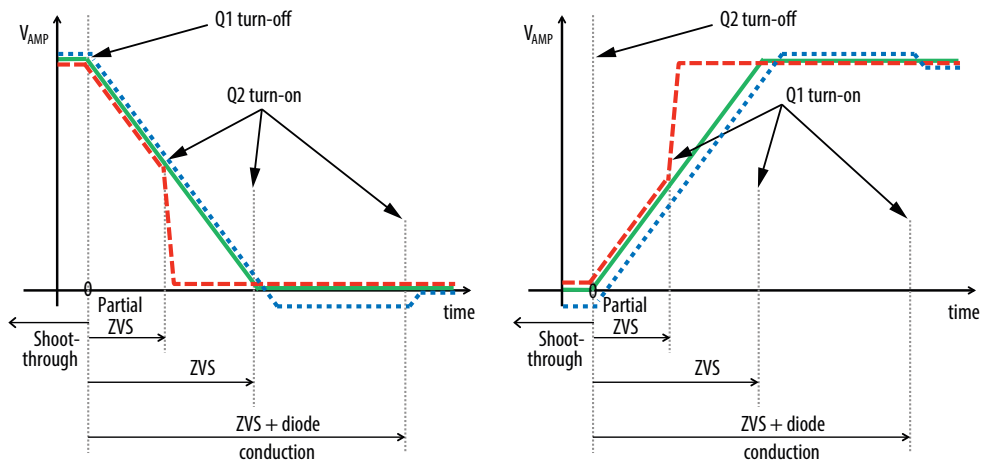


Figure 10: ZVS timing diagrams.

Bill of Materials - EPC9128 Kit Includes: EPC9509 Amplifier Board, Class 3 Source Coil, EPC9513 Category 3 Receive Device, EPC9515 Category 4 Receive Device.

| Item | Qty | Reference | Part Description | Manufacturer | Part # |
|------|-----|--|----------------------------------|-----------------|-------------------------------|
| 1 | 3 | C1_a, C1_b, C80 | 1 μ F, 10 V | TDK | C1005X7S1A105M050BC |
| 2 | 12 | C2_a, C2_b, C4_a, C4_b, C35, C51, C70, C71, C72, C77, C78, C81 | 100 nF, 16 V | Würth | 885012205037 |
| 3 | 3 | C3_a, C3_b, C95 | 22 nF, 25 V | Würth | 885012205052 |
| 4 | 2 | C5_a, C5_b | DNP (100 nF, 16 V) | Würth | 885012205037 |
| 5 | 1 | C20 | DNP (1 nF, 50 V) | Murata | GRM155R71H102KA01D |
| 6 | 1 | C73 | DNP (22 pF, 50 V) | Würth | 885012005057 |
| 7 | 1 | R20 | DNP (10 k Ω) | Panasonic | |
| 8 | 8 | C6_a, C6_b, C7_a, C7_b, C31, C44, C75, C82 | 22 pF, 50 V | Würth | |
| 9 | 4 | C11_a, C11_b, C12_a, C12_b | 10 nF, 100 V | TDK | C1005X7S2A103K050BB |
| 10 | 4 | C15_a, C15_b, C64, C65 | 2.2 μ F, 100 V | Taiyo Yuden | HMK325B7225KN-T |
| 11 | 1 | C21 | 680 pF, 50 V | Murata | GRM155R71H681KA01D |
| 12 | 1 | C22 | 1 nF, 50 V | Murata | GRM155R71H102KA01D |
| 13 | 2 | C30, C50 | 100 nF, 100 V | Murata | GRM188R72A104KA35D |
| 14 | 1 | C32 | 1 nF, 50 V | Murata | GRM1555C1H102JA01D |
| 15 | 1 | C52 | 100 pF | Murata | GRM1555C1H101JA01D |
| 16 | 2 | C53, CR43 (on top of R43) | 10 nF, 50 V | Murata | GRM155R71H103KA88D |
| 17 | 2 | C61, C62 | 4.7 μ F, 50 V | Taiyo Yuden | UMK325BJ475MM-T |
| 18 | 1 | C63 | 10 μ F, 35 V | Taiyo Yuden | GMK325BJ106KN-T |
| 19 | 3 | C90, C91, C92 | 1 μ F, 25 V | Würth | 885012206076 |
| 20 | 2 | Czvs1, Czvs2 | 1 μ F, 50 V | Würth | 885012207103 |
| 21 | 3 | D1_a, D1_b, D95 | 40 V, 300 mA | ST | BAT54KFILM |
| 22 | 10 | D2_a, D2_b, D21, D40, D41, D42, D71, D72, D77, D78 | 40 V, 30 mA | Diodes Inc. | SDM03U40 |
| 23 | 3 | D3_a, D3_b, D20 | 40 V, 30 mA | Diodes Inc. | SDM03U40 |
| 24 | 2 | D4_a, D4_b | 5.1 V, 150 mW | Bournes | CD0603-Z5V1 |
| 25 | 1 | D35 | LED 0603 Yellow | Lite-On | LTST-C193KSKT-5A |
| 26 | 1 | D36 | LED 0603 Green | Lite-On | LTST-C193KGKT-5A |
| 27 | 1 | D37 | LED 0603 Red | Lite-On | LTST-C193KRKT-5A |
| 28 | 1 | D60 | 100 V, 1 A | On-Semi | MBRS1100T3G |
| 29 | 1 | D90 | 40 V, 1 A | Diodes Inc. | PD3S140-7 |
| 30 | 3 | GP1_a, GP1_b, GP60 | .1" Male Vert. | Würth | 61300111121 |
| 31 | 1 | J1 | .156" Male Vert. | Würth | 645002114822 |
| 32 | 1 | J2 | SMA Board Edge | Linx | CONSAM003.062 |
| 33 | 6 | J70, J75, JP1, JP50, JP70, JP71 | .1" Male Vert. | Würth | 61300211121 |
| 34 | 1 | JMP1 | DNP | | |
| 35 | 1 | L60 | 33 μ H, 2.8 A | CoilCraft | MSD1278-334 |
| 36 | 1 | L80 | 10 μ H, 150 mA | Taiyo Yuden | LBR2012T100K |
| 37 | 1 | L90 | 47 μ H, 250mA | Würth | 7440329470 |
| 38 | 1 | Lsns | 110 nH | CoilCraft | 22225Q-111JE |
| 39 | 2 | Lzvs1, Lzvs2 | 390 nH | CoilCraft | 29295Q-391JE |
| 40 | 1 | Lzvs12 | DNP | CoilCraft | TBD |
| 41 | 5 | P25, P71, P72, P77, P78 | 10 k, DNP (1 k) | Bournes, Murata | 3266Y-1-103LF, PV37Y102C01B00 |
| 42 | 2 | Q1_a, Q1_b | 60 V, 150 m Ω with SB | EPC | EPC2108 |
| 43 | 1 | Q60 | 100 V, 65 m Ω | EPC | EPC2036 |
| 44 | 1 | Q61 | DNP (100 V, 6 A, 30 m Ω) | EPC | EPC2007C |
| 45 | 3 | R2_a, R2_b, R82 | 20 Ω | Stackpole | RMCF0402JT20R0 |
| 46 | 2 | R3_a, R3_b | 27 k Ω | Panasonic | ERJ-2GEJ273X |
| 47 | 2 | R4_a, R4_b | 4.7 Ω | Panasonic | ERJ-2GEJ4R7X |
| 48 | 1 | R20 | DNP (10 k Ω) | Panasonic | ERJ-2GEJ103X |
| 49 | 1 | R21 | 100 k Ω | Panasonic | ERJ-2GEJ104X |
| 50 | 1 | R25 | 7.5 k Ω | Panasonic | ERJ-2RKF7501X |
| 51 | 1 | R26 | 2 k Ω | Panasonic | ERJ-2RKF2001X |
| 52 | 1 | R30 | 100 Ω | Panasonic | ERJ-3EKF1000V |
| 53 | 1 | R31 | 51.0 k Ω 1% | Panasonic | ERJ-3EKF5102V |
| 54 | 1 | R32 | 8.2 k Ω 1% | Panasonic | ERJ-2RKF8201X |

(continued on next page)

Table 3: Bill of Materials - EPC9509 Amplifier Board (continued)

| Item | Qty | Reference | Part Description | Manufacturer | Part # |
|------|-----|------------|--------------------------|------------------------|-------------------|
| 55 | 2 | R33, R70 | 47 kΩ | Panasonic | ERJ-2RKF4702X |
| 56 | 2 | R35, R36 | 634 Ω | Panasonic | ERJ-2RKF6340X |
| 57 | 1 | R37 | 150 kΩ 1% | Panasonic | ERJ-2RKF1503X |
| 58 | 2 | R38, R91 | 49.9 kΩ 1% | Panasonic | ERJ-2RKF4992X |
| 59 | 1 | R40 | 196 kΩ | Panasonic | ERJ-3EKF1963V |
| 60 | 1 | R41 | 6.04 kΩ | Panasonic | ERJ-2RKF6041X |
| 61 | 1 | R42 | 24.9 kΩ | Panasonic | ERJ-2RKF2492X |
| 62 | 1 | R43 | 10.5 kΩ | Panasonic | ERJ-2RKF1052X |
| 63 | 2 | R44, R90 | 100 kΩ 1% | Panasonic | ERJ-2RKF1003X |
| 64 | 1 | R50 | 10 Ω | Panasonic | ERJ-3EKF10R0V |
| 65 | 1 | R51 | 124 kΩ 1% | Panasonic | ERJ-2RKF1243X |
| 66 | 1 | R52 | 71.5 kΩ 1% | Panasonic | ERJ-2RKF7152X |
| 67 | 1 | R53 | 1.00 kΩ | Panasonic | ERJ-2RKF1001X |
| 68 | 1 | R54 | 0 Ω | Yageo | RC0402JR-070RL |
| 69 | 1 | R60 | 40 mΩ, 0.4 W | Vishay Dale | WSP0603R0400FEB |
| 70 | 1 | R61 | 150 mΩ, 0.25 W | Vishay Dale | WSL0805R1500FEA18 |
| 71 | 2 | R71, R78 | 124 Ω | Panasonic | ERJ-2RKF1240X |
| 72 | 2 | R72, R77 | 22 Ω | Panasonic | ERJ-2RKF22R0X |
| 73 | 2 | R73, R75 | 10 kΩ | Panasonic | ERJ-2GEJ103X |
| 74 | 1 | R80 | 2.2 Ω | Yageo | RC0402JR-072R2L |
| 75 | 1 | R92 | 9.53 kΩ 1% | Panasonic | ERJ-2RKF9531X |
| 76 | 2 | TP1, TP2 | SMD Probe Loop | Keystone | 5015 |
| 77 | 1 | Tsns | 10 μH, 1:1, 96.9% | CoilCraft | PF3215-103ME |
| 78 | 2 | U1_a, U1_b | 100 V eGaN Driver | National Semiconductor | LM5113TM |
| 79 | 1 | U30 | Power & Current Monitor | Linear | LT2940IMS#PBF |
| 80 | 1 | U35 | DNP (Comparator) | Texas Instruments | TLV3201AIDBVR |
| 81 | 1 | U50 | Boost Controller | Texas Instruments | LM3478MAX/NOPB |
| 82 | 1 | U70 | Programmable Oscillator | KDS Daishinku America | DSO221SHF 6.780 |
| 83 | 2 | U71, U77 | 2 In NAND | Fairchild | NC7SZ00L6X |
| 84 | 2 | U72, U78 | 2 In AND | Fairchild | NC7SZ08L6X |
| 85 | 1 | U80 | Gate Driver with LDO | Texas Instruments | UCC27611DRV |
| 86 | 1 | U90 | 1.4 MHz, 24 V, 0.5A Buck | MPS | MP2357DJ-LF |

Table 4: Bill of Materials - Source Coil

| Item | Qty | Reference | Part Description | Manufacturer | Part # |
|------|-----|-----------|---------------------|--------------|------------------|
| 1 | 1 | Ctrombone | 120 pF, 1000 V | Vishay | VJ1111D12KXGAT |
| 2 | 1 | C1 | 3.3 pF, 1500 V | Vishay | VJ1111D3R3CXRAJ |
| 3 | 1 | C2 | 12 pF, 1500 V | Vishay | VJ1111D1120JXRAJ |
| 4 | 1 | C3 | 120 pF, 1000 V | Vishay | VJ1111D121KXGAT |
| 5 | 1 | PCB1 | Class 3 Coil Former | NuCurrent | R26_RZTX_D1 |
| 6 | 2 | C4, C6 | DNP | — | — |
| 7 | 1 | C5 | 0 Ω, 0612 | Vishay | RCL06120000Z0EA |
| 8 | 1 | J1 | SMA PCB Edge | Linx | CON SMA013.031 |

Table 5: Bill of Materials - EPC9513 Device Board

| Item | Qty | Reference | Part Description | Manufacturer | Part # |
|------|-----|-----------------------------------|------------------------------|--------------|---------------------|
| 1 | 1 | C44 | Capacitor, 100 pF, 25 V, X7R | Würth | 885012205038 |
| 2 | 1 | C50 | Capacitor, 100 nF, 100 V | Murata | GRM188R72A104KA35D |
| 3 | 1 | C51 | Capacitor, 4.7 μF, 100 V | Murata | GRM155R60J475ME47D |
| 4 | 1 | C52 | Capacitor, 100 pF | Murata | GRM1555C1H101JA01D |
| 5 | 1 | C53 | Capacitor, 220 pF, 50 V | Murata | GRM155R71H221KA01D |
| 6 | 2 | C55, C90 | Capacitor, 1 μF, 16 V | TDK | C1005X5R1E105M050BC |
| 7 | 3 | C56, C57, C91 | Capacitor, 100 nF, 16 V | Würth | 885012205037 |
| 8 | 7 | C61, C62, C63, C68, C71, C72, C85 | Capacitor, 10 μF, 50 V | Taiyo Yuden | UMK325BJ106MM-T |
| 9 | 3 | C64, C65, C66 | Capacitor, 22 μF, 35 V | TDK | C3216JB1V226M160AC |
| 10 | 1 | C84 | Capacitor, 100 nF, 50 V | Murata | GRM188R71H104KA93D |
| 11 | 1 | C92 | Capacitor, 22 pF, 50 V | Würth | 885012005057 |

(continued on next page)

Table 5: Bill of Materials - EPC9513 Device Board (continued)

| Item | Qty | Reference | Part Description | Manufacturer | Part # |
|------|-----|--------------------|-------------------------------|-------------------|----------------------------|
| 12 | 1 | CM1 | Capacitor, 560 pF | Vishay | VJ1111D561KXDAT |
| 13 | 1 | CM2 | Capacitor, 20 pF | Vishay | VJ1111D200JXRAJ |
| 14 | 1 | CM12 | Capacitor, 680 pF | Vishay | VJ1111D681KXDAT |
| 15 | 1 | D51 | Schottky Diode, 30 V, 500 mA | ST | STPS0530Z |
| 16 | 1 | D60 | Schottky Diode, 100 V, 3 A | ST | STPS3H100UF |
| 17 | 4 | D80, D81, D82, D83 | Schottky Diode, 40 V, 1 A | Diodes Inc. | PD3S140-7 |
| 18 | 1 | D84 | LED 0603 Green | Lite-On | LTST-C193KGKT-5A |
| 19 | 1 | D85 | Zener Diode, 2.7 V, 250 mW | NXP | BZX84-C2V7,215 |
| 20 | 1 | D86 | LED 0603 Red | Lite-On | LTST-C193KRKT-5A |
| 21 | 1 | D87 | Zener Diode, 33 V, 250 mW | NXP | BZX84-C33,215 |
| 22 | 1 | D88 | TVS Diode, 35 V, 8.2 A | Littelfuse | SMAJ30A |
| 23 | 3 | FD1, FD2, FD3 | Fiducial | N/A | N/A |
| 24 | 1 | J1 | Category 3 Coil | NuCurrent | NC20-R070L03E-079-063-0R71 |
| 25 | 1 | J3 | .1" Male Vert. | Amphenol FCI | 95278-101A04LF |
| 26 | 2 | L60, L61 | Inductor, 22 µH, 4.3 A | Vishay Dale | IHLP3232DZER220M11 |
| 27 | 1 | L90 | Inductor, 10 µH, 150 mA | Taiyo Yuden | LBR2012T100K |
| 28 | 1 | LE1 | Inductor, 18 µH, 3.8 mA | Eaton | CMS1-4-R |
| 29 | 2 | LM1, LM11 | Inductor, 32 nH | Würth | 744912182 |
| 30 | 1 | Q60 | eGaN FET, 200 V, 9 A, 43 mΩ | EPC | EPC2019 |
| 31 | 1 | R40 | Resistor, 17.8 k Ω 1%, 1/10 W | Panasonic | ERJ-3EKF1782V |
| 32 | 1 | R41 | Resistor, 6.04 k Ω 1%, 1/10 W | Panasonic | ERJ-2RKF6041X |
| 33 | 1 | R50 | Resistor, 10 Ω 1%, 1/10 W | Panasonic | ERJ-3EKF10R0V |
| 34 | 1 | R51 | Resistor, 124 k Ω 1%, 1/10 W | Panasonic | ERJ-2RKF1243X |
| 35 | 1 | R52 | Resistor, 62 k Ω 1%, 1/10 W | Panasonic | ERJ-2RKF6202X |
| 36 | 1 | R53 | Resistor, 12 Ω 1%, 1/10 W | Panasonic | ERJ-2RKF12R0X |
| 37 | 1 | R54 | Resistor, 0 Ω JUMPER, 1/16 W | Yageo | RC0402JR-070RL |
| 38 | 1 | R57 | Resistor, 1 mΩ 1%, 1/10 W | Panasonic | ERJ-3EKF1004V |
| 39 | 1 | R58 | Resistor, 150 k Ω 1%, 1/10 W | Panasonic | ERJ-2RKF1503X |
| 40 | 1 | R60 | Resistor, 40 mΩ 1%, 0.4 W | Vishay Dale | WSLP0603R0400FEB |
| 41 | 1 | R80 | Resistor, 75 mΩ 1%, 2 W | Stackpole | CSRN2512FK75L0 |
| 42 | 1 | R81 | Resistor, 4.7 k Ω 1%, 1/4 W | Stackpole | RMCF1206FT4K70 |
| 43 | 1 | R82 | Resistor, 422 Ω 1%, 1/10 W | Yageo | RMCF0603FT422R |
| 44 | 1 | R90 | Resistor, 2.2 Ω 5%, 1/16 W | Yageo | RC0402JR-072R2L |
| 45 | 1 | R92 | Resistor, 20 Ω 5%, 1/16 W | Stackpole | RMCF0402JT20R0 |
| 46 | 4 | TP1, TP2, TP3, TP4 | SMD Probe Loop, Keystone 5015 | Keystone | 36-5015TR-ND |
| 47 | 1 | U50 | IC, Boost Controller | Texas Instruments | LM3481MM/NOPB |
| 48 | 1 | U90 | IC, Gate Driver with LDO | Texas Instruments | UCC27611DRV |

Table 6: Optional Components

| Item | Qty | Reference | Part Description | Manufacturer | Part # |
|------|-----|--------------------------------|---|--------------------|-----------------------------------|
| 1 | 2 | C54, R55 | Capacitor, 0.022 µF, 50 V, X7R Resistor, 23.2 k Ω 1%, 1/10 W | Murata, Panasonic | GRM155R71H223KA12D, ERJ-2RKF2322X |
| 2 | 1 | C67 | Capacitor, 10000 pF, 100 V, X7R | TDK | C1608X7R2A103K080AA |
| 3 | 6 | CM5, CM6, CM7, CM8, CMP3, CMP4 | Optional Capacitor | TBD | |
| 4 | 3 | CM11, CMP1, CMP2 | Optional Capacitor | TBD | |
| 5 | 1 | D67 | Schottky Diode, 200 V | Diodes Inc. | DFLS1200 |
| 6 | 1 | D90 | Zener Diode, 5.1 V, 150 mW | Comchip Technology | CZRU52C5V1 |
| 7 | 1 | GP60 | CONN HEADER 1 POS 2.54 | Würth | 61300111121 |
| 8 | 1 | J2 | Connector | Amphenol FCI | |
| 9 | 1 | JP50 | Connector | | |
| 10 | 1 | PH60 | | | |
| 11 | 1 | R67 | Resistor, 10 k Ω 5%, 2/3 W | Panasonic | ERJ-P08J103V |

Table 7: Bill of Materials -EPC9515 Device Board

| Item | Qty | Reference | Part Description | Manufacturer | Part # |
|------|-----|-----------------------------------|-------------------------------|-------------------|----------------------------|
| 1 | 1 | C44 | Capacitor, 100 pF, 25 V | Würth | 885012205038 |
| 2 | 1 | C50 | Capacitor, 100 nF, 100 V | Murata | GRM188R72A104KA35D |
| 3 | 1 | C51 | Capacitor, 4.7 µF, 6.3 V | Murata | GRM155R60J475ME47D |
| 4 | 1 | C52 | Capacitor, 100 pF, 50 V | Murata | GRM1555C1H101JA01D |
| 5 | 1 | C53 | Capacitor, 220 pF, 50 V | Murata | GRM155R71H221KA01D |
| 6 | 2 | C55, C90 | Capacitor, 1 µF, 25 V | TDK | C1005X5R1E105M050BC |
| 7 | 3 | C56, C57, C91 | Capacitor, 100 nF, 16 V | Würth | |
| 8 | 7 | C61, C62, C63, C68, C71, C72, C85 | Capacitor, 10 µF, 50 V | Taiyo Yuden | |
| 9 | 3 | C64, C65, C66 | Capacitor, 22 µF, 35 V | TDK | C3216JB1V226M160AC |
| 10 | 1 | C84 | Capacitor, 100 nF, 50 V | Würth | 885012206095 |
| 11 | 1 | C92 | Capacitor, 22 pF, 50 V | Würth | 885012005057 |
| 12 | 4 | CM1, CM2, CM11, CM12 | Capacitor, 470 pF size 1111 | Johanson | VJ1111D561KXDAT |
| 13 | 1 | D51 | Schottky Diode, 30 V, 500 mA | ST | STPS0530Z |
| 14 | 1 | D60 | Schottky Diode, 100 V, 3 A | ST | STPS3H100UF |
| 15 | 4 | D80, D81, D82, D83 | Schottky Diode, 40 V, 1 A | Diodes Inc. | PD3S140-7 |
| 16 | 1 | D84 | LED 0603 Green | Lite-On | LTST-C193KGT-5A |
| 17 | 1 | D85 | Zener Diode, 2.7 V, 250 mW | NXP | BZX84-C2V7,215 |
| 18 | 1 | D86 | LED 0603 Red | Lite-On | LTST-C193KRKT-5A |
| 19 | 1 | D87 | Zener Diode, 33 V, 250 mW | NXP | BZX84-C33,215 |
| 20 | 1 | D88 | TVS Diode, 35 V, 8.2 A | Littelfuse | SMAJ30A |
| 21 | 1 | J1 | Category 4 Coil | NuCurrent | NC20-R064M10E-112-066-1R27 |
| 22 | 1 | J3 | .1" Male Vert. SMD 2 x 2 | Amphenol FCI | 95278-101A04LF |
| 23 | 2 | L60, L61 | Inductor, 22 µH, 4.3 A | Vishay Dale | IHLP3232DZER220M11 |
| 24 | 1 | L90 | Inductor, 10 µH, 150 mA | Taiyo Yuden | LBR2012T100K |
| 25 | 1 | LE1 | Inductor, 18 µH, 3.8 mA | Eaton | CMS1-4-R |
| 26 | 2 | LM1, LM11 | Inductor, 82 nH | Würth | 744912182 |
| 27 | 1 | Q60 | eGaN FET, 200 V, 9 A, 43 mΩ | EPC | EPC2019 |
| 28 | 1 | R40 | Resistor, 17.8 k Ω 1%, 1/10 W | Panasonic | ERJ-3EKF1782V |
| 29 | 1 | R41 | Resistor, 6.04 k Ω 1%, 1/10 W | Panasonic | ERJ-2RKF6041X |
| 30 | 1 | R50 | Resistor, 10 Ω 1%, 1/10 W | Panasonic | ERJ-3EKF10R0V |
| 31 | 1 | R51 | Resistor, 124 k Ω 1%, 1/10 W | Panasonic | ERJ-2RKF1243X |
| 32 | 1 | R52 | Resistor, 62 k Ω 1%, 1/10 W | Panasonic | ERJ-2RKF6202X |
| 33 | 1 | R53 | Resistor, 12 Ω 1%, 1/10 W | Panasonic | ERJ-2RKF12R0X |
| 34 | 1 | R54 | Resistor, 0 Ω JUMPER, 1/16 W | Yageo | RC0402JR-070RL |
| 35 | 1 | R57 | Resistor, 1 mΩ 1%, 1/10 W | Panasonic | ERJ-3EKF1004V |
| 36 | 1 | R58 | Resistor, 150 k Ω 1%, 1/10 W | Panasonic | ERJ-2RKF1503X |
| 37 | 1 | R60 | Resistor, 40 mΩ 1%, 0.4 W | Vishay Dale | WSLP0603R0400FEB |
| 38 | 1 | R80 | Resistor, 75 mΩ 1%, 2 W | Stackpole | CSRN2512FK75L0 |
| 39 | 1 | R81 | Resistor, 4.7 k Ω 1%, 1/4 W | Stackpole | RMCF1206FT4K70 |
| 40 | 1 | R82 | Resistor, 422 Ω 1%, 1/10 W | Yageo | RMCF0603FT422R |
| 41 | 1 | R90 | Resistor, 2.2 Ω 5%, 1/16 W | Yageo | RC0402JR-072R2L |
| 42 | 1 | R92 | Resistor, 20 Ω 5%, 1/16 W | Stackpole | RMCF0402JT20R0 |
| 43 | 4 | TP1, TP2, TP3, TP4 | SMD Probe Loop | Keystone | 5015 |
| 44 | 1 | U50 | IC, Boost Controller | Texas Instruments | LM3481MM/NOPB |
| 45 | 1 | U90 | IC, Gate Driver with LDO | Texas Instruments | UCC27611DRV |

Table 8: Optional Components

| Item | Qty | Reference | Part Description | Manufacturer | Part # |
|------|-----|--------------------------------|--------------------------------|--------------------|---------------------|
| 1 | 1 | C54 | Capacitor, 0.022 µF, 50 V, X7R | Murata | GRM155R71H223KA12D |
| 2 | 1 | C67 | Capacitor, 10 nF, 100 V, X7R | TDK | C1608X7R2A103K080AA |
| 3 | 6 | CM5, CM6, CM7, CM8, CMP3, CMP4 | Capacitor RF Size 0505 (B) | TBD | TBD |
| 4 | 2 | CMP1, CMP2 | Capacitor RF Size 1111 (B) | TBD | TBD |
| 5 | 1 | D67 | Schottky Diode, 200 V | Diodes Inc. | DFLS1200 |
| 6 | 1 | D90 | Zener Diode, 5.1 V 150 mW | Comchip Technology | CZRU52C5V1 |
| 7 | 1 | GP60 | CONN HEADER 1 POS 2.54 | Würth | 61300111121 |
| 8 | 1 | J2 | .1" Male Vert. SMD 2 x 2 | Amphenol FCI | 95278-101A04LF |
| 9 | 1 | JP50 | .05" 2 pos Male Vert Connector | Sullins | GRPB021VWVN-RC |
| 10 | | R67 | Resistor, 10 k Ω 5%, 2/3 W | Panasonic | ERJ-P08J103V |
| 11 | 1 | R55 | Resistor, 23.2 k Ω 1%, 1/10 W | Panasonic | ERJ-2RKF2322X |

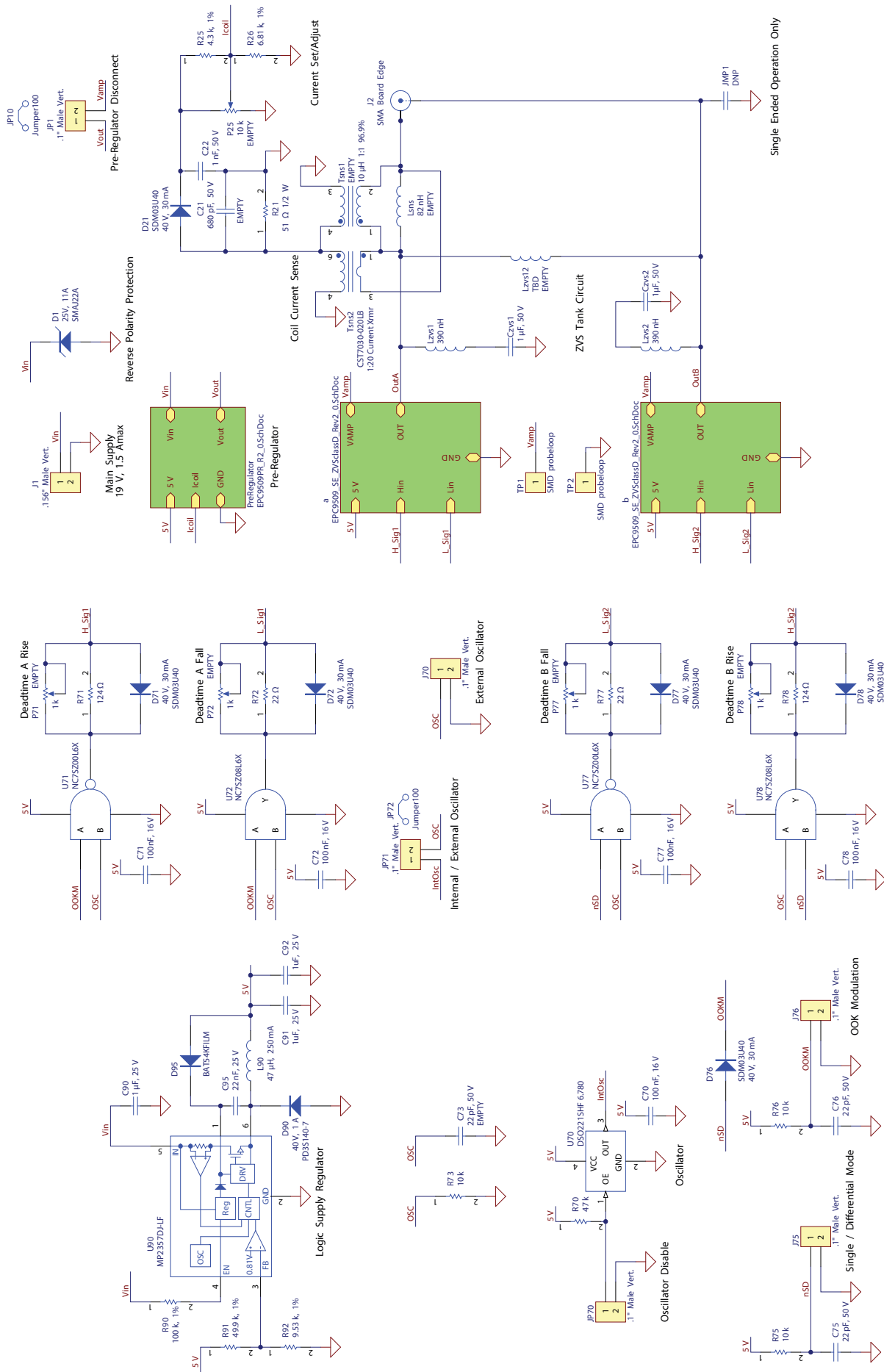


Figure 11: EPC9509 - ZVS class-D amplifier schematic

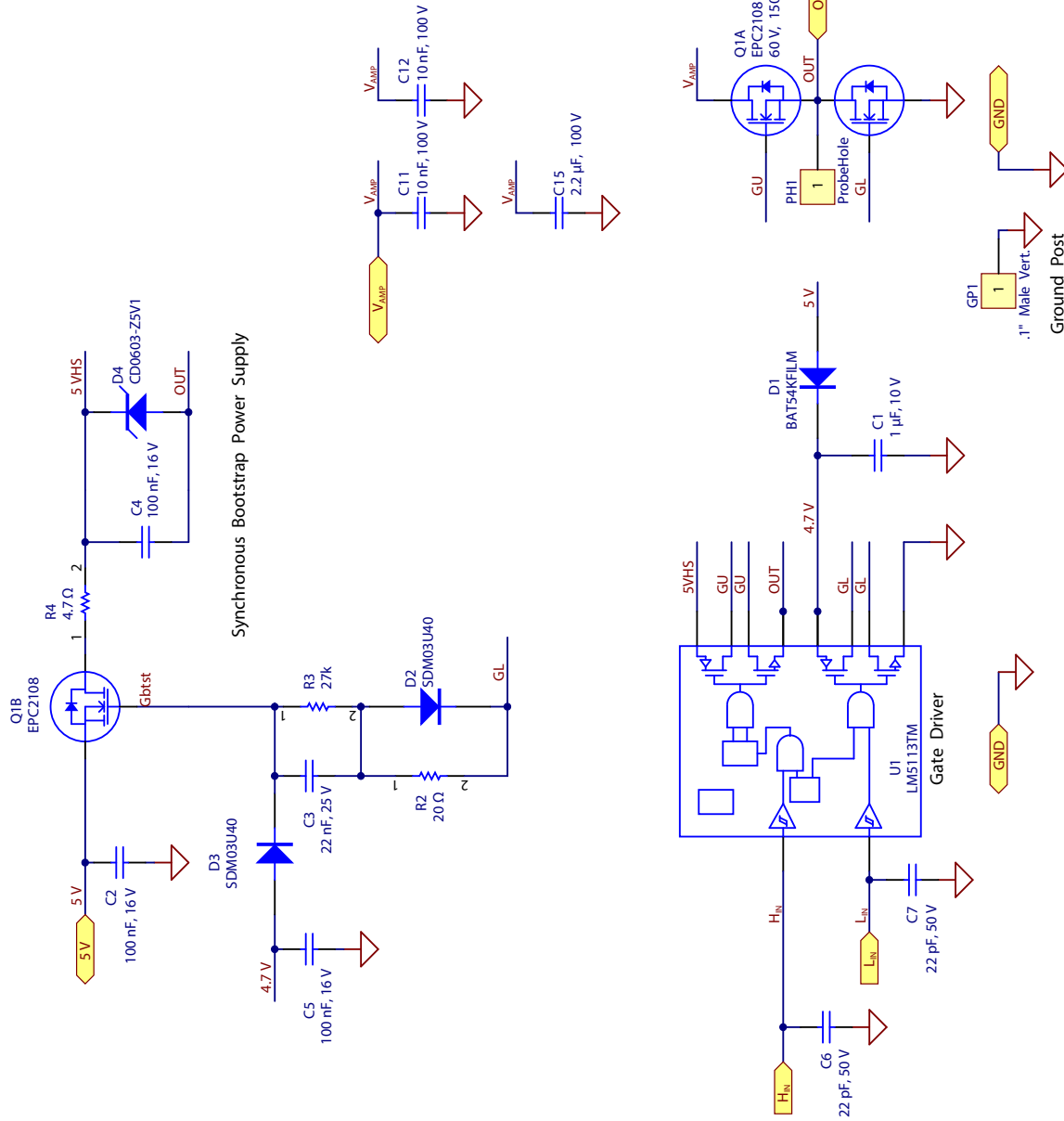


Figure 12: EPC9509 - Gate driver and power devices schematic
This schematic is repeated for each single-ended ZVS class D amplifier.

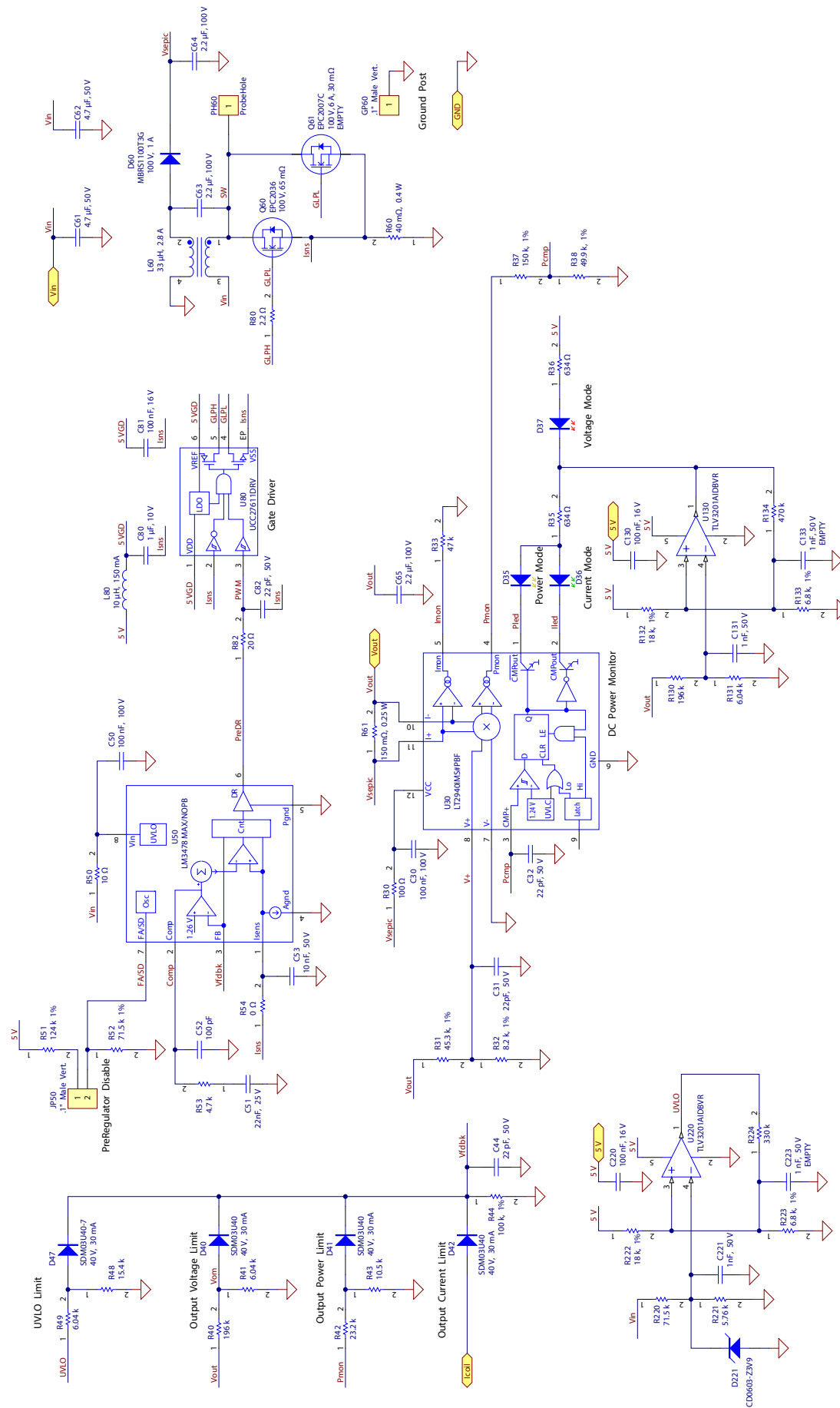


Figure 13: EPC9509 - Pre-regulator schematic.

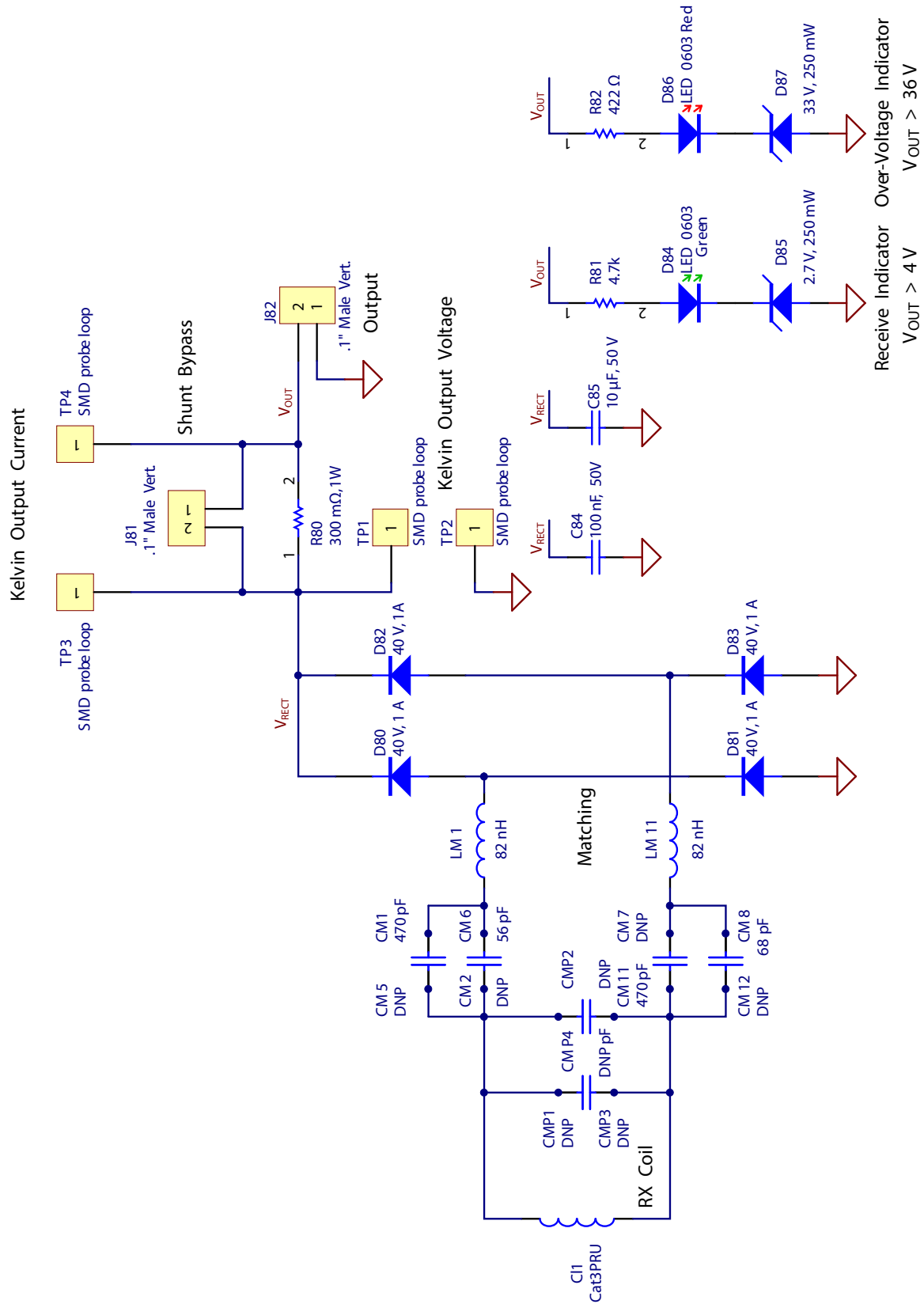


Figure 14: Category 3 device board schematic

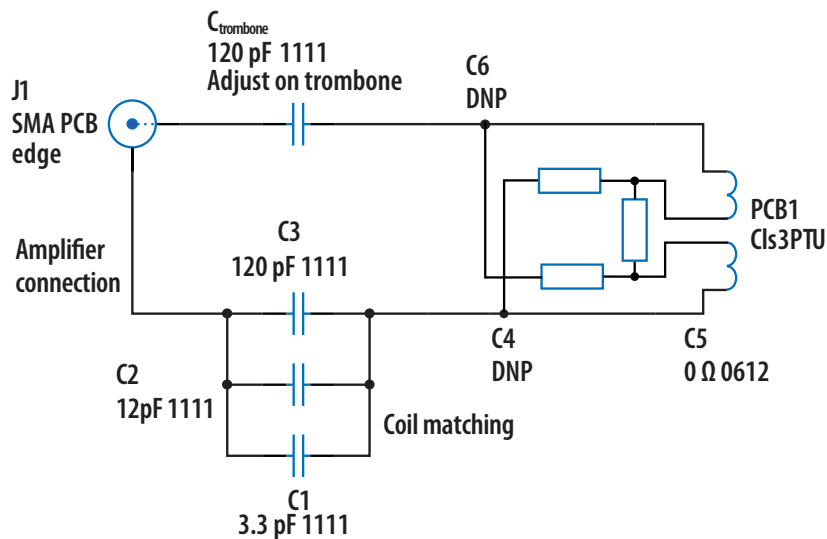


Figure 15: Class 3 Source Board Schematic



EPC would like to acknowledge Würth Elektronik (www.we-online.com) for their support of this project.

Würth Elektronik is a premier manufacturer of electronic and electromechanical passive components. EPC has partnered up with Würth Elektronik for a variety of passive component requirements due to the performance, quality and range of products available. The EPC9128 demonstration system features various Würth Elektronik product lines including capacitors, LEDs and connectors.

Also featured on the board are numerous Würth Elektronik power inductor technologies including WE-AIR air core inductors. The inductors were chosen for their balance between size, efficiency, current handling capability, reliability, and lowest DCR losses.

Learn more at www.we-online.com.



EPC would like to acknowledge NuCurrent (www.NuCurrent.com) for their support of this project.

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