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ISL6558EVAL2 - Low-Profile, 5V/12V Input, 500kHz, and 90% Efficiency DC/DC Converter

Application Note

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Introduction

The changing computer performance landscape has brought about the need for flexible power solutions. Peripheral performance continues to increase as higher speed bus interfaces are made available. Router designs continue to grow in complexity as on-board processors perform more functions within a limited board space while continuing to increase the speed of data transfer. This places higher power density requirements on the DC/DC converters which supply them.

Intersil's Endura™ multi-phase controllers (HIP63xx and ISL65xx) and synchronous-rectified buck MOSFET drivers (HIP66xx and ISL66xx) are suitable for the interleaved DC/DC buck converter implementation, as shown in Figure 1, and provide superior performance solutions with their space economical MLFP packages.

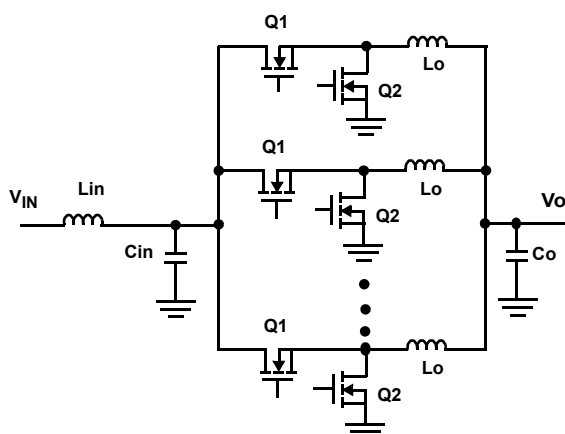


FIGURE 1. MULTI-PHASE INTERLEAVED BUCK CONVERTER

This application note first gives a brief introduction of Intersil's four-phase controller ISL6558 and synchronous-rectified driver ISL6609. A summary of the ISL6558 and ISL6609 based design follows. The experimental results for a low-profile 5V-to-1.35V@30A, 500kHz, and 90% efficiency converter in two-phase operation using the interleaved approach and with their space economical MLFP package ICs are discussed. The evaluation board can be pushed up to 80A in four-phase operation, or modified for 12V input applications by replacing the input capacitors with higher voltage rating capacitors. Term Definitions, Reference, Schematics, Bill of Materials, and Layout are included at the end of this application note.

Intersil's ISL6558 and ISL6609

The ISL6558 controller, coupled with ISL6609 single-channel driver ICs, forms the basic building blocks for applications which demand high current, rapid load transient response, and high efficiency performance at high switching frequency within a limited board area and height.

The ISL6558 regulates output voltage and balances load currents for two to four synchronous-rectified buck converter channels; its internal structure is shown in Figure 2. The internal 0.8V reference allows output voltage selection down to that level with a 1% system accuracy over temperature. The current-channel balance loop provides good thermal balance among all phases. Output voltage droop or active voltage positioning is optional. Overvoltage and overcurrent monitors and protection functions of the IC provide a safe environment for the microprocessor or other load. The controller is available in a 16-lead SOIC package and a 5x5mm² 20-lead MLFP package with some space savings. For more detailed descriptions of the ISL6558 functionality, refer to the device datasheet [1].

The ISL6609 is a 5V driver IC capable of delivering up to 4A of gate current for rapidly switching both MOSFETs in a synchronous-rectified bridge; its internal structure is shown in Figure 2. It is especially designed for voltage regulators that require high efficiency performance at high switching frequency within a limited board space. The ISL6609 accepts a single logic input to control both upper and lower MOSFETs. Its Tri-State® feature, working together with Intersil's Multi-Phase PWM controllers, helps prevent a negative transient on the output voltage when the output is being shut down. This eliminates the Schottky diode that is used in some systems for protecting the microprocessor from reversed-output-voltage damage. Furthermore, adaptive shoot-through protection is implemented on both switching edges to provide optimal dead time and minimize conduction losses. Bootstrap circuitry permits greater enhancement of the upper MOSFET. The driver is available in a 8-lead SOIC package and a space economical 3x3mm² 8-lead MLFP package. For a more detailed description of the ISL6609, refer to the device data sheet [2].

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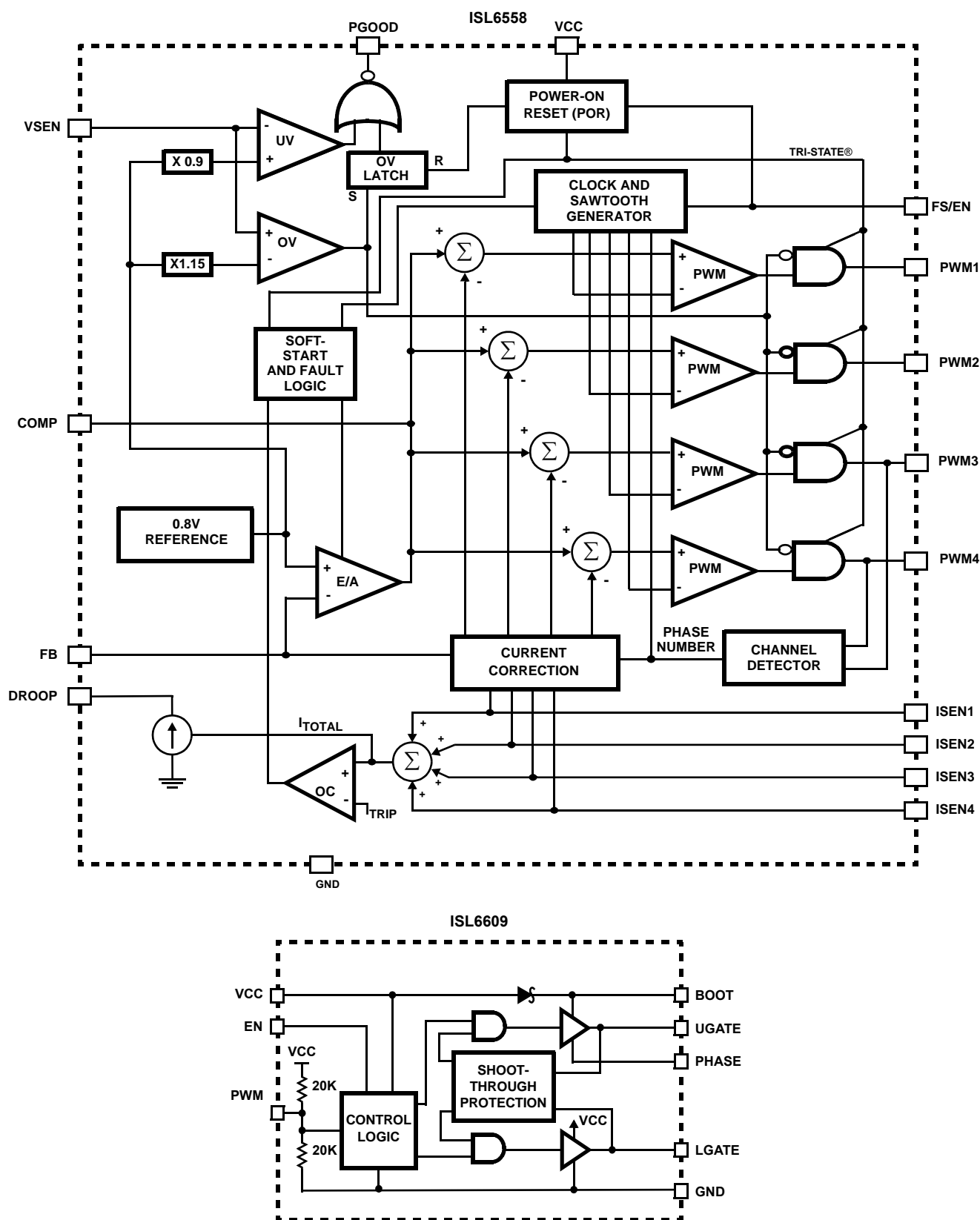


FIGURE 2. SIMPLIFIED ISL6558 AND ISL6609 INTERNAL STRUCTURE

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Summary of Design

Table 1 summarizes the specifications of a power converter for mid-range router applications. The ISL6558 and ISL6609 based evaluation board has been designed to meet these criteria.

TABLE 1. ISL6558EVAL2 SPECIFICATIONS

| PARAMETER | CONDITION | MIN | TYP | MAX |
|--------------------------------|----------------------|-----------------------|--------------------|-----------------------|
| Input Voltage | V _{IN} | 4.5V | 5V | 5.5V |
| Output Regulation | 0.1% R16 and R19 | 1.336 | 1.35 | 1.365 |
| Transient Regulation | 6.5A Step 200A/μs | V _O - 20mV | | V _O + 20mV |
| Continuous Load | 25°C with 200LFM | | 30A | |
| Transient Slew Rate | | | 200A/μs | |
| Over Current | 25°C with 200LFM | | 43A | |
| Minimum Airflow | | | 0 LFM | |
| Channel Switching Frequency | | | 500kHz | |
| Efficiency | 25°C with 200LFM | | 89.7% | |
| | 25°C with No Airflow | | 89.3% | |
| Undervoltage Rising Threshold | | | 0.92V _O | |
| Undervoltage Falling Threshold | | | 0.9V _O | |
| Overvoltage Threshold | | | 1.15V _O | |

Table 2 shows the calculation results of critical design parameters for the reference design, a two-phase interleaved DC/DC buck converter.

TABLE 2. CRITICAL DESIGN PARAMETERS

| PARAMETER | CONDITIONS | VALUE | UNIT |
|---|---|-------|------|
| DUTY CYCLE AND SWITCHING FREQUENCY | | | |
| D | V _{IN} = 5, V _O = 1.35 | 28.3 | % |
| F _{sw} | R _T = 51.1kΩ (measured) | 500 | kHz |
| INPUT INDUCTOR AND CAPACITORS | | | |
| C _{in} (min) | I _O = 30A, N = 2, ΔV _{IN,CAP} = 20mV | 180 | μF |
| I _{IN,RMS} | V _{IN} = 5.5V, I _O = 30A | 7.63 | A |
| L _{in} (min) | C _{in} = 180μF×3, dI _{in} /dt = 0.1A/μs | 300 | nH |
| OUTPUT CAPACITORS | | | |
| Co(min) | f _c = F _{sw} /5 = 100kHz, f(Istep) = 20mV | 517 | μF |
| I _{ORMS} | Lo(I _O) = 0.3μH, V _{IN} = 5.5V | 1.34 | A |
| ESR(max) | Istep = 6.5A, f(step) = 20mV | 3.07 | mΩ |

TABLE 2. CRITICAL DESIGN PARAMETERS (Continued)

| PARAMETER | CONDITIONS | VALUE | UNIT |
|--|--|-------|------|
| OUTPUT INDUCTORS (ASSUMING EQUAL DISTRIBUTION AMONG OUTPUT INDUCTORS) | | | |
| I _{Lo,PP} | Lo(I _O) = 0.3μH, V _{IN} = 5.5V | 6.88 | A |
| I _{PP} | Lo(I _O) = 0.3μH, V _{IN} = 5.5V, N = 2 | 4.65 | A |
| I _{Lo,Peak} | Lo(I _O) = 0.3μH, V _{IN} = 5.5V | 18.44 | A |
| I _{Lo,RMS} | Lo(I _O) = 0.3μH, V _{IN} = 5.5V | 15.13 | A |
| UPPER FETs | | | |
| I _{Q1,RMS} | Lo(I _O) = 0.3μH, V _{IN} = 4.5V | 8.48 | A |
| LOWER FETs | | | |
| I _{Q1,RMS} | Lo(I _O) = 0.3μH, V _{IN} = 5.5V | 13.04 | A |

Table 3 summarizes a rough power dissipation analysis for the referenced design.

TABLE 3. FULL-LOAD POWER DISSIPATION BUDGET

| ELEMENTS | POWER DISSIPATION AT 30A LOAD | | |
|----------------------------------|-------------------------------|----------|---------|
| | 4.5V | 5.0V | 5.5V |
| CALCULATION CONDITIONS | | | |
| Switching Frequency | 500kHz | | |
| Per-Channel Output Inductor | 0.3μH at Full load | | |
| Number of Active Channels | N = 2 | | |
| PER-CHANNEL LOSSES (xN) | | | |
| Upper FETs Conduction | 0.395W | 0.356W | 0.323W |
| Upper FETs Switching | 0.461W | 0.516W | 0.572W |
| Lower FETs Conduction | 0.333W | 0.328W | 0.340W |
| Lower FETs Body-diode Conduction | 0.233W | 0.232W | 0.231W |
| Output Inductor Copper | 0.123W | 0.123W | 0.123W |
| Output Inductor Core (Estimated) | 0.036W | 0.0.036W | 0.036W |
| Per-Channel Driver | 0.305W | 0.375W | 0.454W |
| OTHERS (x1) | | | |
| Input Inductors Copper | 0.055W | 0.044W | 0.037W |
| Input Inductors Core | Negligible | | |
| Input Capacitors | 0.273W | 0.287W | 0.291W |
| Output Capacitors | 0.0035W | 0.0048W | 0.0061W |
| Controller | 0.078W | 0.078W | 0.078W |
| PCB Copper | 0.196W | 0.184W | 0.176W |
| Miscounted and Error | 0.32W | 0.28W | 0.29W |
| TOTAL | 4.655W | 4.688W | 4.737W |

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Experimental Results

The ISL6558EVAL2 evaluation board as configured is capable of 30A continuous load current and handling 200A/ μ s or higher speed load transients. The evaluation board meets the design specifications indicated in Table 1. Table 4 summarizes the equipment that was used for the performance evaluation.

TABLE 4. EQUIPMENT LIST

| Equipment | EQUIPMENT DESCRIPTIONS |
|-------------------------|--|
| Boards Used | ISL6558EVAL2 Rev. A, #1 and #2 |
| Power Supplies | 1. Hewlett Packard 6653A, 35V, 15A. S/N: 3621A-03425 |
| Oscilloscope | LeCroy LT364L. S/N: 01106 |
| Multimeters | Fluke 8050A. S/N: 2466115 & 3200834 |
| Load | 1. Chroma 63103. S/N: 631030002967 2. Chroma 63103. S/N: 631030003051 |
| Current Probe Amplifier | LeCroy AP015. SN: 3293 |
| Fan | POPST-MOOREN TYP 4600X (4098547) |

ISL6558EVAL2 OPERATION AND MODIFICATION TIPS

- Apply the input voltage (V_{IN}) prior to the control voltage V_{CC5} (5V). This sequencing results in initializing the ISL6609 driver before the ISL6558 starts, and retains the soft-start interval. Vice versa, the ISL6558 could produce maximum duty cycle PWM drive signal, which results in an overcurrent or overvoltage trip due to lack of soft-start. The evaluation board is configured to power up from a single 5V supply, and it eliminates the problem discussed above.
- SW1 is used to engage or remove the load transient generator.
- Droop option is not selected in the reference design since the required load transient step is not greater than 50% of the full load. In another word, the droop only helps reduce the number of output capacitors and still retains the same transient performance when the load transient step is greater than 50% of full load.
- For 3-phase operation, add the current sense resistor R17 and place JP4 to ON position (away from TP8). The compensation gain (R11) should be scaled by 2/3 for system stability with a reasonable phase margin.
- For 4-phase operation, add the current sense resistors R2 & R17 and place JP4 & JP2 to ON position (away from TP8 and TP5). The compensation gain (R11) should be scaled by 1/2 for system stability with a reasonable phase margin.
- Use R25, R26, R28, and R29 to program the load transient speed. The higher values these resistors, the slower the transient.

- If there is sufficient airflow, use a single LPAK Hitachi HAT1264 for the upper FET and two SO-8 Siliconix Si4842DYs for the lower FETs in each channel; but it comes with the penalty of 1% lower efficiency, as shown in Table 5. Note that the current sense resistors (R2 and R17) need to be adjusted to get a proper over current setpoint.
- For 12V input operation, the jumper JP1 should be removed to prevent the controller and drivers from overvoltage damage. A 5V supply is required to power up the controller and the drivers; the diode D1 is to protect both the drivers and controller from reversed-bias damage. The 12V supply should be applied prior to the 5V; otherwise, the output voltage will lack soft-start and cause an over overcurrent or overvoltage at the output. Furthermore, the input capacitors should be replaced with higher voltage rating (16V or above) capacitors. In addition, the compensation gain (R11) should be scaled by 5/12 for system stability with a reasonable phase margin.
- Any change of the output filter will require the compensation network to change for an optimum transient response. If very lower ESR capacitors are used at the output, a type III compensation network is required to boost up the phase for a better transient performance.
- The feedback resistor (R19) can cause some delay in the soft-start interval, as discussed in the ISL6557A data sheet section SOFT-START [3]. It should not be a very high impedance resistor.

EFFICIENCY

The efficiency data, as plotted in Figure 3, are taken with a PAPST-MOTOREN TYP 4600X fan turned on 8" away from the input end of the evaluation board at room temperature (approximate 200LFM). This figure shows that the converter operates less efficiently at high line and low-to-medium load since the switching loss is the dominant portion of the total losses in that operating condition. As the load increases, the dominant conduction losses help cut down the difference.

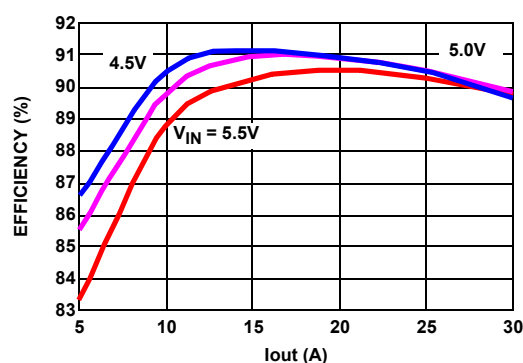


FIGURE 3. EFFICIENCY AT 500kHz AND 200LFM

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Figure 4 shows the efficiency for various frequencies and airflow conditions.

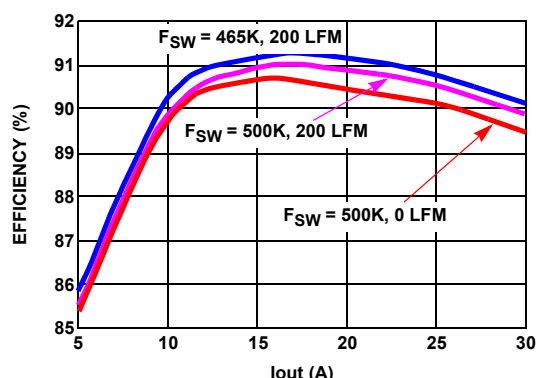


FIGURE 4. EFFICIENCY FOR VARIOUS FREQUENCY AND AIRFLOW AT $V_{IN}=5V$

Different combinations of upper and lower MOSFETs have been evaluated at $V_{in} = 5V$ and $F_{sw} = 500kHz$ with 200LFM airflow, as shown in Table 5. The last combination with one Hitachi HAT2164 upper FET and two Siliconix Si4842DY lower FETs provides high efficiency and good thermal performance with some space and cost reduction.

TABLE 5. EFFICIENCY WITH DIFF. UPPER & LOWER MOSFETs

| # | UPPER FET | LOWER FET | EFFICIENCY |
|---|------------|-------------|------------|
| 1 | HAT2168 x2 | HAT2164 x2 | 89.85% |
| 2 | HAT2168 x1 | HAT2164 x2 | 87.94% |
| 3 | HAT2168 x2 | Si4842DY x2 | 89.50% |
| 4 | HAT2164 x1 | Si4842DY x2 | 88.90% |

OUTPUT SOFT-START AND TURN-OFF

As the control voltage V_{CC5} reaches the POR rising threshold (4.38V nominal) of the ISL6558, the FS/EN pin is released from ground; the output begins a monotonic rise comprised of 2048 digital steps, as shown in Figure 4. At the end of the soft-start interval, the PGOOD signal transitions to indicate the output voltage is within specification.

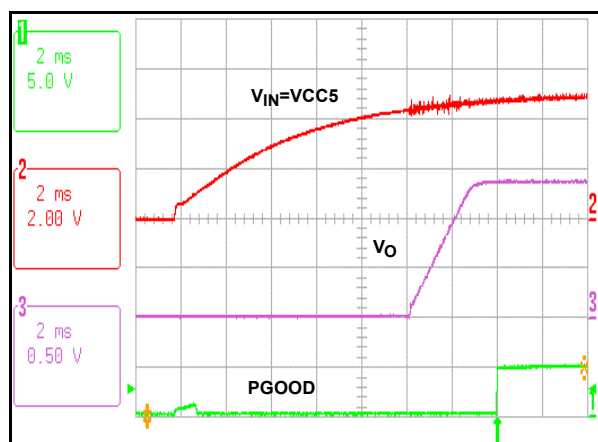


FIGURE 5. SOFT-START WAVEFORMS

As shown in Figure 6, the converter is disabled when the control voltage (V_{CC5}) is pulled below the POR falling threshold (3.88V nominal) of the ISL6558. The PGOOD signal falls low indicating the output voltage is out of regulation. The ISL6609 enters Tri-State® and holds both upper and lower drive signals low. The L-C resonant tank is broken and cannot cause negative ringing at the output since the lower FETs are turned off, blocking any negative current.

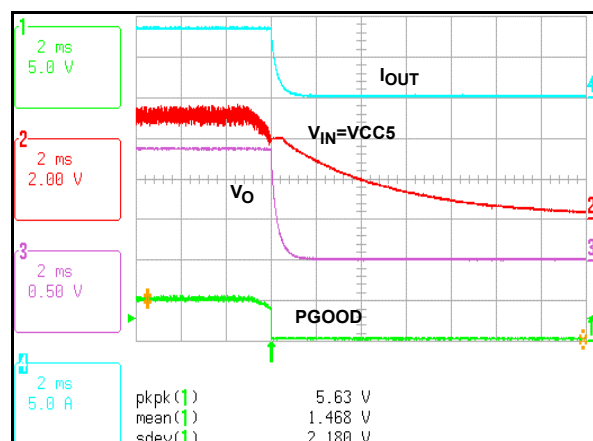


FIGURE 6. TURN-OFF WAVEFORMS

TRANSIENT RESPONSES

A transient load generator is populated on the board to evaluate the response of the converter at high-speed load transients. Current setting of the generator provides about 6.5A load step with 160A/μs on the rising edge and 210A/μs on the falling edge without output droop configuration.

The input current rises/falls at a speed limited by the input inductor and capacitors during step-up/step-down transients. Figure 7 shows a very low ramping up speed (0.02A/μs) of the input current at the load transient condition. This is due to a large effective input inductance seen by the converter. The effective input inductance is the sum of the on-board input inductance and the inductance of the long source leads of the bench power supply.

The transient performance at different operating conditions has been summarized in Table 6. Little difference is noted for various line and load conditions. Note that the ripple portion has been included.

TABLE 6. TRANSIENT RESPONSE (6.5A STEP)

| INPUT VOLTAGE/LOAD CURRENT | STEP-UP/DOWN |
|----------------------------|---------------|
| 4.5V/0A | 21.9mV/21.9mV |
| 4.5V/25A | 21.9mV/21.9mV |
| 5.0V/0A | 21.9mV/23.1mV |
| 5.0V/25A | 22.5mV/21.9mV |
| 5.5V/0A | 21.9mV/21.2mV |
| 5.5V/25A | 23.8mV/24.4mV |

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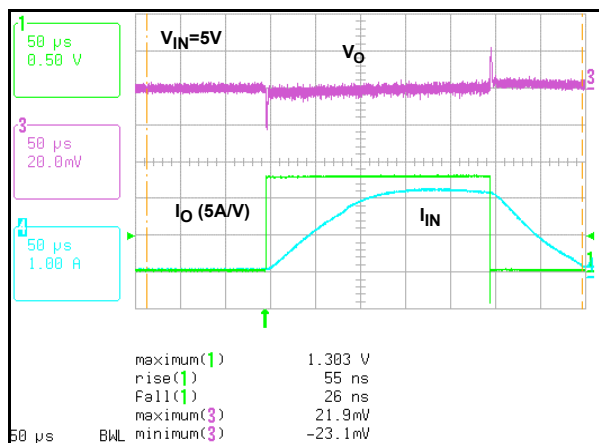


FIGURE 7. TRANSIENT RESPONSE AT NO LOAD ($V_{IN} = 5.0V$)

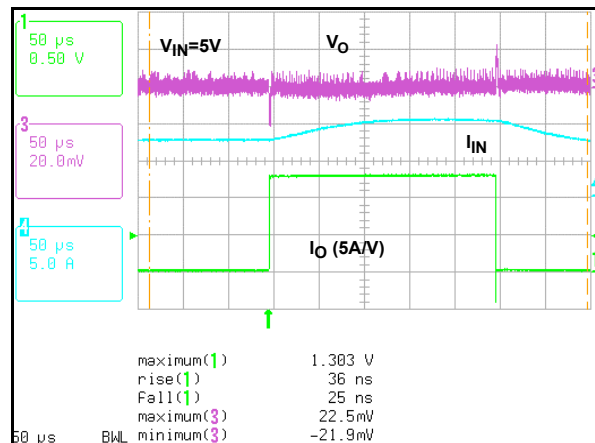


FIGURE 10. TRANSIENT RESPONSE AT 25A ($V_{IN} = 5.0V$)

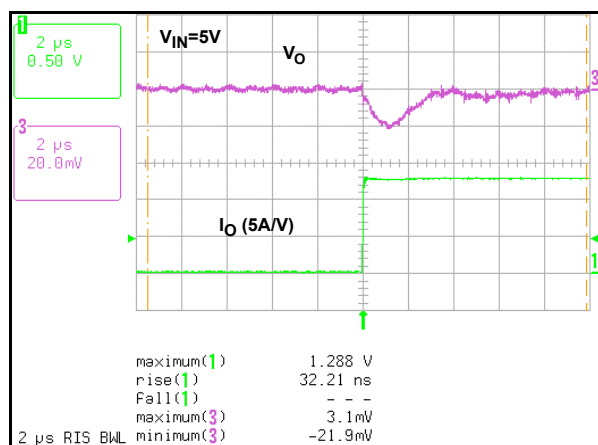


FIGURE 8. STEP-UP TRANSIENTS AT NO LOAD ($V_{IN} = 5.0V$)

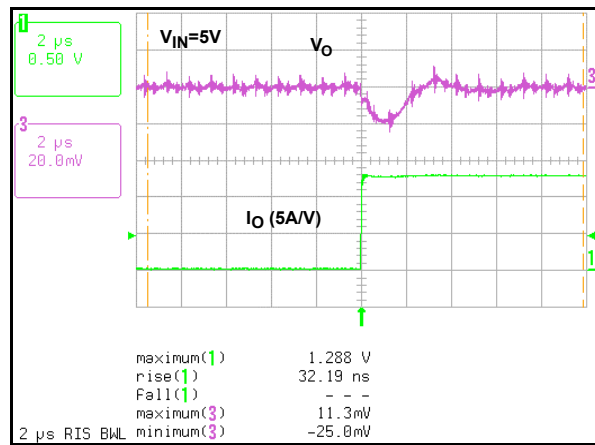


FIGURE 11. STEP-UP TRANSIENTS AT 25A ($V_{IN} = 5.0V$)

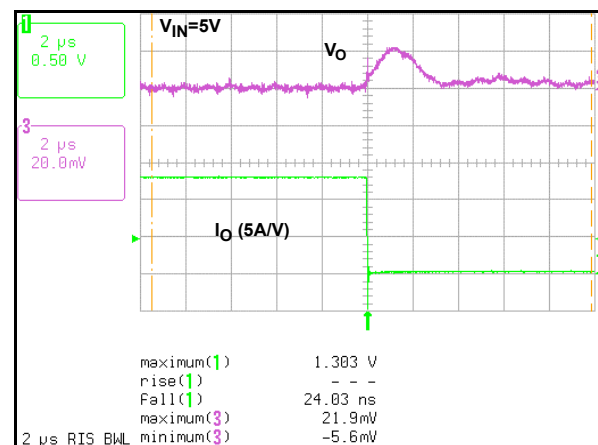


FIGURE 9. STEP-DOWN TRANSIENTS AT NO LOAD ($V_{IN} = 5.0V$)

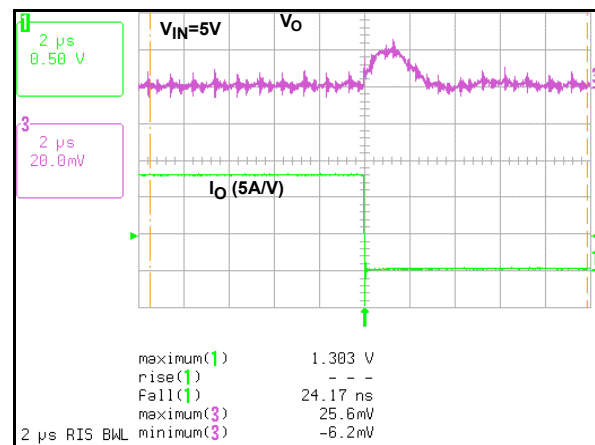


FIGURE 12. STEP-DOWN TRANSIENTS AT 25A ($V_{IN} = 5.0V$)

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OVER CURRENT AND SHORT CIRCUIT

When the converter is momentarily shorted or overloaded, as shown in Figure 13, the converter enters hiccup mode with a narrow duty cycle and long switching period. PGOOD stays low during the overcurrent period; it indicates the output voltage is within regulation limits after the short is removed and the output completes a soft-start interval.

As shown in Figure 14, the converter can sustain a permanent short circuit remaining in hiccup mode with a frequency of 185Hz. The average load current and the average power dissipation in each power component are reduced significantly; thus, the converter can stay at a short without causing any permanent damage or thermal issues.

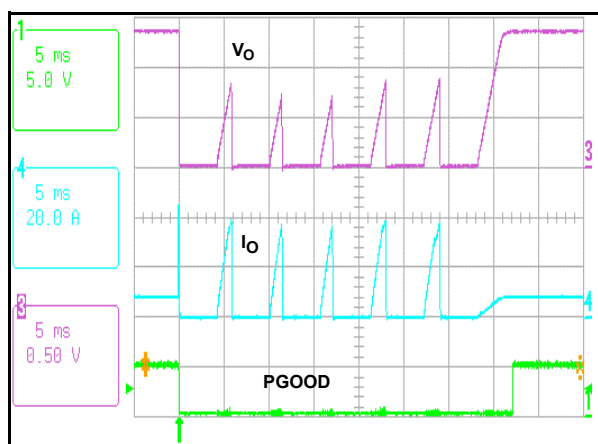


FIGURE 13. OVER-LOADED OUTPUT WAVEFORMS

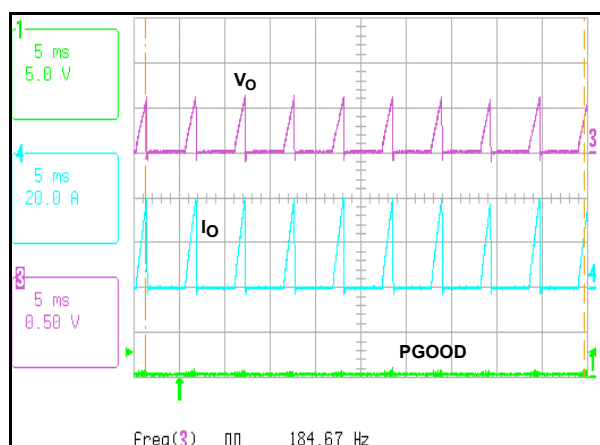


FIGURE 14. SHORT-CIRCUIT WAVEFORMS

OVERVOLTAGE SHUTDOWN

With the COMP pin momentarily tied to a 4V voltage source with respect to the ground, the error voltage jumps high and the duty cycle increases. Thus, the output voltage rises up immediately until it reaches the overvoltage threshold setting the OV latch and triggers the PWM outputs low. PGOOD is pulled low indicating output out of regulation, as shown in Figure 15.

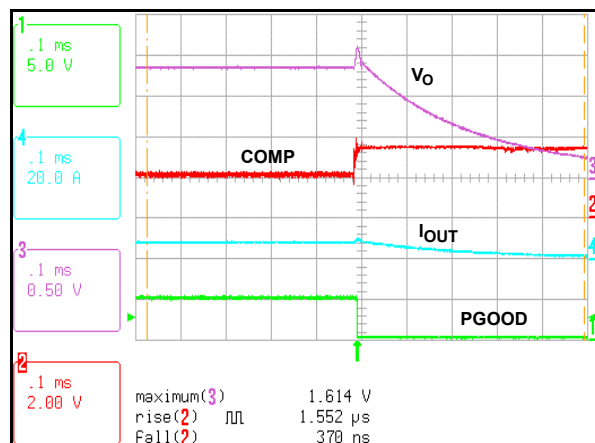


FIGURE 15. OVERVOLTAGE WAVEFORMS

Conclusion

The superior performance of Intersil's ISL6558 four-phase controller, coupled with Intersil's ISL6609 driver, has been demonstrated in the low-profile reference design of a 40W, 500kHz interleaved DC/DC buck converter. An ultra high efficiency of 90% at 1.35V output and 30A full load has been achieved.

The extensive experimental results give users a better understanding of the operation of the converter, the ISL6558 four-phase PWM controller, and the ISL6609 synchronous-rectified driver.

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Term Definitions

| | |
|---------------------|--|
| Cin | Input Capacitance |
| Co | Output Capacitance |
| D | Ratio of ON Interval of Upper FET to Single-Channel Switching Period, Duty Cycle |
| $\Delta V_{IN,CAP}$ | Allowable Input Voltage Ripple Contributed by the Input Capacitors |
| ESR | Overall ESR of Output Capacitors |
| f_c | System Closed-Loop Bandwidth |
| Fsw | Per-Channel Switching Frequency |
| I_{IN} | Input Current |
| $I_{IN,RMS}$ | RMS Current thru Input Capacitors |
| I_{LO} | Current thru Each-Channel Inductor |
| $I_{LO,PEAK}$ | Peak Current thru Each-Channel Inductor |
| $I_{LO,PP}$ | Ripple Current thru Each-Channel Inductor |
| $I_{LO,RMS}$ | RMS Current thru Each-Channel Inductor |
| I_{PP} | Overall Ripdple Current thru Output Capacitors |
| I_o | Output Load Current |
| $I_{Q1,RMS}$ | RMS Current thru Upper FET, Q1 |
| $I_{Q2,RMS}$ | RMS Current thru Upper FET, Q2 |
| Istep | Load Transient Step |
| Lin | Input Inductor |
| Lo | Inductance of Each-Channel Inductor |
| N | Number of Active Channels |
| Po | Output Power |
| η | Output Efficiency |
| V_{IN} | Input Voltage |
| Vo | Output Voltage |

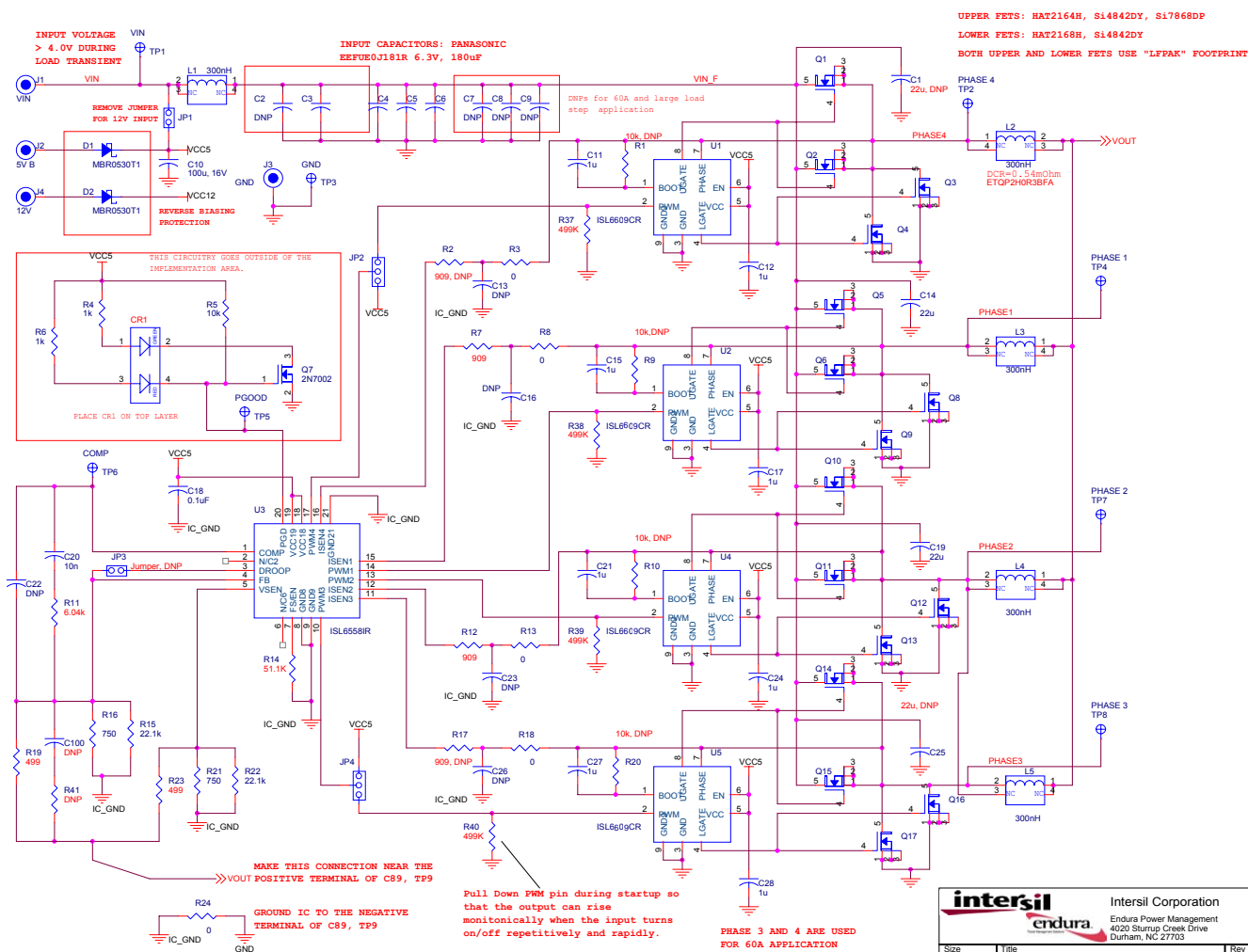
References


Intersil documents are available on the web at <http://www.intersil.com>.

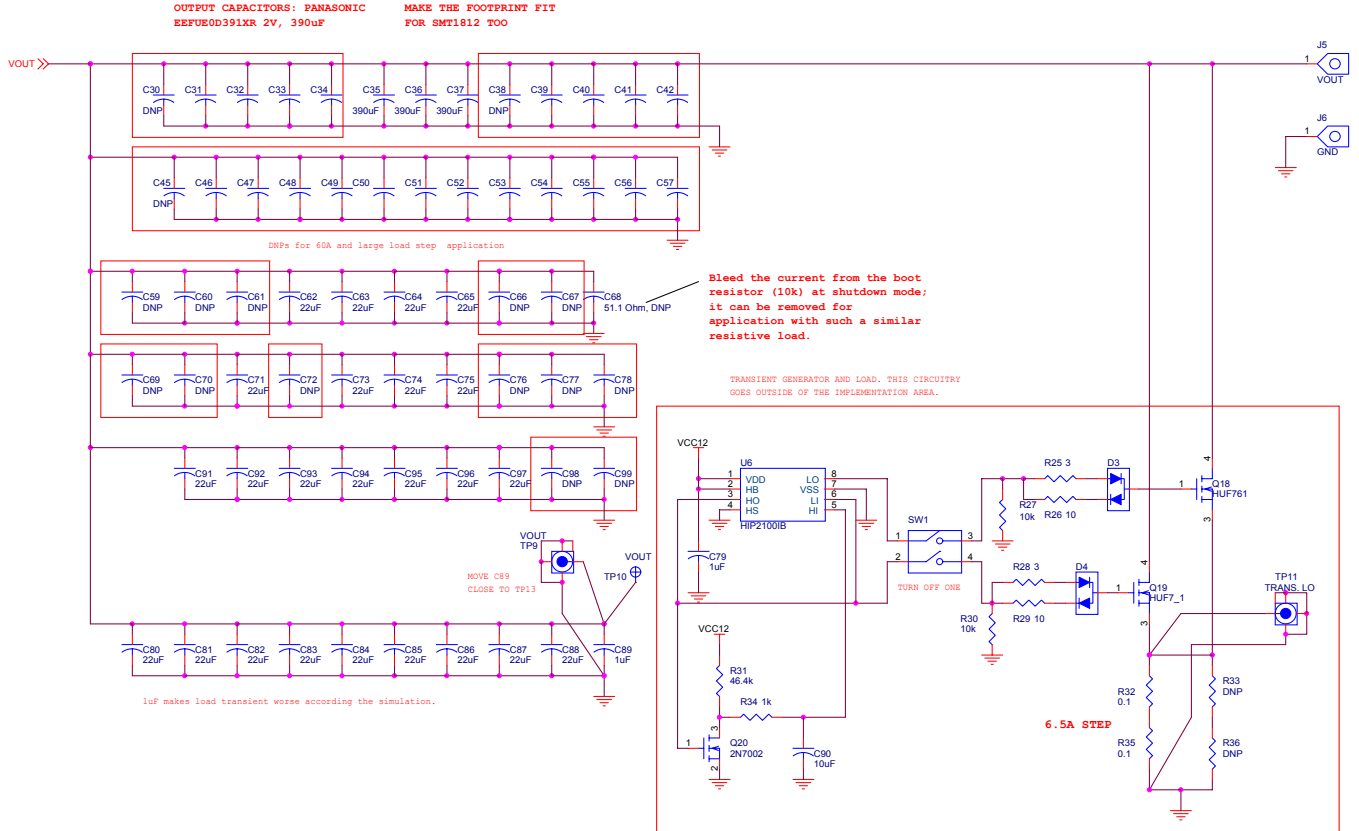
- [1] Intersil's ISL6558 Data Sheet.
- [2] Intersil's ISL6609 Data Sheet.
- [3] Intersil's ISL6557A Data Sheet

Appendix

- 1. Schematics of Reference Design and Load Transient Generator.
- 2. Bill of Materials and Layout of Evaluation Board.



| | | | |
|---|--|---|--|
|  | | Intersil Corporation Endura Power Management 4200 Sturup Creek Drive Durham, NC 27703 | |
| Size Custom | Title ISL6558EVAL2, 5V-TO-1.35V@30A, 500kHz | Rev B | |
| Date: Wednesday, November 20, 2002 | | Sheet 1 of 2 | |



| | | | |
|-----------------------------------|---------------------------------------|---|--|
| intersil | | Intersil Corporation | |
| Endura | | Endura Power Management 4020 Stump Creek Drive Durham, NC 27703 | |
| Size | Title | Rev | |
| Custom | ISL6558EVAL2, 5V-TO-1.35V@30A, 500kHz | B | |
| Date: Thursday, December 25, 2002 | Sheet 2 of 2 | | |

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Bill of Materials

| QUANTITY | REFERENCE | DESCRIPTION | PACKAGE | VENDOR | PART NO. |
|----------|---|---|--------------|--------------------|----------------|
| 1 | CR1 | Dual LED | | PANASONIC | LN2162C13-(TR) |
| 0 | C1, C25 | 22μF | SM/C_1206 | | DNP |
| 0 | C2, C3 | 680μF, 6.3V, AVX, TPS III, TPSV687M006R0035 | CAP_7361 | AVX | DNP |
| 3 | C4, C5, C6 | 180μF, 6.3V | CAP_TECAP | PANASONIC | EEFUE0J181XR |
| 0 | C7, C8, C9 | 180μF, 6.3V | CAP_TECAP | PANASONIC | DNP |
| 1 | C10 | 100μ, 16V | PTH | Panasonic | ECA1CHG101 |
| 10 | C11, C12, C15, C17, C21, C24, C27, C28, C79, C89 | 1μ | SM/C_1206 | Various | 6.3V, X5R |
| 0 | C13, C16, C22, C23, C26 | DNP | SM/C_0603 | | DNP |
| 1 | C18 | 0.1μF | SM/C_0805 | Various | 25V, X7R |
| 1 | C20 | 10n | SM/C_0603 | Various | 25V, X7R |
| 3 | C35, C36, C37 | 390μF, 2V, 10mΩ | CAP_TECAP | PANASONIC | EEFUE0D391XR |
| 0 | C30-C34, C38, C39, C40, C41, C42, C45-C57 | DNP | CAP_TECAP | | DNP |
| 26 | C14, C19, C62-C65, C71, C73-C75, C80-C88, C91-C97 | 22μF | SM/C_1206 | Various | 6.3V, X5R |
| 0 | C59-61, C66, C67-C70, C72, C76-C78, C98-C99 | DNP | SM/C_1206 | | DNP |
| 1 | C90 | 10μF | SM/C_1206 | Various | 6.3V, X5R |
| 2 | D2, D1 | MBR0530T1 | SOD123 | On Semiconductor | MBR0530T1 |
| 2 | D3, D4 | BAV99LT1 | SOT23 | Various | BAV99 |
| 2 | JP3, JP1 | 2-pin Header | TP\2P | Berg | 68000-236 |
| 2 | JP2, JP4 | 3-pin Header | TP\3P | Berg | 68000-236 |
| 3 | | Shunt for JP1, JP2 and JP4 | | Berg | 71363-102 |
| 1 | J1 | VIN | BINDING/POST | Johnson Components | 111-0702-001 |
| 1 | J2 | 5V BIAS | BINDING/POST | Johnson Components | 111-0702-001 |
| 1 | J3 | GND | BINDING/POST | Johnson Components | 111-0703-001 |
| 1 | J4 | 12V BIAS | BINDING/POST | Johnson Components | 111-0707-001 |
| 1 | J5 | VOUT | BINDING/POST | Burndy | KPA8CTP |
| 1 | J6 | GND | BINDING/POST | Burndy | KPA8CTP |
| 4 | L1, L2, L3, L4, L5 | 300nH | SMT | Panasonic | ETQP2H0R3BFA |
| 8 | Q1, Q2, Q5, Q6, Q10, Q11, Q14, Q15 | 9.4mΩ, 30V | LFPK | HITACHI | HAT2168H |
| 8 | Q3, Q4, Q8, Q9, Q12, Q13, Q16, Q17 | 4.4mΩ, 30V | LFPK | HITACHI | HAT2164H |
| 2 | Q20, Q7 | 2N7002 | SOT23 | On Semiconductor | 2N7002LT1 |
| 2 | Q18, Q19 | HUF76129D3S | DPK | Fairchild | HUF76129D3S |
| 0 | R1, R9, R10, R20 | 10k | SM/R_0805 | Various | DNP |
| 2 | R7, R12 | 909 | SM/R_0805 | Various | 1% |
| 0 | R2, R17 | 909 | SM/R_0805 | Various | DNP |

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Bill of Materials (Continued)

| QUANTITY | REFERENCE | DESCRIPTION | PACKAGE | VENDOR | PART NO. |
|----------|-----------------------|-------------------------------|--------------|------------|-------------|
| 5 | R3, R8, R13, R18, R24 | 0 | SM/R_0603 | Various | 1% |
| 2 | R4, R6 | 1k | SM/R_0805 | Various | 1% |
| 3 | R5, R27, R30 | 10k | SM/R_0603 | Various | 1% |
| 1 | R11 | 6.04k | SM/R_0603 | Various | 1% |
| 1 | R14 | 51.1K | SM/R_0603 | Various | 1% |
| 2 | R22, R15 | 22.1k | SM/R_0603 | Various | 1% |
| 1 | R16 | 750 (only 1% on board) | SM/R_0603 | Various | 0.1% |
| 1 | R19 | 499 (only 1% on board) | SM/R_0603 | Various | 0.1% |
| 1 | R21 | 750 | SM/R_0603 | Various | 1% |
| 1 | R23 | 499 | SM/R_0603 | Various | 1% |
| 2 | R25, R28 | 3.01 | SM/R_0603 | Various | 1% |
| 2 | R26, R29 | 10 | SM/R_0603 | Various | 1% |
| 1 | R31 | 46.4k | SM/R_0603 | Various | 1% |
| 2 | R32, R35 | 0.1 | SM/R_2512 | Panasonic | 1% |
| 2 | R33, R36 | DNP | SM/R_2512 | Various | DNP |
| 1 | R34 | 1k | SM/R_0603 | Various | 1% |
| 1 | SW1 | DPST SWITCH | | Grayhill | 76SB02 |
| 1 | TP1 | VIN | TP | Keystone | 5002 |
| 1 | TP2 | PHASE 4 | TP | Keystone | 5002 |
| 1 | TP3 | GND | TP | Keystone | 5002 |
| 1 | TP4 | PHASE 1 | TP | Keystone | 5002 |
| 1 | TP5 | PGOOD | TP | Keystone | 5002 |
| 1 | TP6 | COMP | TP | Keystone | 5002 |
| 1 | TP7 | PHASE 2 | TP | Keystone | 5002 |
| 1 | TP8 | PHASE 3 | TP | Keystone | 5002 |
| 1 | TP9 | VOUT | PROBE-SOCKET | Tektronics | 1314353-00 |
| 1 | TP10 | VOUT | TP | Keystone | 5002 |
| 1 | TP11 | LOAD CURRENT | PROBE-SOCKET | Tektronics | 1314353-00 |
| 4 | U1, U2, U4, U5 | ISL6609CR | MLFP8_3X3 | Intersil | ISL6609CR |
| 1 | U3 | ISL6558IR | MLFP20_5X5 | Intersil | ISL6558IR |
| 1 | U6 | HIP2100IB | SOIC8 | Intersil | HIP2100 |
| 4 | R37-R40 | 499k | SM/R_0603 | Various | 1% |
| 0 | C100, R41 | DNP | SM/R_0603 | Various | DNP |

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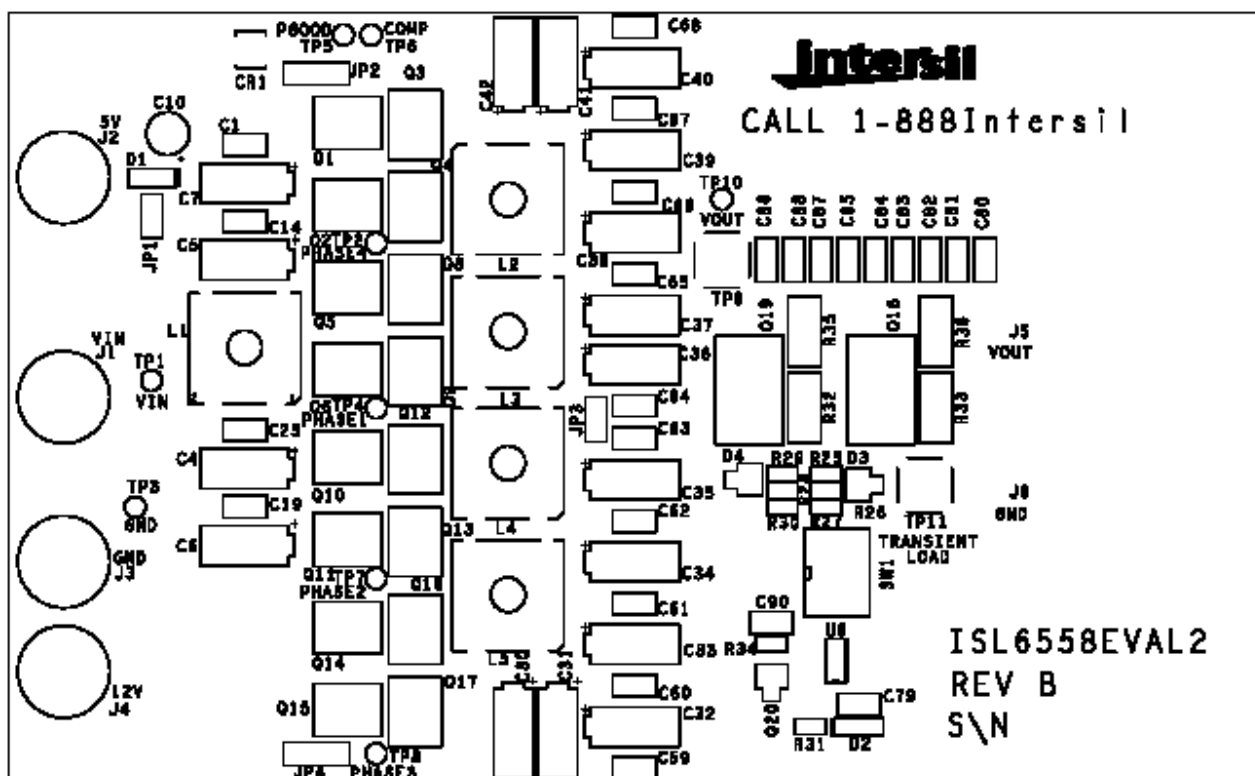


FIGURE 16. TOP LAYER SILK SCREEN

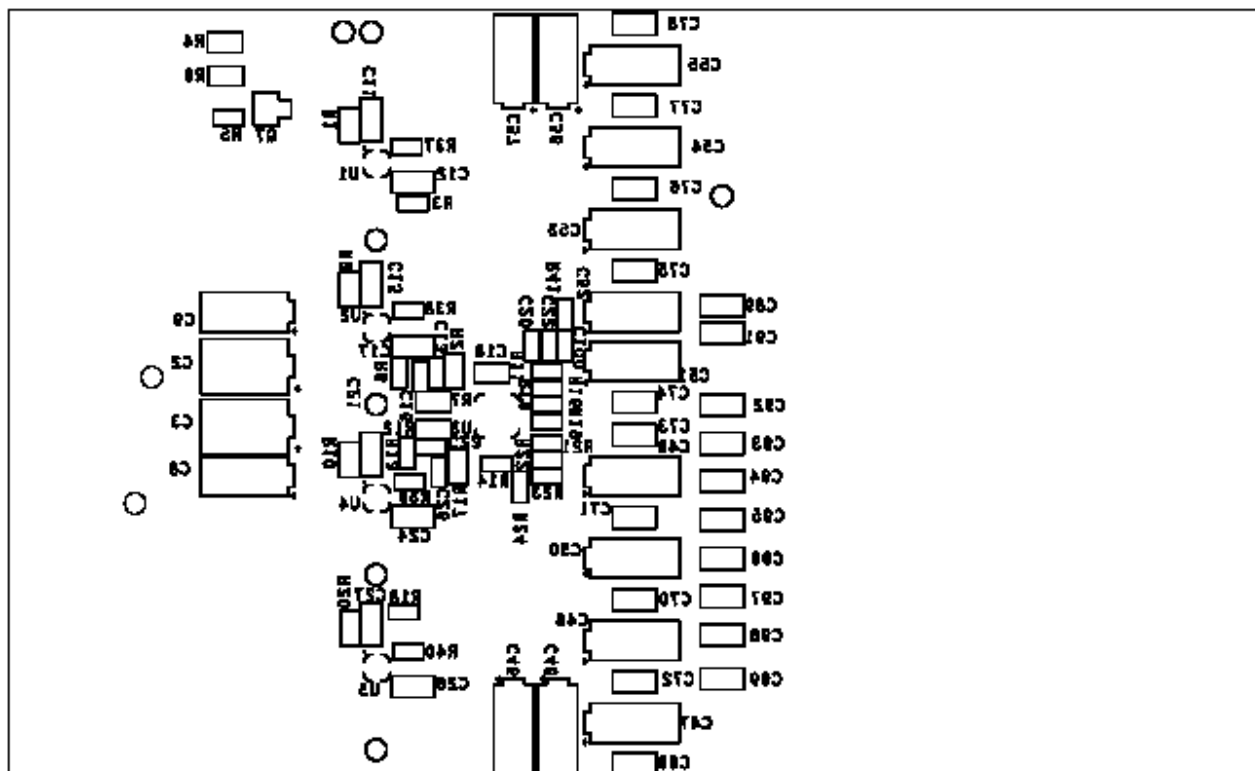


FIGURE 17. BOTTOM LAYER SILK SCREEN

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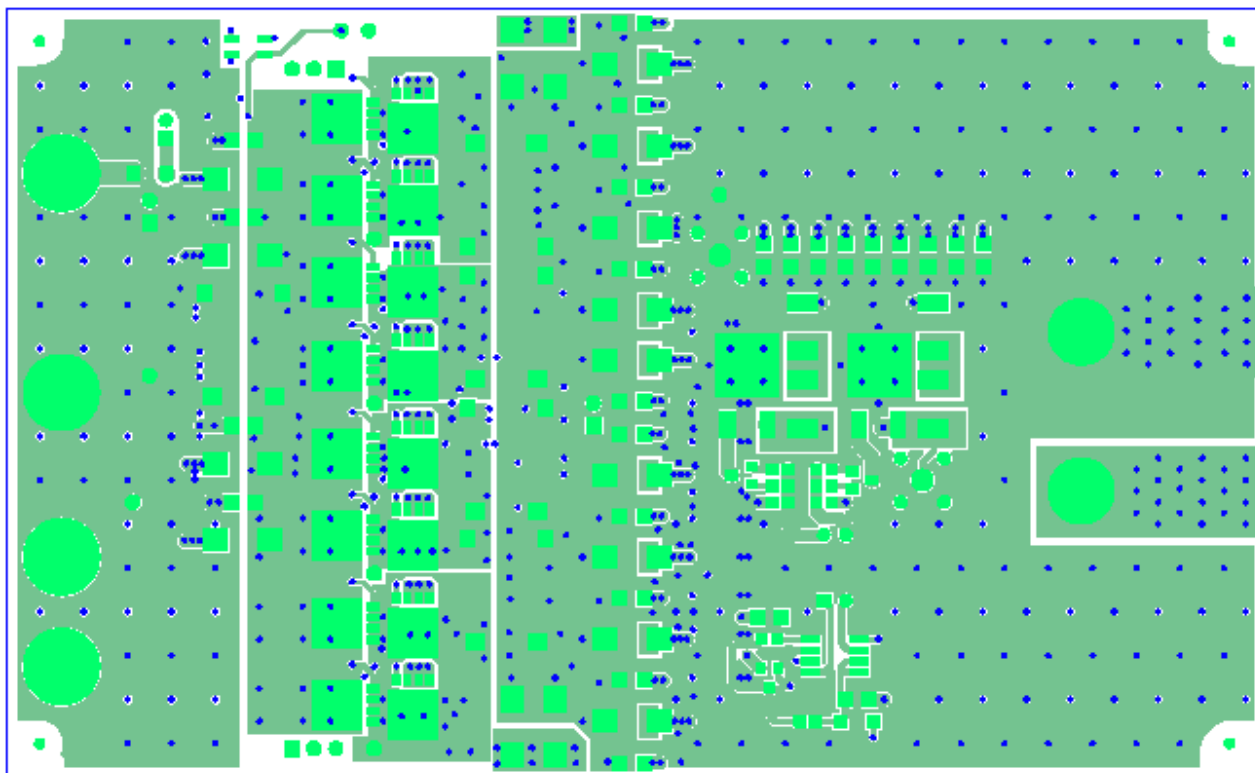


FIGURE 18. TOP LAYER COMPONENT SIDE

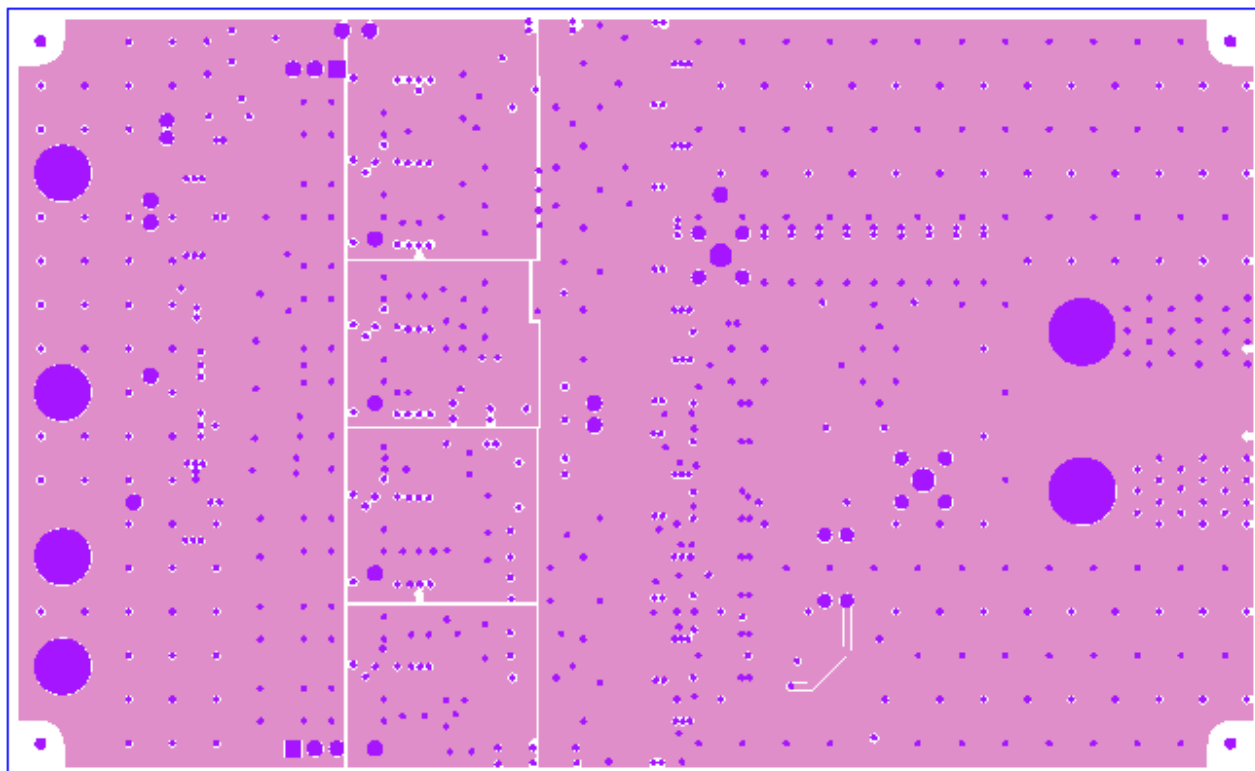


FIGURE 19. LAYER 2

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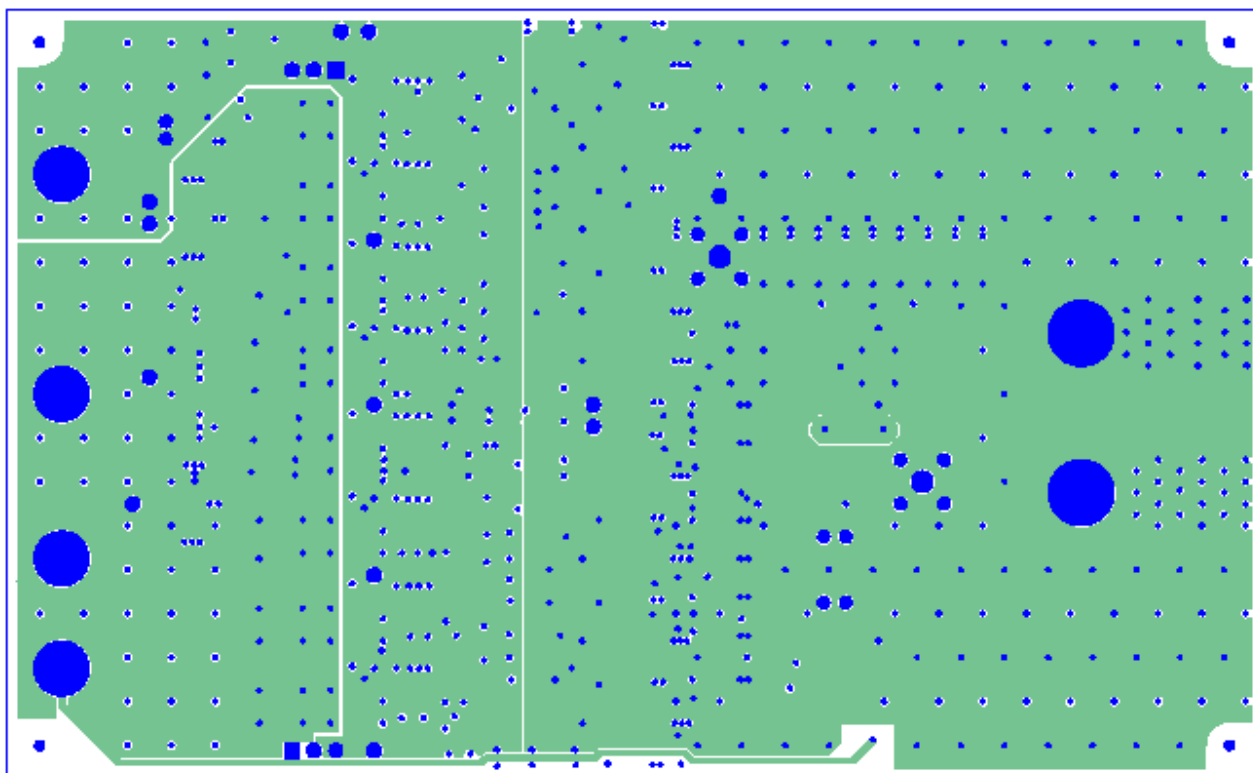


FIGURE 20. LAYER 3

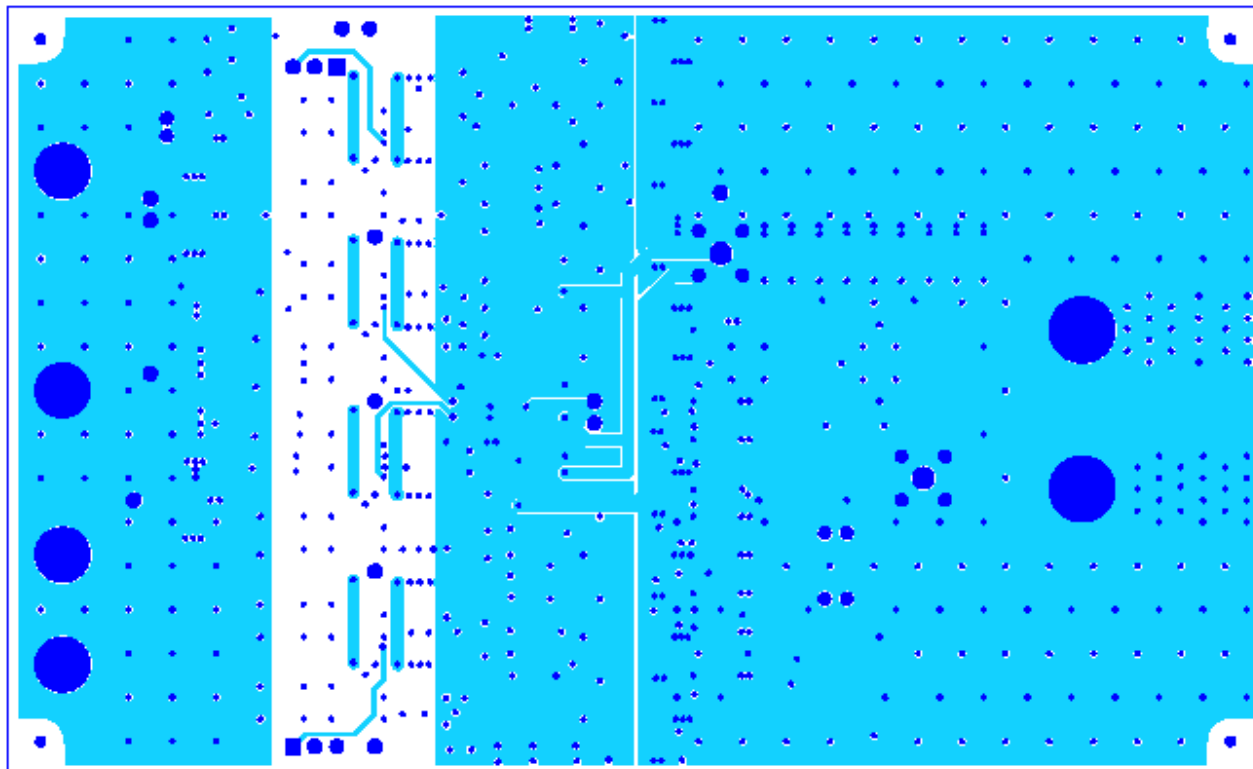


FIGURE 21. LAYER 4

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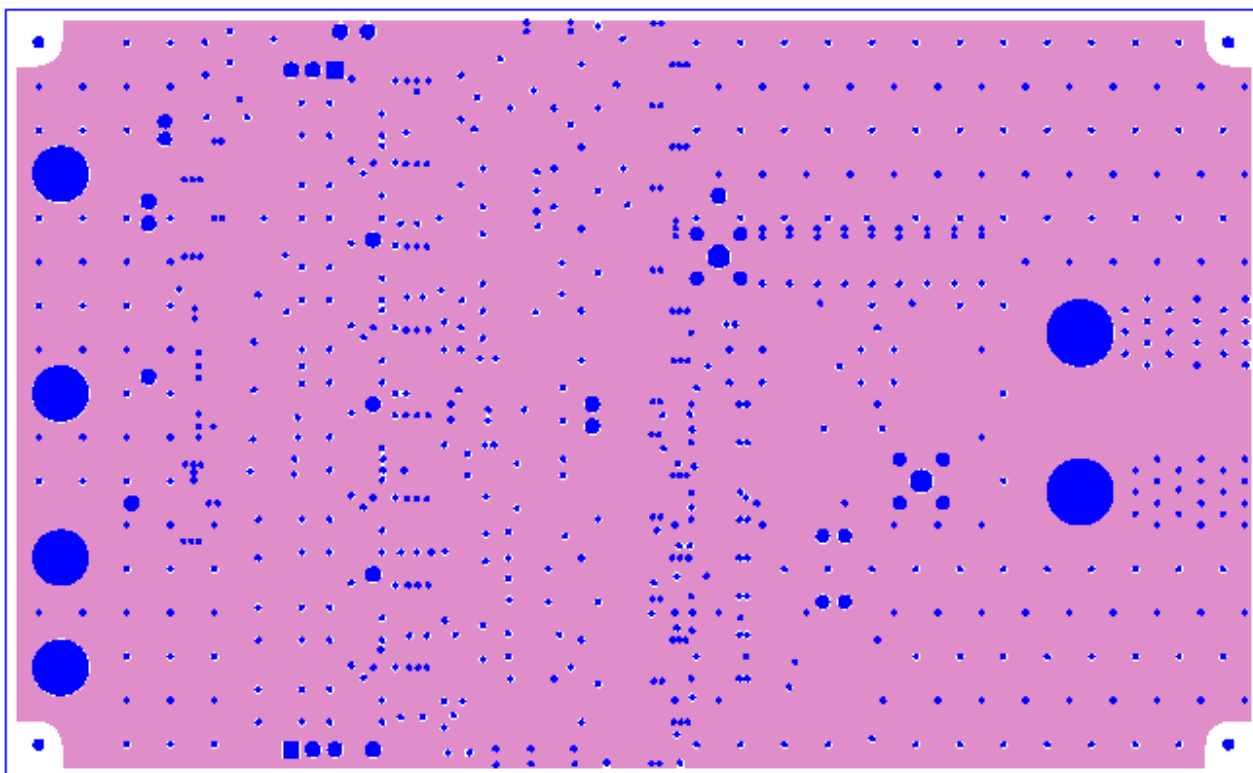


FIGURE 22. LAYER 5

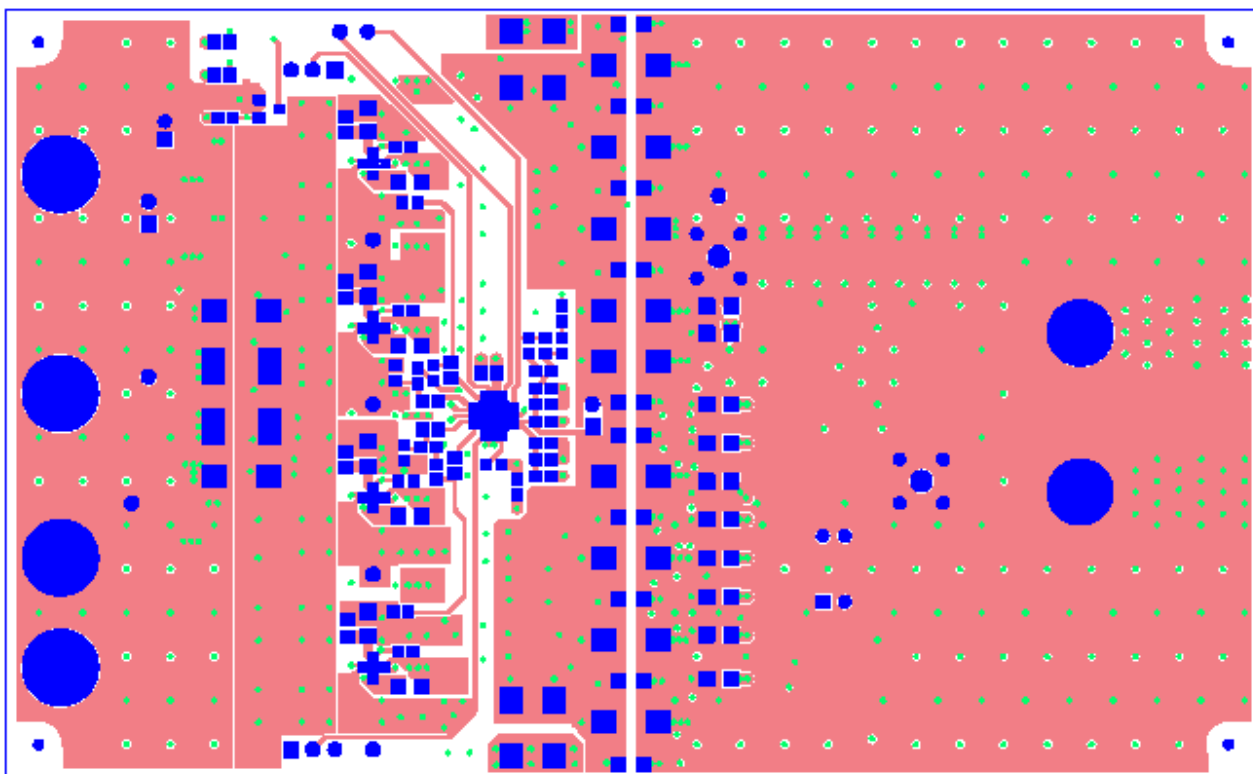


FIGURE 23. BOTTOM LAYER COMPONENT SIDE