MPQ4470

5A, 36V Synchronous Buck Converter in a 3x4mm Package Application Note

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INTRODUCTION

The MPQ4470 offers an ultra-compact and highly efficient solution for applications with higher power requirements. The MPQ4470 has an input-voltage range of 4.5V to 36V (40V abs. max) with integrated 40mΩ and 20mΩ MOSFETs (HS/LS) in a 3x4mm QFN package. The integrated MOSFETs simplify circuit design significantly, compared to buck controllers with external MOSFETs. MPQ automotive and industrial grade ICs are characterized and tested to guarantee specifications over the full operating temperature range. MP standard ICs guarantee parameters at room temperature and operation from -40°C to +125°C, typically. The MPQ4470A features output over-voltage protection (OVP) with latch-off removed. The MPQ4470 operates in the -40 °C to +125 °C temperature range and is offered in an automotive version with AEC-Q100 G1 qualification.

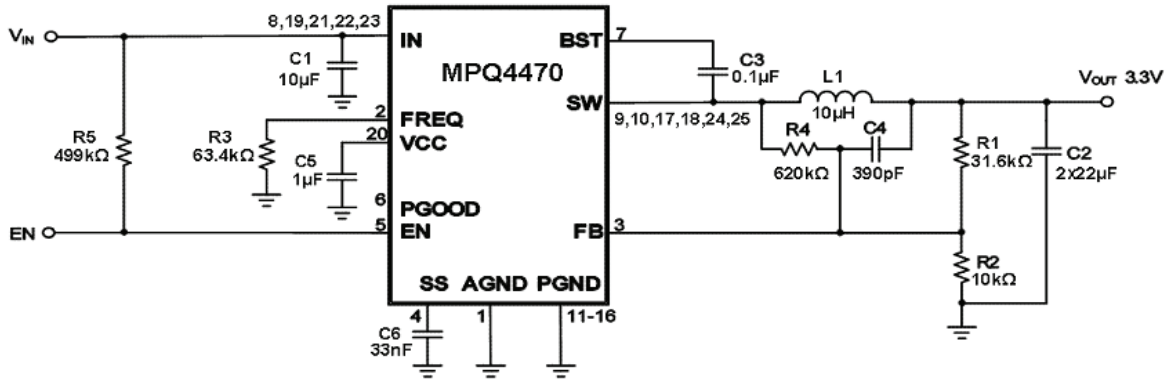

FIGURE 1. MPQ4470 Circuit – 5A with only 2x22µF MLCC at Output (f_sw = 500kHz)

To provide excellent load-step performance for demanding FPGAs or GSM modules, the MPQ4470 uses an adaptive constant on-time (COT) method for control. Normally, COT controllers have the disadvantage of switching frequencies that depend on the input voltage and the ESR of the output capacitor, which is undesirable in many applications. The MPQ4470 has an internal adaptive on-time that changes depending on the input voltage, resulting in a nearly constant switching frequency for the entire input-voltage range. Through R4 and C4, an additional ripple signal is fed into the feedback network (R1 and R2) making the switching frequency independent of the ESR of the output capacitor (see Fig. 1). The adaptive control loop and feedback network topology results in a COT controller with a remarkably constant operating frequency, functioning stably with low ESR output ceramic capacitors.

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ADJUSTBABLE SWITCHING FREQUENCY

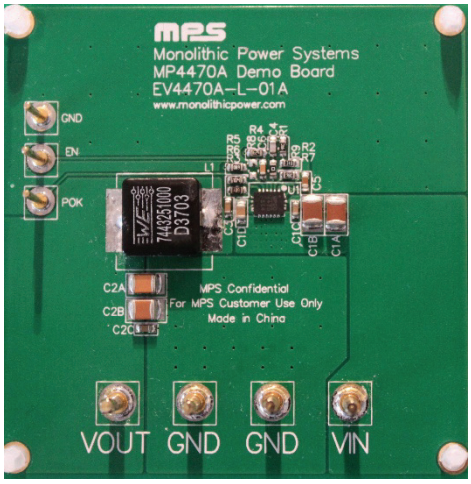

FIGURE 2. MPQ4470 Evaluation Board - 94.6% Efficiency

To optimize the external component size and reduce switching loss, the MPQ4470 offers an adjustable switching frequency. In a 24V to 3.3V and 3A load application, the efficiency drops from 92.3% (at 350kHz) to 91.8% (at 500kHz) or 90.6% (at 700kHz). Therefore, a doubling of the switching frequency results in 200mW (1.7%) higher losses for this operating point. If the circuit is supplied with 12V at the input, the efficiency is 94.1% (at 3A) for 350kHz operation, and 93.7% (at 700kHz). In a lower input-voltage application, the efficiency decreases by only 0.4% (45mW). In order to reduce power dissipation, applications that require a high-load current at output levels exceeding 5V should use switching frequencies in the range of 300kHz to 500kHz. This is true especially for input voltages of 24V and higher. For 12V input systems needing medium load currents and output voltages of 5V or less, frequencies up to 1MHz are recommended. Fig. 2 shows the MPQ4470 evaluation board.

Formula (1) gives the relationship between V_{OUT} and the resistor value of R_{FREQ} = R3 in Fig. 1:

$$f_{SW}(kHz) = \frac{10^6}{\left[\frac{96 \times R_{FREQ}(k\Omega)}{V_{IN}} + t_{DELAY}(ns)\right] \times \frac{V_{IN}}{V_{OUT}}} \quad \text{with } t_{DELAY} = 20ns \tag{1}$$

Tables 1 through 3 show recommended component values for the feedback dividers R1 and R2, as well as the slope components for R4 and C4.

TABLE 1. 300kHz, 24V_{IN}

V_{OUT} (V)	L (µH)	R1 (kΩ)	R2 (kΩ)	R4 (kΩ)	C4 (pF)	R_{FREQ} (kΩ)
3.3	10	30.9	10	953	390	110
5	10	53.6	10	845	560	169
12	22	68.1	4.7	820	300	412

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TABLE 2. 500kHz, 24V_{IN}

V_{OUT} (V)	L (µH)	R1 (kΩ)	R2 (kΩ)	R4 (kΩ)	C4 (pF)	R_{FREQ} (kΩ)
3.3	10	31.6	10	620	390	63.4
5	10	53.6	10	845	390	100
12	22	68.1	4.64	820	390	249

TABLE 3. 700kHz, 24V_{IN}

V_{OUT} (V)	L (µH)	R1 (kΩ)	R2 (kΩ)	R4 (kΩ)	C4 (pF)	R_{FREQ} (kΩ)
3.3	10	31.6	10	560	390	44.2
5	10	54.9	10	620	390	69.8

R_{FREQ} is the resistor that sets the switching frequency.

Fig. 3 compares 12V and 24V supplies at the same switching frequency. The difference is 1.8% (350kHz) or 3.1% (700kHz). The curves show the load current when the converter changes from a fixed-frequency continuous conduction mode (CCM) to light-load mode. The blue curve (24V input with 350kHz) is at approximately 600mA. In light-load mode, the efficiency is increased, but the output-ripple voltage increases as well. For a given switching frequency and input voltage, this point can be changed by changing the value of the inductor. A larger value of L extends the low ripple fixed-frequency CCM to lower load currents.

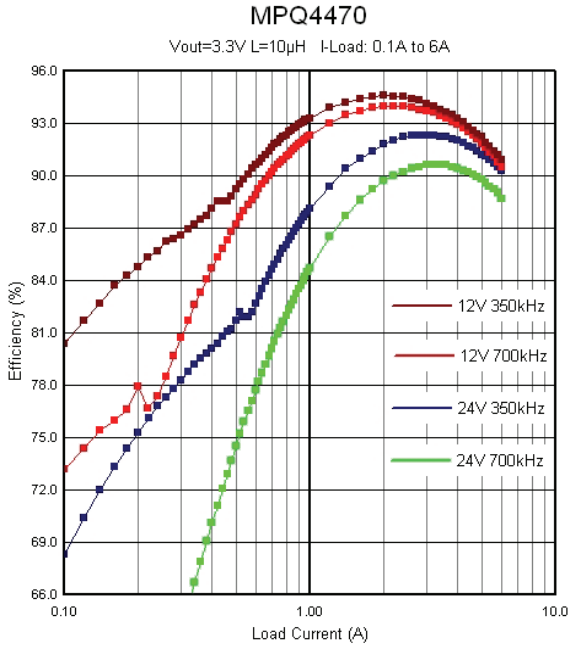

FIGURE 3. MPQ4470 Efficiency Comparison for 12V & 24V Supply (f_sw = 350kHz and f_sw = 700kHz)

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SWITCHING LOSSSES INCREASE LINERALY WITH FREQUENCY AND WITH THE SQUARE OF THE SUPPLY VOLTAGE

Compared to traditional controllers, the COT method provides significantly improved load change behavior. In the COT approach, a comparator reacts directly to the falling output voltage with a switch-on pulse, compared to the slower response of a conventional PWM style loop containing an error amplifier and integrator. For a buck regulator with a fixed-switching frequency (f_sw), generally the cut-off frequency of the control loop is in the range of 1/5 to 1/10 of the switching frequency. When f_sw = 500kHz, the control-time constant is 10µs to 20µs. Depending on the design of the controller, for a large load-step, 30µs to 100µs is required to switch back to a steady-state output voltage.

COT CIRCUIT ACHIEVES THE SAME DEVIATION WITH LESS OUTPUT CAPACITANCE

Fig. 4 shows a sharp load-step from 0.5A to 2.6A load with a rise time of 2A/µs. Although there are no more than 2x22µF ceramic capacitors at the output, the output voltage decreases only 80mV. Compare this to a GSM system that requires a rise time of only 0.15A/µs for the current.

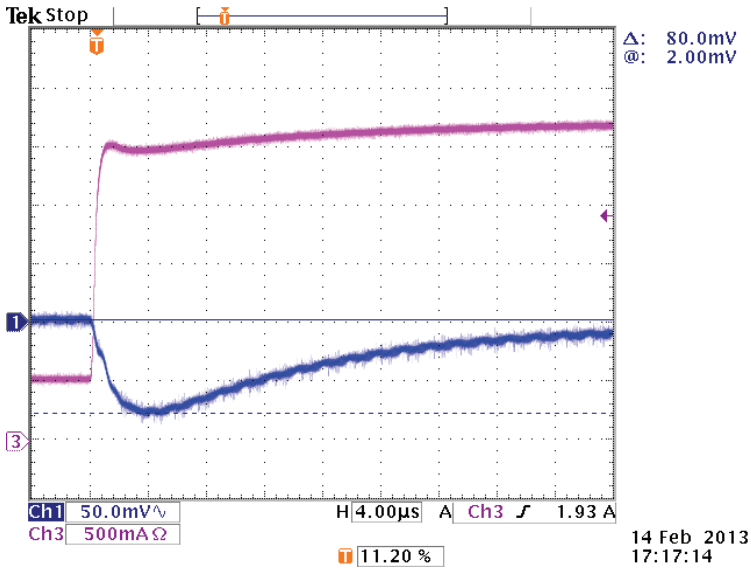

FIGURE 4. Load-Step from 0.5A to 2.6A with 2A/µs – 80mV Drop with Only 2x22µF Output Capacitance. f_sw = 500kHz, CH1 = Vout (50mV/div AC) CH3 = I_Load (500mA/div)

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Fig. 5 shows a simulated GSM load-step with 0.25A/µs from 0.5A to 2.5A in a 12V to 3.3V application with 2x22uF output capacitors. The output under- and overshoot is no more than 2%.

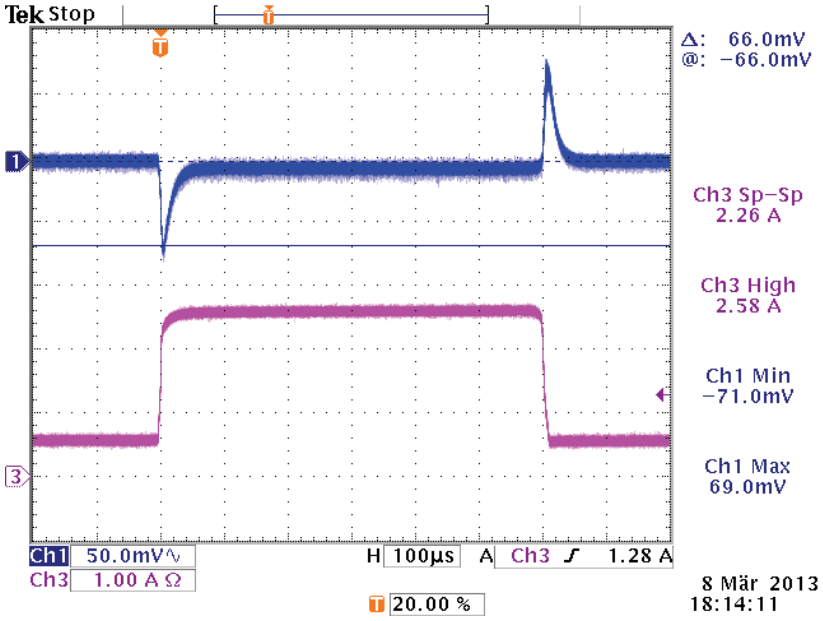

FIGURE 5. Simulated GSM Load-Step with 0.25A/µs from 0.5A to 2.5A in a 12V to 3.3V Application 2x22µF at Output

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COMPACT MONOLITHIC SOLUTION HAS EMC ADVANTAGES

As a monolithic IC in a compact, low-inductance flip-chip package, the MPQ4470 offers significant EMC advantages, compared to solutions using a controller IC and discrete FETs. This holds true in comparison to monolithic buck ICs from competitors that consist of several die connected internally with bond wires. Therefore, the interference critical antenna loop (formed by the input capacitors and the two power FETs) can be kept very small. Place two sets of input bypass capacitors symmetrically on each side of the MPQ4470 package (see Fig. 6). This way the effective parasitic inductance between the two internal MOSFETs and the bypass capacitance is cut in half, reducing ringing. IC-Power-GND pins and bypass capacitors GND connections are routed together on a local GND area (which is not connected to the top side GND area of the PCB). This noisy, local power GND area is connected to the system GND through vias.

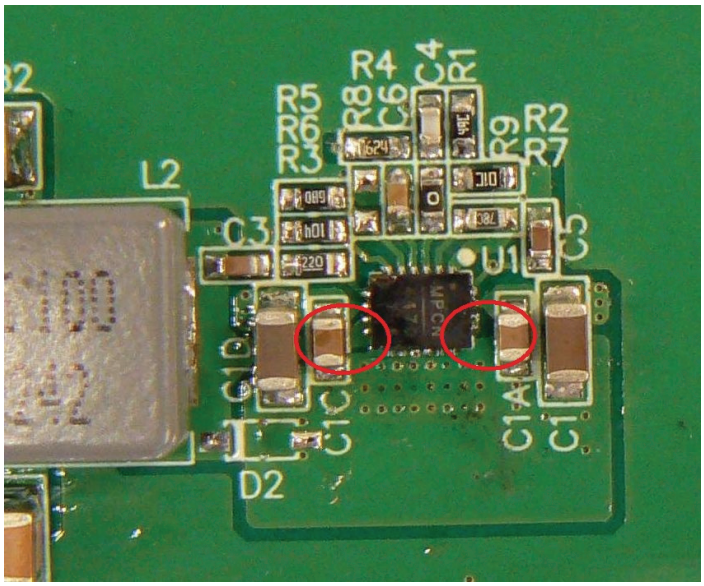

FIGURE 6. MPQ4470s Very Small Input Loops with High di/dt

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BST-PIN RESISTOR REDUCES OVERSHOOT AND RADIATION

To reduce rise time and overshoot at the switch node, place a small resistor between the bootstrap pin (BST) and C3 (see Fig. 1). This resistor reduces the gate-source capacitance charging-current of the upper power FET. The recommended default is 5Ω. Depending on the value and application, a reduction of about 3-6dB in radiated emission is possible; however, this increases switching losses. In a 3.3V and 3A output-load application (at 500kHz switching frequency), a change from 5Ω to 22Ω results in 1% (~100mW) higher losses for a 24V supply. With an input voltage of 12V, these losses increase only 0.4% (~40mW).

In the PCB design, a local GND has to be placed in the layer directly under the MPQ4470 circuit, keeping the distance minimal. A dielectricum of 50µm thickness between the component side and the first GND is ideal, less than 250µm is recommended. Impedance of the GND plane increases with the trace height above the plane. Fig. 7 shows an example of a 4-layer PCB configuration. The DC/DC converter circuit is placed on the top side layer (L1). In layer L2, there is a local GND area with at least the same size as the DC/DC converter circuit. This provides a local, low impedance return path for all high-frequency switching signals. Layer L3 is a solid GND layer across the full size of the PCB. No routings should be made in the GND layer, and extra care should be taken to avoid larger cut-outs due to multiple signal vias in close proximity. The copper-free areas around the vias easily create large holes and slits in the GND plane, increasing its effective impedance. The use of a local DC/DC converter GND in layer L2 and a solid GND plane in layer L3 helps keep high-frequency currents away from the system GND. Depending on the system, layer 2 can be used for low-speed signal routing or as a return GND for higher speed signals in the top layer (L1). Sensitive signals should NOT be routed close to the DC/DC converter circuit on the same layer! Never route any signal directly under a DC/DC converter in layer L2. On the opposite side of the DC/DC converter in the bottom layer (L4), an additional, local GND area should be used in order to reduce the thermal resistance of the circuit. Copper areas on the top layer (L1) and bottom layer (L4) reduce significantly the thermal resistance of the PCB.

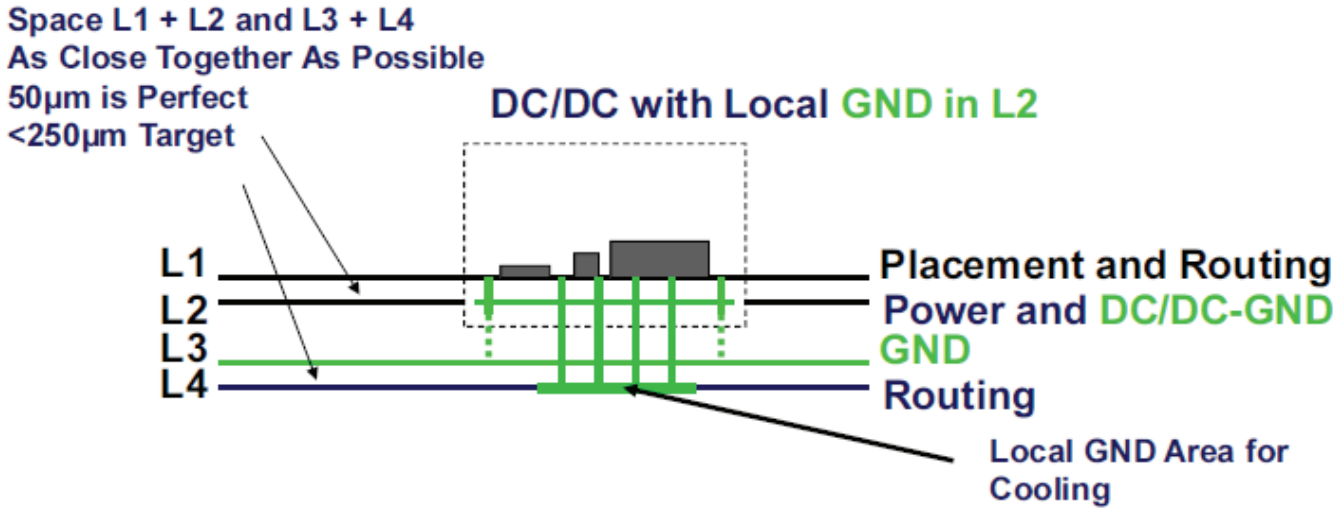

FIGURE 7. Recommended Layer Configuration for a 4-Layer PCB

The DC/DC converter has alternating magnetic fields around the input loop and the storage inductor (see Fig. 8). Depending on the type of inductor, the actual layout, and the distance to connectors and cables, these magnetic fields can be a major source of radiation. A shielded ferrite inductor offers very

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low stray fields, however, no signal lines should be routed near the air-gap. Molded iron-powder coils offer very high saturation currents for a given volume (due to the “distributed air-gap”), but they show a significant stray field around the component. Un-shielded coils should NOT be used in noise sensitive systems. Semi-shielded inductors often provide a good compromise between saturation current, stray fields, and cost.

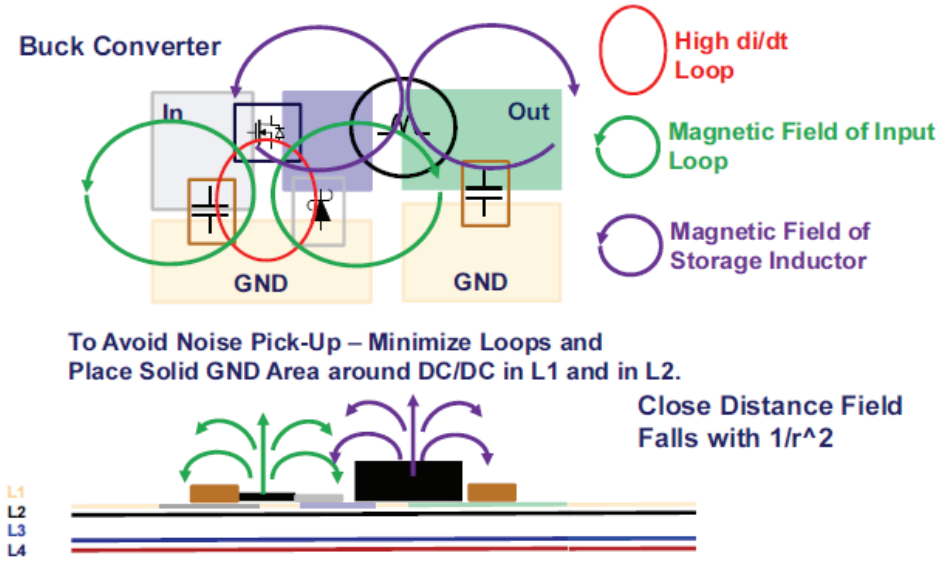

FIGURE 8. Magnetic Fields at DC/DC Buck Regulator

For lowest interference, a guard band with GND should be placed around the DC/DC converter on the component side. All signals should be routed on the opposite side of a GND layer to avoid magnetic coupling into the lines and cables (see Fig. 9). The alternating magnetic fields of the DC/DC induce eddy currents in the copper of the GND area. These eddy currents create magnetic fields with opposite orientation, resulting in a significant reduction of the fields below the GND area.

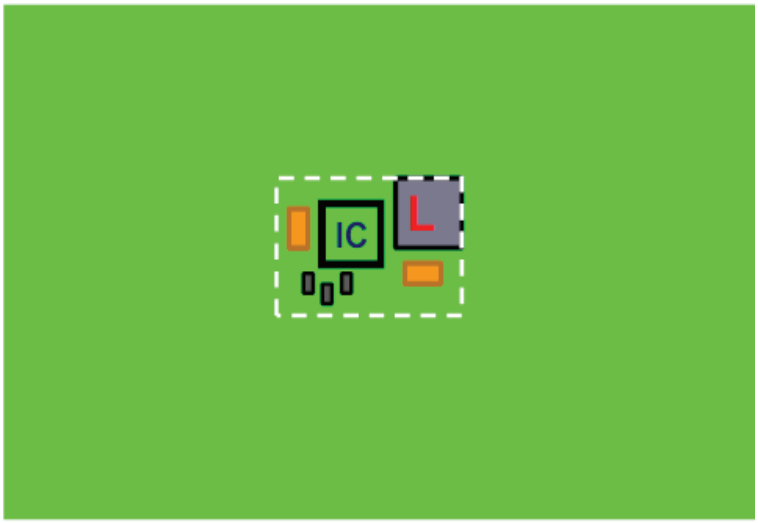

FIGURE 9. Large GND on Top around DC/DC Block

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GENERAL INPUT PROTECTION AND EMC FILTER STRUCTURE

In automotive and industrial systems, several additional input filter and protection components are required. Transient voltage suppressor (TVS) diodes clamp high-voltage spikes on the cables; they act like fast, large Zener diodes. In automotive systems, TVS diodes with a 28V nominal-off voltage are used to prevent conduction during jump-start. Depending on the type and source impedance of the transient, the TVS diodes clamp between 33V and 45V. Place a high-voltage ceramic capacitor (around 10nF) close to the input-power supply. This reduces high-frequency radiation on the cable and helps to block ESD. Most systems require a reverse-polarity diode. For high-current applications, a reverse-polarity diode can be replaced by a PFET (see Appendix B). To block the high-frequency noise caused by the system entering the cable, use a capacitor with several nF and a ferrite bead. The nominal current rating of a multi-layer ferrite bead is based on the thermal capabilities of the device, not on the saturation of the magnetic material. A small, typical 3A 100Ω@100MHz 0805 ferrite offers less than 10Ω at 1.5A current. Fig.10 shows the input protection and EMC filter structure. The yellow sections are high-frequency filters, and the blue section is a low-frequency filter.

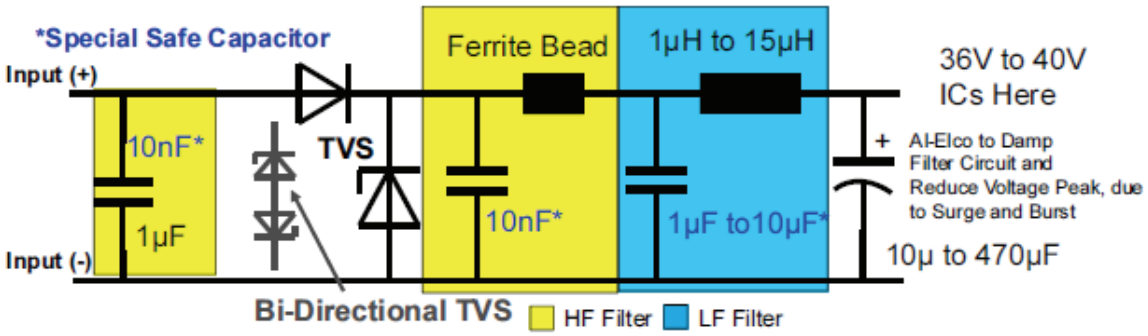

FIGURE 10. Input Protection and EMC Filter Structure

For multi-layer ceramic capacitors (MLCC) connected directly to a low-impedance source, safe capacitors like “OpenMode” or “FlexiTerm” offer a reliable solution. Standard MLCC may fail with a short circuit and cause excessive current and heat.

The fundamental switching frequency and the first harmonics need to be filtered with a LC Filter consisting of an inductor with several µH and one or more MLCC with a capacity of several µF. For a switching frequency of 500kHz, a 10µH and 10µF low-pass filter offers (in theory) close to 60dB damping. In reality, the effective capacitance of a type 3 MLCC will depend on its size and the applied DC voltage. Typical parts have roughly 50% remaining capacity at 50% of the rated voltage. The low-frequency input filter can alternatively be designed as a two-stage filter with much lower individual inductor values. This means two low-profile coils can replace one larger inductor and allow placement on a height-restricted bottom side.

The low-frequency input filter and the input cable form a high Q tank circuit that rings. To avoid over voltage at the DC/DC input, use a damping capacitor. A low-cost aluminum electrolytic capacitor with a few Ohm ESR is ideal. The capacity of the damping element should be 5 times greater than the input ceramic capacitor. If Al-Elcos are undesired, a series RC damper can be used instead. The low-frequency input filter with the damping capacitor reduces the voltage step at the DC/DC input in case of a low-impedance transient on the input cable.

In general, the EMC filter components must be placed away from the DC/DC converter to avoid degradation due to magnetic coupling. Ideally, they are not placed on the same side of the PCB.

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RADIATED AND CONDUCTED EMC TEST RESULTS ACCORDING TO CISPR25/EN55025

Fig. 11 shows the complete schematic of the MPQ4470 EMC test board. In addition to Fig. 9, the circuit on the EMC test PCB uses a low-frequency input filter (consisting of a 6.8µH coil and 2x1210 X7R ceramic capacitors, placed on the bottom side of the PCB) and a high-frequency input filter (using a multi-layer ferrite and 1nF, 100nF, and 47nF capacitors). The high-frequency capacitors were placed at different PCB locations.

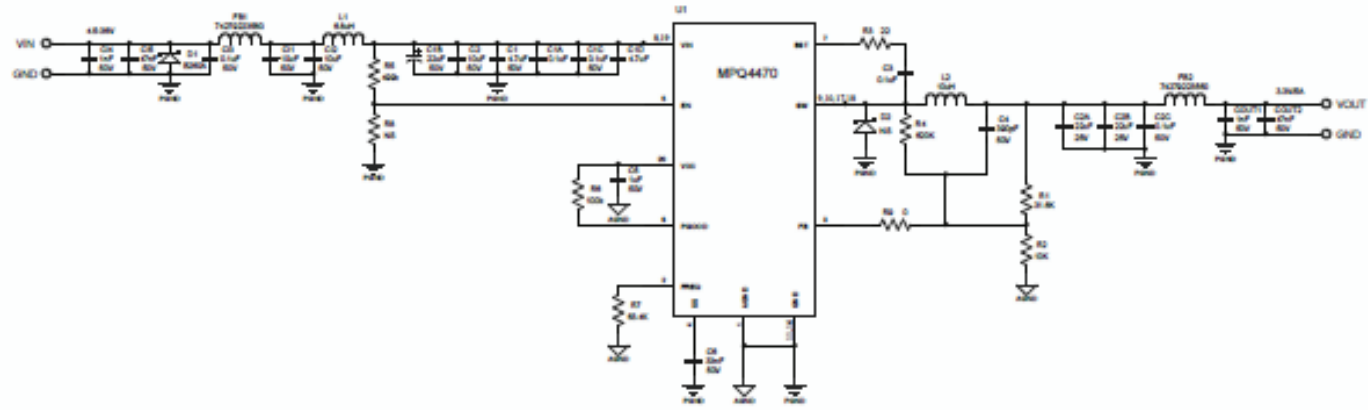

FIGURE 11. MPQ4470 Test Board Schematic

Fig. 12 shows the top layer of the test board. In the picture, the EV-Board is equipped with a molded iron-powder coil. The switching frequency is set to 450kHz to balance power losses and component size. Also, the switching frequency places the fundamental switching frequency in the upper half of the 300kHz to 530kHz band of CISPR25 without limits.

FIGURE 12. Top Layer of EV-Board

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EMC tests were performed with a 13V input supply (lead acid car battery) and a 5V output (with 4.5A load current). For the radiated EMC tests, the input source was connected through the 5µH LISN network and a 1m input cable. The output-load resistor was connected with a 1m cable. For the conducted EMC tests the input was connected to the LISN with a 20cm cable.
Fig.13 shows the conducted EMC results according to CISPR25 / EN55025 average.

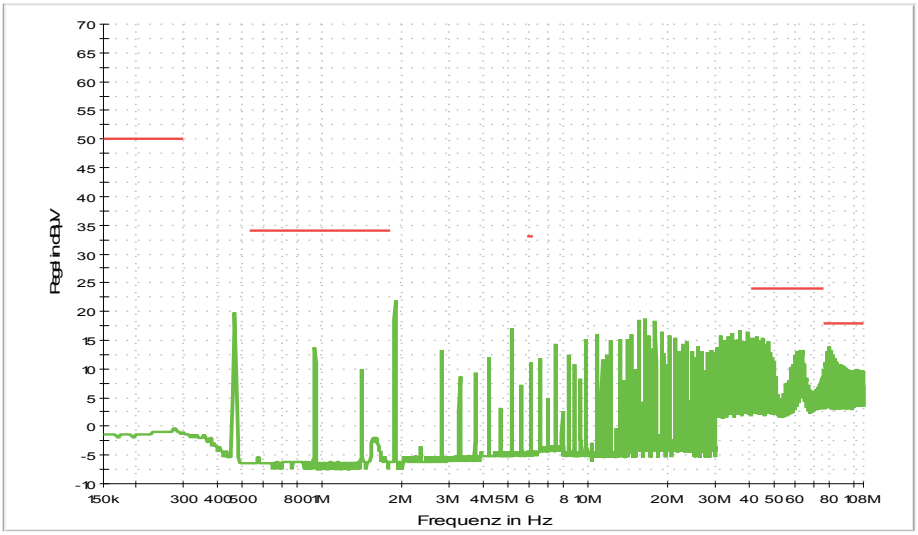

FIGURE 13. Conducted EMC Results according to CISPR25/EN55025 Average

Fig. 14 shows the radiated EMC results according to CISPR25 / EN55025 average. However, this measurement was taken with a shielded ferrite coil placed on the PCB, with the start of the winding connected to the SW node. Depending on the coil material and construction, the placement of the coil can lead to several dB differences.

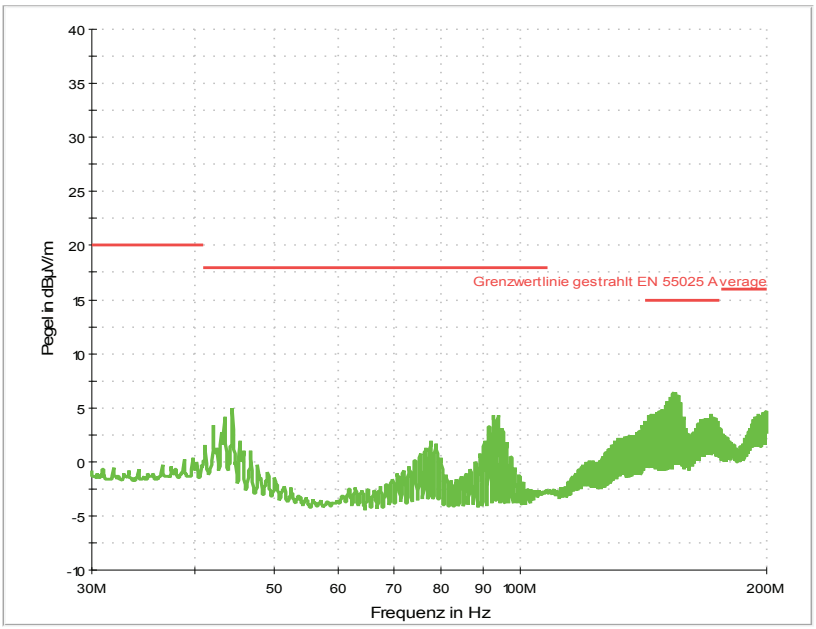

FIGURE 14: Radiated EMC Results according to CISPR25/EN55025 Average with Shielded Ferrite Coil

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Fig. 15 shows the same test with a molded iron-powder coil instead of a shielded ferrite coil. At 180MHz the worst-case result is ~ 18dB higher radiation.
The high-level between 150MHz and 180MHz is due to the molded iron-powder coil. The stray field of this coil couples into the output, creating common mode radiation. This can be reduced by using a shielded ferrite coil (as shown in the previous test) or by increasing the distance from the storage inductor to the output. The area between the coil and the connector should be filled with a solid GND on the component side.

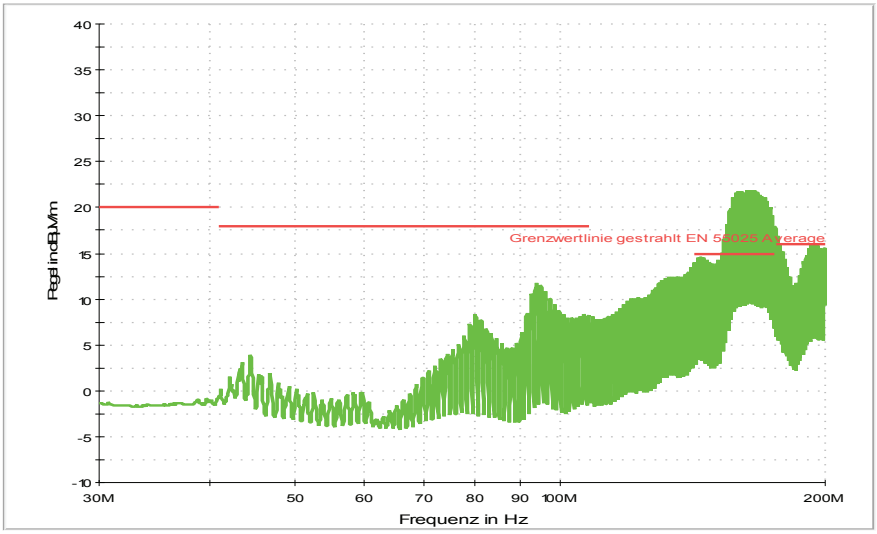

FIGURE 15. Radiated EMC Results according to CISPR25/EN55025 Average with Molded-Iron Coil

Using the right components and a good layout, the MPQ4470 can meet CISPR25 level 5 limits conducted and radiated with margin.

LOW-INPUT VOLTAGE OPERATION AND DROP-OUT PERFORMANCE

Multi-rail automotive systems often use MPQ4470A as a first-step regulator to generate a 5V intermediated supply (which is needed for peripheral components like CAN transceivers and as input to lower voltage POL regulators that supply the processer core and I/O). Automotive OEM customers specify the car board net voltage down to less than 5V during cold-crank. The 5V intermediated rail is allowed to drop during this condition, but interruptions are not accepted, as these would result in a power fail of the following POL regulators. The consequence is a processor re-set and a re-start of the firmware. This is a difficult requirement for buck regulators with N-channel high-side FETs. MPQ4470A has special, internal circuitry to handle this situation.

Fig. 16 shows the MPQ4470A in a 12V to 5V with 2.5A load configuration. During cold-crank pulse, the input falls below the nominal-output voltage (Ch3, 5V/division, pink). The output follows the input with very low offset (Ch2, 1V/division, light blue). The high-side NFET is turned on continuously, with short switching cycles, to refresh the BST circuit (Ch1, 10V/division, dark blue).

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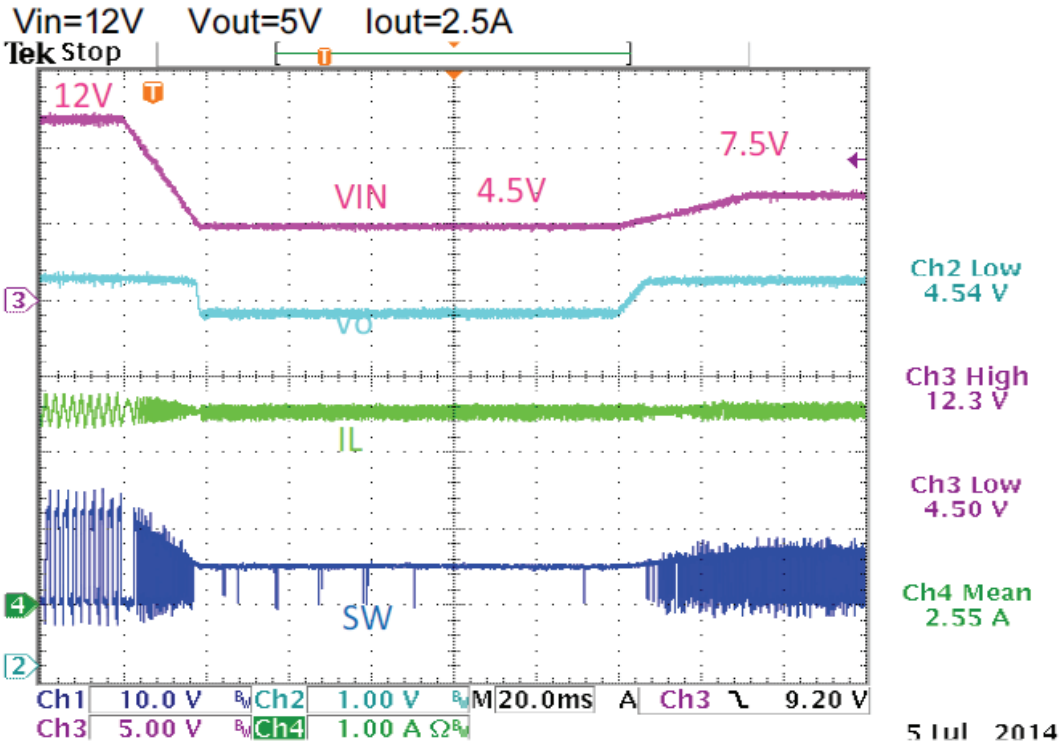

FIGURE 16. 12V to 4.5V Cold-Crank Input Pulse at 2.5A Load. Vout Shows Clean Drop-Out Mode

Fig. 17 shows the output voltage in drop-out operation for different load currents. The input is 4.50V. At 2.5A load current, it is only 230mV lower than the input. At 5A, the output is 3.9V (600mV lower than the input).

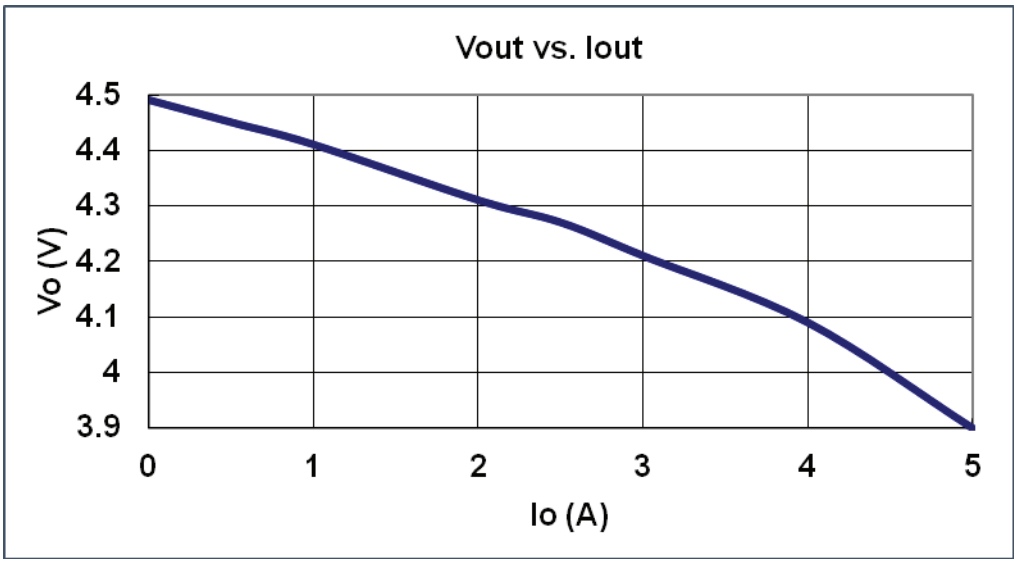

FIGURE 17. Output Voltage in Drop-Out with 4.5V at the Input for Different Load Currents

The MPQ4470 maximum input under-voltage lockout level for a rising input is 4.3V. For a falling V_{IN}, it's maximum input under-voltage lockout level is 3.4V. These levels facilitate operation of the converter (once started at a higher input voltage) with falling input voltages as low as 3.4V.

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LOW- INPUT VOLATGE OPERATION FOR 3.3V NOMINAL OUTPUT

If the MPQ4470 is used for a 3.3V output rail in an automotive system, it delivers a stable 3.3V output as low as V_{IN}=3.7V at a load of 3A. For lower input voltages, MPQ4470 enters the special low-drop mode.

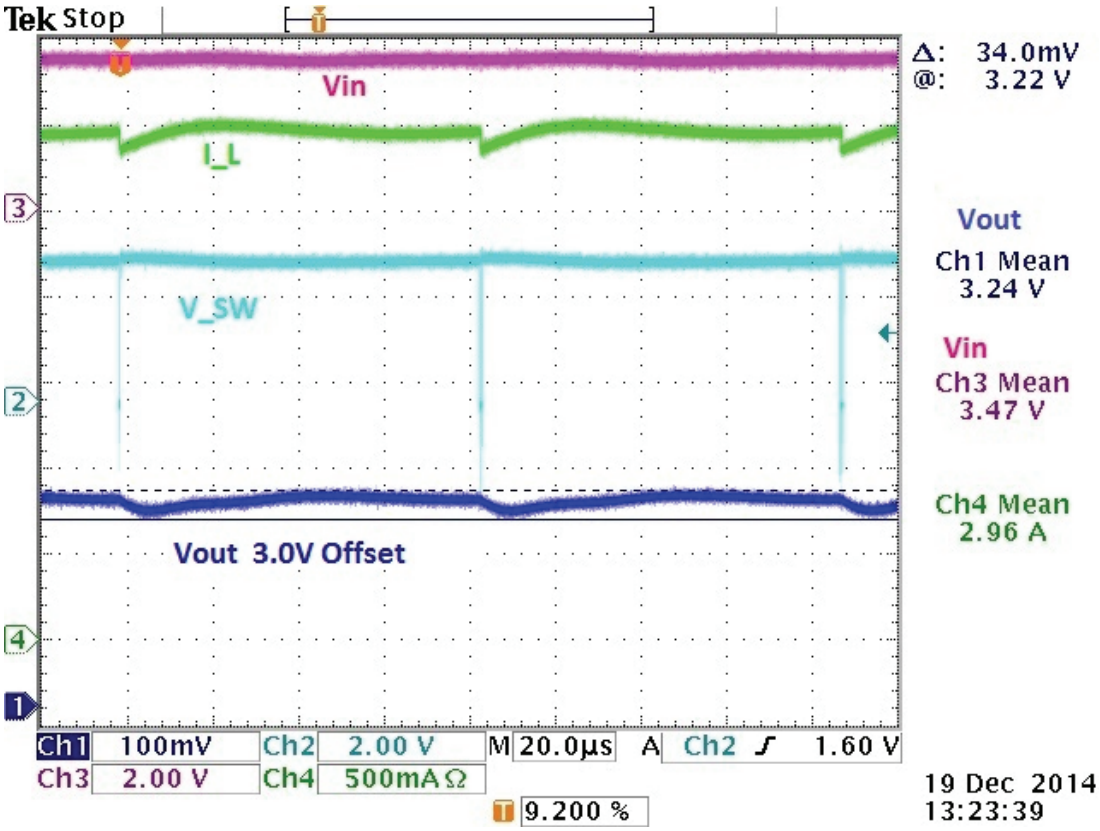

FIGURE 18. MPQ4470 Low-Input Operation with 3.3V 3A Output

Fig. 18 shows the input (Ch3, 2V/division, pink), the inductor current (Ch4, 0.5A/division, green), the switch node (Ch2, 2V/division, light blue), and the output (Ch1, 100mV/division, 3.0V offset, dark blue) waveforms for an input voltage of 3.5V and the resulting output of 3.24V with 3A load. The measurement is taken with the special EMC test PCB and includes the input filter ferrite and coil. Note the BST refresh switching every 84µs. MPQ4470 provides a stable 3.3V output with an input voltage as low as 3.5V at 3A.

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CONCLUSION

The MPQ4470 is a monolithic, synchronous, step-down switching regulator that allows the realization of applications with high-power density, due to its outstanding efficiency and few external components. The wide input-voltage range (4.5V to 36V) makes the MPQ4470 optimal for a variety of industrial and automotive applications. Moreover, the controller's adaptive constant on-time architecture combines the advantages of a classic COT controller's excellent load-step response with a nearly constant switching frequency, previously reserved for PWM controllers. The modern flip-chip QFN package with low-inductance copper bump gives the IC advantages for stringent EMC automotive applications.
The MPQ4470s excellent drop-out performance offers a solution for automotive applications with input voltage drops as low as 3.5V during cold-crank.

Notes:

1) H. W. Ott, *Electromagnetic Compatibility Engineering,* Indianapolis, IN: John Wiley and Sons Inc., *2009.*
2) For additional details, please refer to MPQ4470 datasheet on the MPS website.

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APPENDIX A: POSITIVE TO NEGATIVE OUTPUT CONVERTER

MPQ4470 offers a compact solution for positive to negative converters. Fig. 19 shows a -12V output converter for up to 2.5A load current. In this topology, the circuit is referenced to the negative rail instead of GND in a standard buck configuration. The maximum input voltage (plus the absolute of V_{OUT}), must stay below 36V.The IC input bypass capacitors are placed between the input and the negative output.

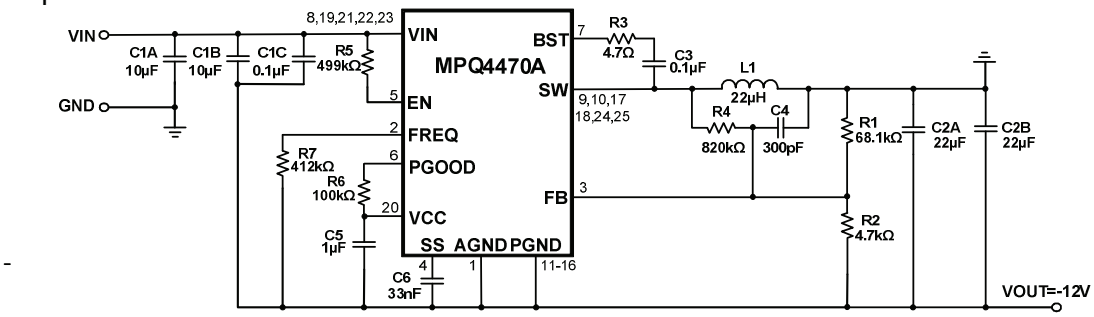

FIGURE 19. Positive to Negative Converter for -12V Output

The circuit is calculated like a buck converter, with the effective input voltage of V_{IN} plus $|V_{OUT}|$ to $|V_{OUT}|$. In the buck converter, the load current is equal to the average inductor current. In this circuit, the available load current is the average of the low-side FET current. Depending on the effective input to output voltage ratio, this is significantly lower than the buck converter.

The duty-cycle (d.c.) is calculated by:

$$d.c. = \frac{|Vout|}{(Vin+|Vout|)}$$

$$Maximum\ load\ current = (1 - d.c.) * 5A$$

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Fig. 20 shows the efficiency curve for a 12V to -12V converter with MPQ4470. Above a 2A load current the dissipated power increases rapidly.

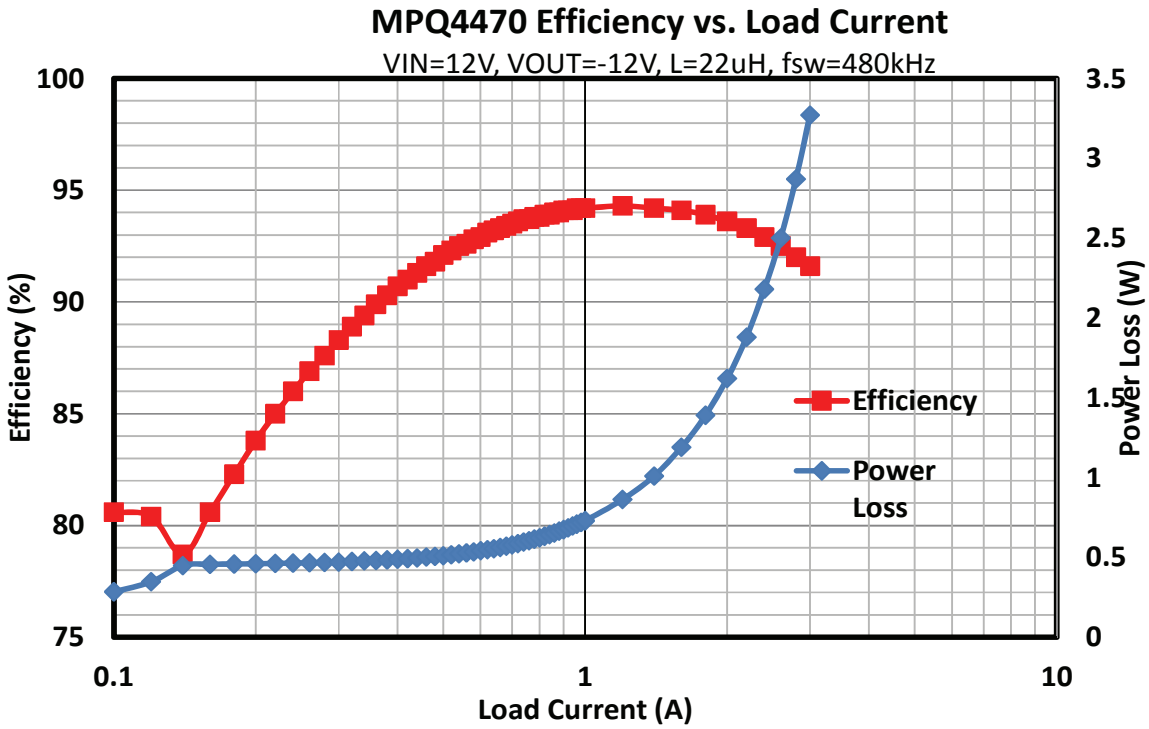

FIGURE 20. Efficiency of MPQ4470 12V to -12V Converter

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APPENDIX B: REVERSE-POLARITY PROTECTION PFET CIRCUIT

Fig. 21 shows a circuit with reverse-polarity protection using a PFET (M1) in the high-side. The PFETs body diode has the orientation of the normal, reverse-polarity protection diode. At positive input voltage, the PFET (M1) is turned on via the voltage dividers R1 and R5. The 10V Zener-diode D1 protects the gate of M1 against over-voltage. Values of R1 and R5 are determined by the input-voltage range and quiescent current requirements. In case of a negative input voltage, M2 is turned on via R3 and R4, which turns off M1. The gate of M2 is protected with the 10V Zener-diode D2.

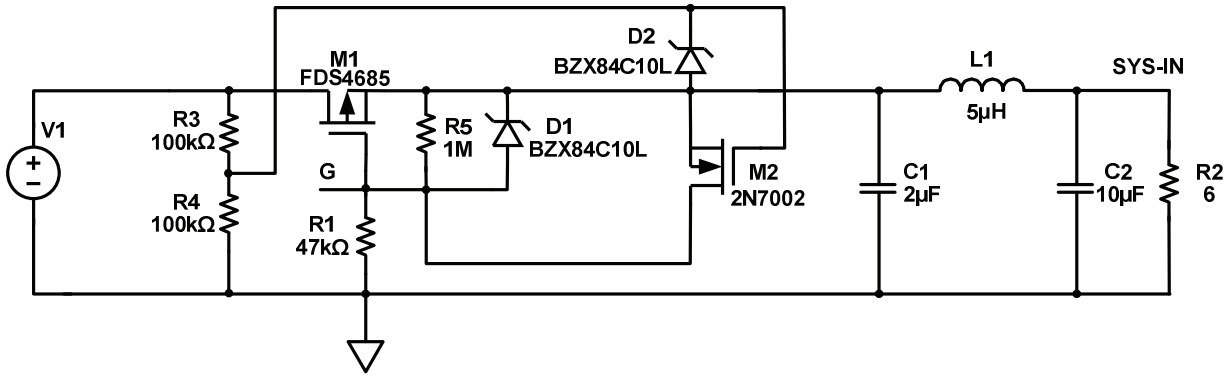

FIGURE 21. Reverse-Polarity Protection with PFET

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APPENDIX C: INPUT-TRANSIENT PROTECTION CIRCUIT WITH NFET

Fig. 22 shows a circuit with an input-transient protection circuit with a NFET (M1) in front of the MPQ4470A input. At start-up, M1 is turned on via R8, charging up the input capacitors of MPQ4470A. When MPQ4470A starts switching, the capacitor C8 is charged to ~4.5V above V_{in} from the MPQ4470A BST circuit via R10 and D2. This way M1 is turned on completely to 10mΩ between the system source and MPQ4470A input. In case input-transient voltage exceeds 36V, the gate of M1 is clamped by D1. The voltage at MPQ4470A input is limited to 36V minus M1's V_{GS}. M1 must handle the power dissipation of the voltage difference between input transient and regulator input, times the system input-supply current.

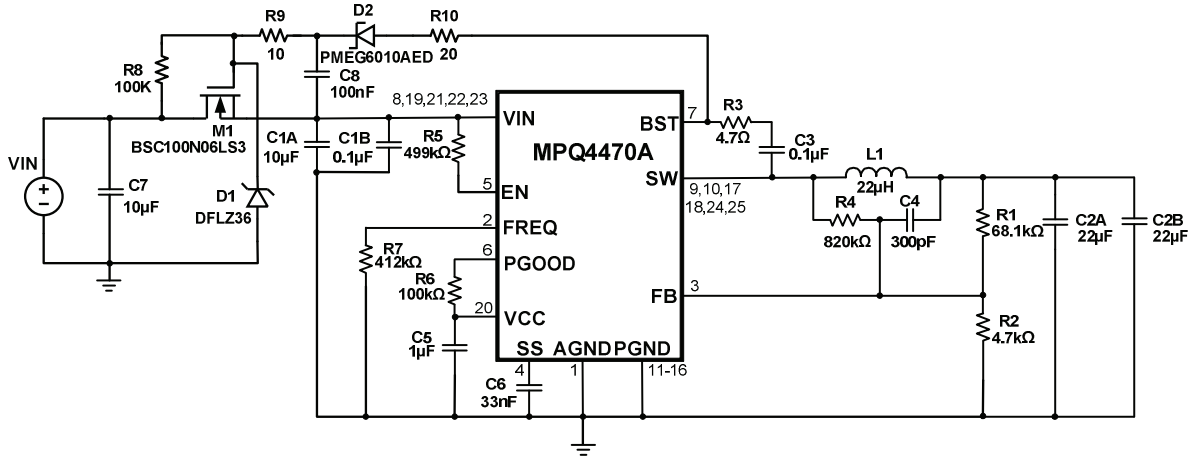

FIGURE 22. Input-Transient Protection with NFET

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APPENDIX D: EFFICIENCY CURVES

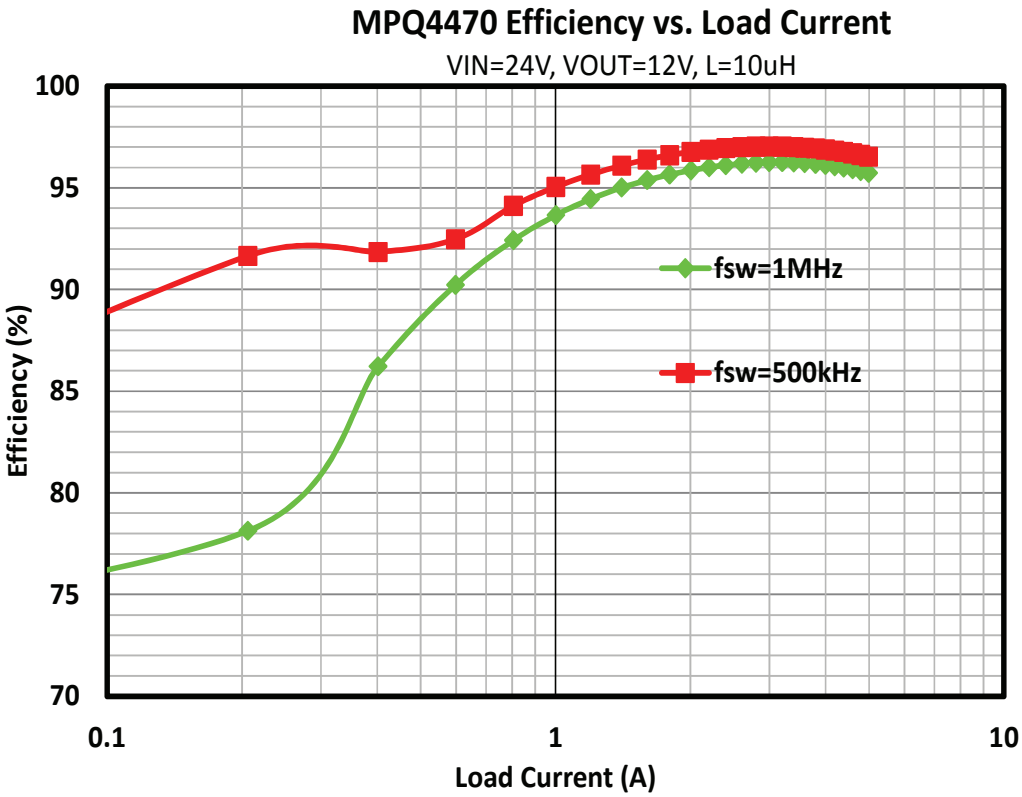

FIGURE 23. Efficiency vs. Load Current VIN=24V, VOUT=12V, L=10uH

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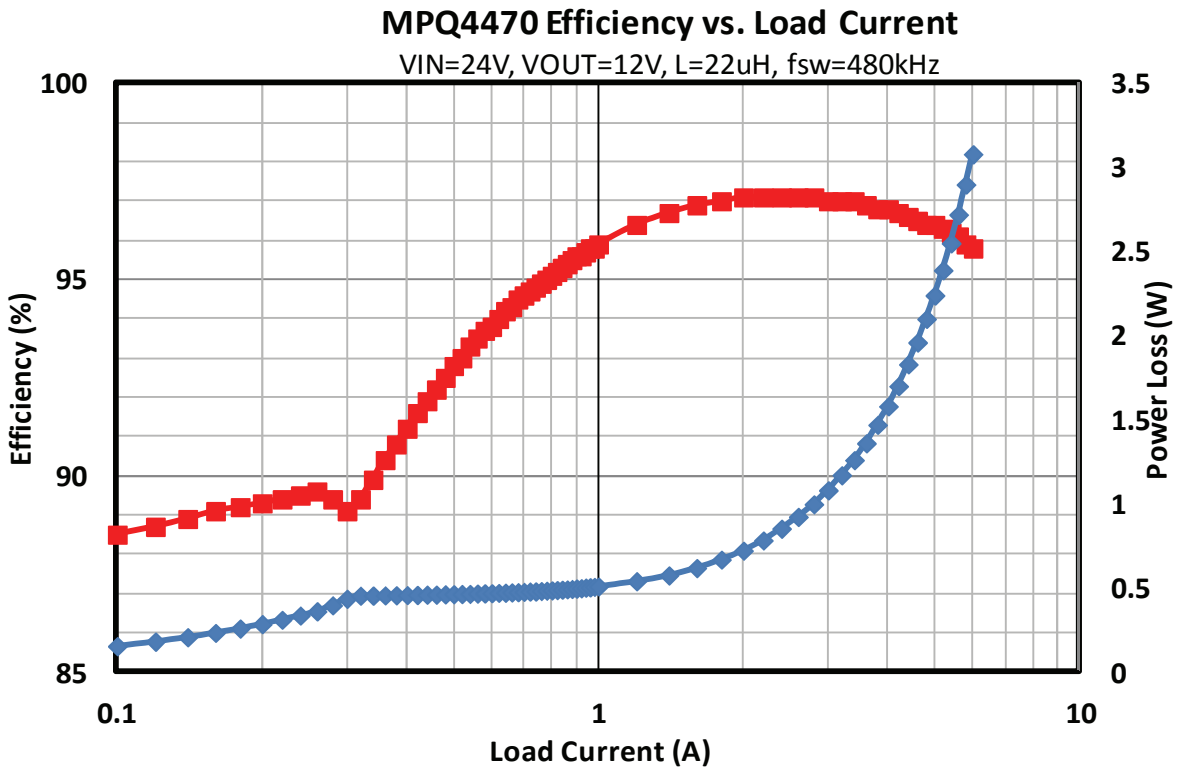

FIGURE 24. Efficiency vs. Load Current VIN=24V, VOUT=12V, fsw=480

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