ECE 534 Final Project Report

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Abstract:
This report details the analysis and iterative design process of a quadratic buck converter, emphasizing power loss allocation and ripple minimization. The project aimed to meet strict specifications, including frequency variations between 50kHz and 100kHz, minimal current and voltage ripple, and efficiency thresholds above 80%. Iterative designs incorporated non-idealities, passive component losses, frequency changes, and advanced materials such as silicon carbide (SiC) MOSFETs. The results demonstrate the trade-offs between switching frequency, component selection, and efficiency. Design improvements from ideal to non-ideal analyses and increased frequencies highlight the efficacy of the quadratic buck for high-performance DC-DC converters. The final designs achieved the desired specifications, showcasing how simple changes widely influence converter functionality.

Academic Integrity Statement:
I affirm that I have not given or received any unauthorized help on this project and that all work is my own. I will complete this project in a fair, honest, respectful, responsible, and trustworthy manner.

Design of a Quadratic Buck Converter

ECE 534: Power electronics

I. Introduction

THIS report describes the analysis and design process of a quadratic buck converter. In it, multiple design iterations are discussed for the converter, varying in power loss allocation, switching frequency, and material used. The report consists of an ideal analysis, CCM-DCM boundary analysis, and non ideal power loss analysis of the quadratic buck converter, followed by designs that follow the principles outlined in the analysis section. An ideal quadratic buck converter circuit and the design specs are given below:

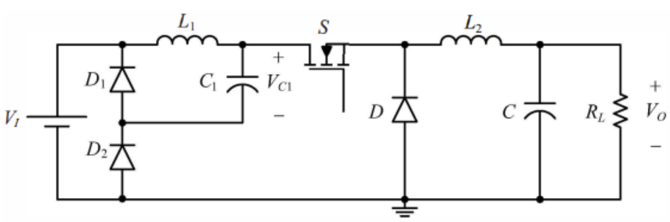


Fig. 1. Quadratic Buck Converter

Specification	Value
Input Voltage	400 V
Output Voltage	12 V
Output Power Range	40W - 120W
Maximum output current ripple (peak-peak)	0.1A
Maximum output voltage ripple (peak-peak)	0.12V
Minimum efficiency	80%
Switching Frequency	50kHz $\leq f \leq$ 100kHz

TABLE I
CONVERTER SPECIFICATIONS

II. Ideal Quadratic Buck Converter Analysis

Using the ideal circuit, analysis can be done for the time period that the MOSFET is on, and the time period that the MOSFET is off.

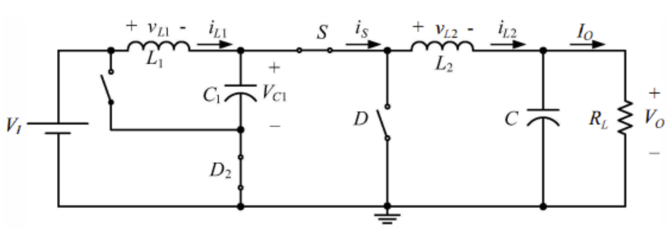


Fig. 2. Quadratic Buck Converter in the DT_S period (switch on)

Circuit analysis for Figure 2 ($0 \leq t \leq DT_s$):

$$V_{L1} = V_g - V_{C1}, \quad i_{C1} = i_{L1} - i_{L2}$$

$$V_{L2} = V_{C1} - V, \quad i_{C2} = i_{L2} - I_o$$

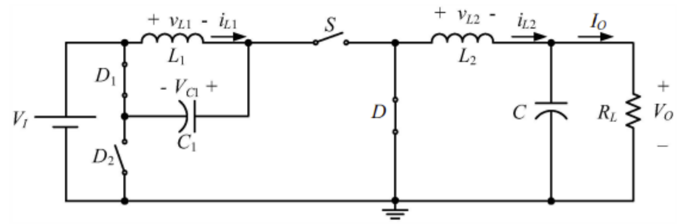


Fig. 3. Quadratic Buck Converter in the $D'T_S$ period (switch off)

Circuit analysis for Figure 3 ($DT_s \leq t \leq T_s$):

$$V_{L1} = -V_{C1}, \quad i_{C1} = i_{L1}$$

$$V_{L2} = -V_o, \quad i_{C2} = i_{L2} - I_o$$

Time-Averaged Voltage and Current Relationships:

1. Voltage across L_1:

$$\langle V_{L1}\rangle_{T_s} = 0 = D(V_g - V_{C1}) + D'(-V_{C1})$$

$$\langle V_{L1}\rangle_{T_s} = DV_g - V_{C1}$$

$$V_{C1} = DV_g$$

2. Voltage across L_2:

$$\langle V_{L2}\rangle_{T_s} = 0 = D(V_{C1} - V_o) + D'(-V_o)$$

$$\langle V_{L2}\rangle_{T_s} = DV_{C1} - DV_o - D'V_o$$

$$0 = DV_{C1} - V_o$$

$$V_o = DV_{C1}, \quad V_{C1} = \frac{V_o}{D}$$

3. Current through C_1:

$$\langle i_{C1}\rangle_{T_s} = 0 = D(i_{L1} - i_{L2}) + D'(i_{L1})$$

$$\langle i_{C1}\rangle_{T_s} = i_{L1} - Di_{L2}$$

$$i_{L1} = Di_{L2}$$

4. Current through C_2:

$$\langle i_{C2}\rangle_{T_s} = 0 = D\left(i_{L2} - \frac{V_o}{R}\right) + D'\left(i_{L2} - \frac{V_o}{R}\right)$$

$$\langle i_{C2}\rangle_{T_s} = i_{L2} - \frac{V_o}{R}$$

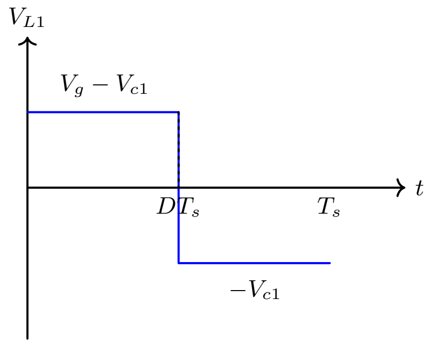
$$i_{L2} = \frac{V_o}{R}$$

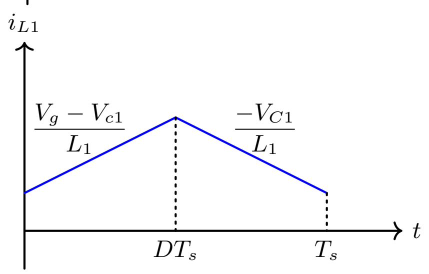
Using the converter specification shown in Table I and the results of the volt second balance equations above, the duty cycle for an ideal circuit can be calculated as follows:

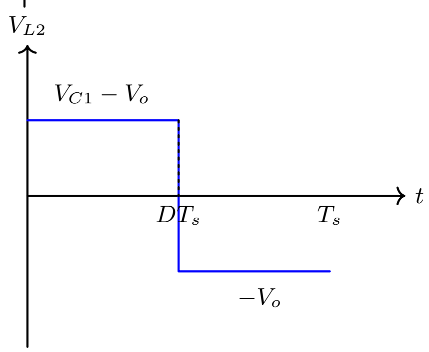
$$M(D) = \frac{V_o}{V_g} = D^2$$

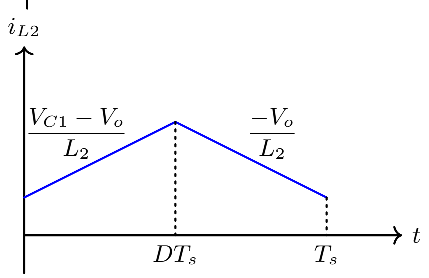
$$D = \sqrt{\frac{V}{V_g}} = \sqrt{\frac{12}{400}} = 0.1732$$

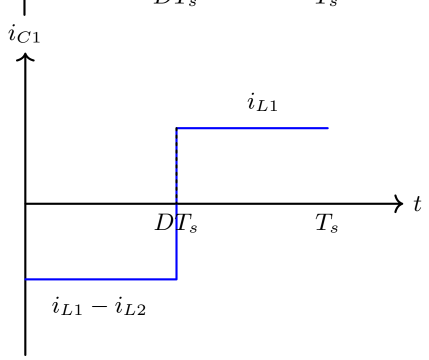
Using circuit analysis and the volt second balance equations above, currents and voltages of the circuit components can be graphed in relation to the time period (T_s).

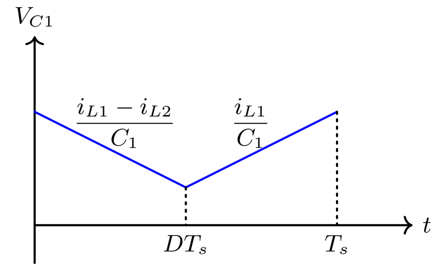


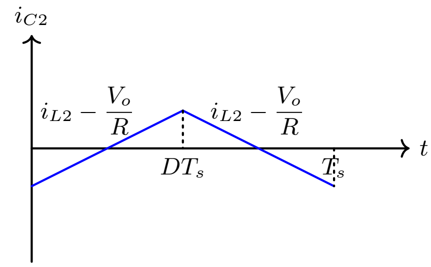


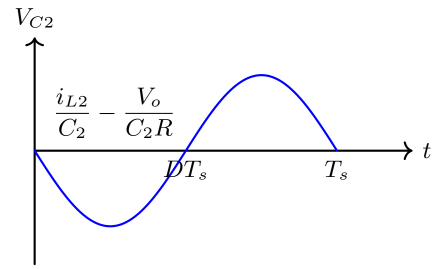


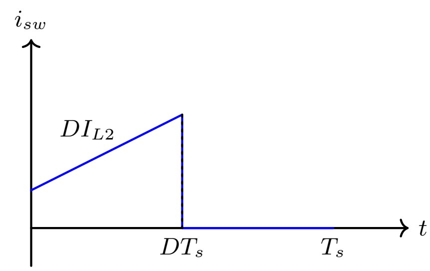


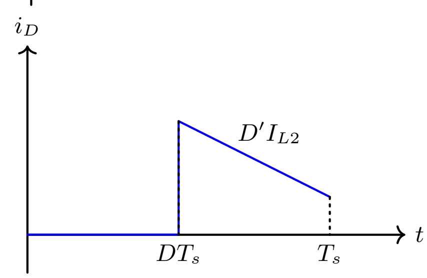


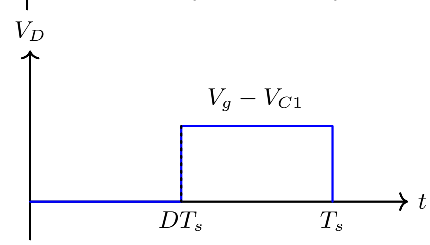












The volt second balance equations and graphs can then be used to derive the following equations for inductor ripple currents and capacitor ripple voltages within a Quadratic Buck Converter:

$$\Delta i_{L1} = \frac{V_g D D' T_s}{2L_1}$$

$$\Delta i_{L2} = \frac{V_g D^2 D' T_s}{2L_2}$$

$$\Delta V_{C1} = \frac{D^3 V_g D'}{R C_1 f_s}$$

$$\Delta V_{C2} = \frac{V_g D^2 D' T_s^2}{8 L_2 C_2}$$

Manipulating the inductor current ripple equations are then used to calculate ideal values of L_1 and L_2 using the specs in Table I:

$$L_1 = \frac{400(0.1732)(1-0.1732)}{(50,000)(0.1)} = 11.456 \times 10^{-3}\,\mathrm{H}$$

$$L_2 = \frac{400(0.1732)^2(1-0.1732)}{(50,000)(0.1)} = 1.984 \times 10^{-3}\,\mathrm{H}$$

Manipulating the capacitor voltage ripple equations are then used to calculate ideal values for C_1 and C_2 using the specs in Table I. Note that the equation used for C_1 is in accordance with Ayachit et al. [1]:

$$C_1 = \frac{I_{o,\max} D^2 D'}{f_s \Delta V_{C1}} = \frac{10(0.1732)^2(1-0.1732)}{50,000 \cdot 0.12} = 41.34\,\mu\mathrm{F}$$

$$C_2 = \frac{V_o D'}{8 L_2 f_s^2 \Delta V_{C2}} = \frac{400(1-0.1732)}{8(1.984 \times 10^{-3})(50,000)^2 \cdot 0.12}$$
$$C_2 = 2.0833\,\mu\mathrm{F}$$

The last step in ideal analysis is determining the peak voltage and current values for each component in the circuit. When choosing components, the designs in this report aim to account for 1.5 times the peak voltage and current values shown below in order to ensure that the circuit works safely even in the worst case scenario. These calculations were performed using circuit analysis, and the graphs shown above. The final calculated peak values are shown in the table below:

Component	Max Voltage (V)	Max Current (A)
L1	330.72	1.832
L2	57.28	10.1
C1	69.4	1.832
C2	12.12	0.1
D1	400	1.832
D2	400	8.268
D0	69.4	10.1
Q	469.4	10.1

TABLE II
IDEAL COMPONENT PEAK VALUE CALCULATIONS

It is important to note that these values are for an ideal quadratic buck converter with the exact converter specifications shown in Table I. This table is used as a continuous reference point for choosing components throughout the project. Using these values with ideal components, the PLECS simulation yields the following output current, voltage, and power.

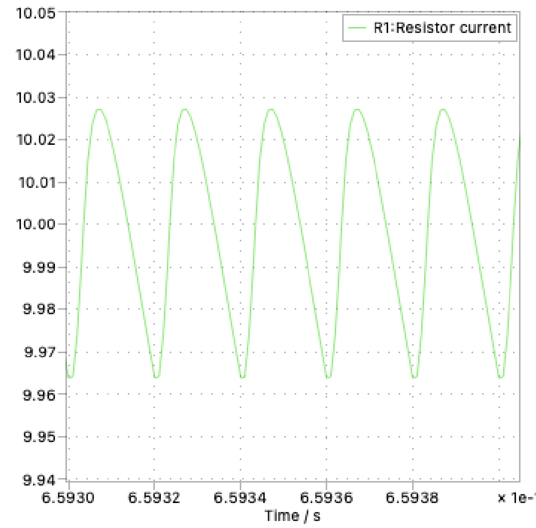


Fig. 4. Ideal Buck Converter Output Current Ripple

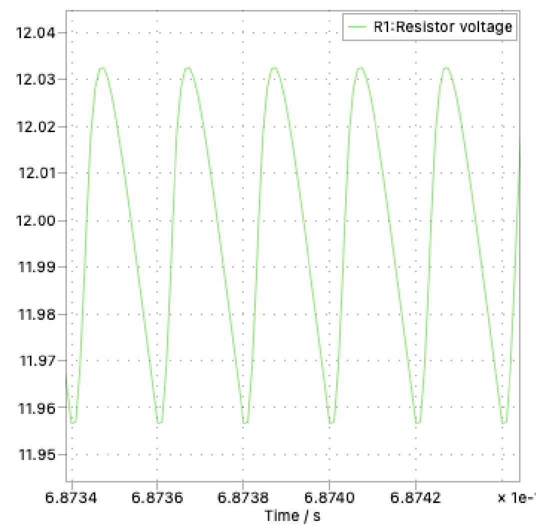


Fig. 5. Ideal Buck Converter Output Voltage Ripple

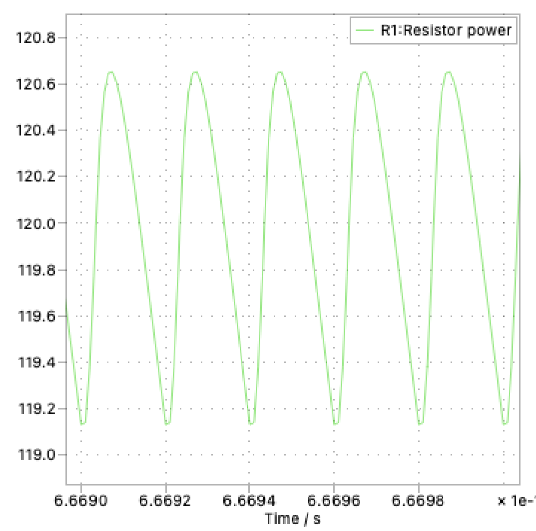
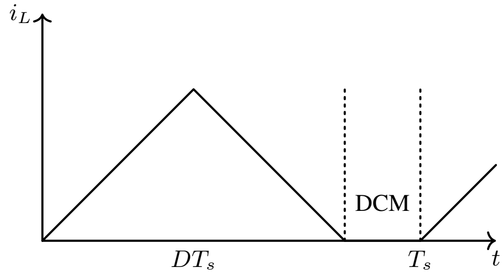


Fig. 6. Ideal Buck Converter Output Power

III. DCM CIRCUIT ANALYSIS

At the boundary of CCM and DCM, the ripple current through inductor L_2 is equal to the inductor current i_{L2}, causing there to be a period in which the inductor current is zero. This is represented by the graph shown below:



If $\dot{i}_{L1}$ and $\dot{i}_{L2} = 0$, the converter goes into DCM. When the converter is in DCM, the switching of at least one diode is not synchronous with the transistor switching, and the lower limit of output voltage range is limited. For CCM Operation:

$$k_1 > \frac{1-D}{D^2} \quad (\text{for } D_2);$$
$$k_2 > 1-D \quad (\text{for } D_o);$$
$$\left|\frac{1}{k_2} - \frac{1}{Dk_1}\right| < 1 \quad (\text{for } D_1)$$

where:

$$k_1 = \frac{2L_1}{RT_S}, \quad k_2 = \frac{2L_2}{RT_S}.$$

In order to keep each design in CCM, minimum inductor and capacitor values need to be calculated. In *Steady-state Analysis of PWM Quadratic Buck Converter in CCM*, Ayachit et al. [2] provides comprehensive derivation for CCM-DCM boundary conditions in a quadratic buck converter. The derived minimum inductance and capacitance equations are as follows:

$$L_{2\text{min}} = \frac{V_O(1-D)}{2f_s I_o}$$
$$L_{1\text{min}} = \frac{L_{2\text{min}}}{D}$$
$$C_{1\text{min}} = \frac{(1-D)}{D} \cdot \frac{V_O}{4L_1 v_{C1p-p} f_s^2}$$
$$C_2\text{min} = \frac{V_O(1-D_{\text{max}})}{L_2 f_s^2 v_{op-p}}$$

Using these equations, minimum inductance and capacitance values can be calculated for future converter design.

IV. Non Ideal Component Power Loss Equations

Component power losses are constantly being calculated throughout this report. These power loss and efficiency equations are derived by Ayachit et al. in *Power Losses and Efficiency Analysis of the Quadratic Buck Converter in CCM*[1] .

Losses in inductor L_1:

$$P_{r_{L_1}} = r_{L_1} I_{L_1\text{rms}}^2 = r_{L_1}(DI_O)^2 = \frac{r_{L_1}}{R_L} D^2 P_O.$$

Losses in inductor L_2:

$$P_{r_{L_2}} = r_{L_2} I_{L_2\text{rms}}^2 = r_{L_2} I_O^2 = \frac{r_{L_2}}{R_L} P_O.$$

Losses in capacitor C_1:

$$P_{C_1} = I_{C_1\text{rms}}^2 r_{C_1}$$

Losses in capacitor C_2:

$$P_{C_2} = \frac{r_{C_2}\Delta i_{L_2}^2}{12}.$$

Losses in diode D_1:

$$P_{D_1} = P_{R_{F1}} + P_{V_{F1}} = I_{D_1\text{rms}}^2 R_{F1} + V_{F1} I_{D_1\text{avg}}$$

Losses in diode D_2:

$$P_{D_2} = P_{R_{F2}} + P_{V_{F2}} = I_{D_2\text{rms}}^2 R_{F2} + V_{F2} I_{D_2\text{avg}}$$

Losses in diode D_o:

$$P_{D_0} = P_{R_{F0}} + P_{V_{F0}} = I_{D_0\text{rms}}^2 R_{F0} + V_{F0} I_{D_0\text{avg}}$$

Losses in the MOSFET Q due to conduction losses:

$$P_{r_{DS}} = I_{s\text{rms}}^2 r_{DS} = \frac{r_{DS}}{R_L} D P_O.$$

Losses in the MOSFET Q due to switching losses:

$$P_{sw} = f_s C_o (DV_I)^2 = f_s C_o \frac{V_O}{V_I} V_I^2 = f_s C_o \frac{V_I}{I_O} P_O.$$

Converter efficiency can then be determined using the equation:

$$\eta = \frac{P_O}{P_I}.$$

$$\eta = \frac{P_O}{P_O + P_{LOSS}} = \frac{1}{1 + \frac{P_{LOSS}}{P_O}},$$

Given the specs in table I, to account for an 80% efficiency supplying a full load of 120W, each design aims for total losses of around 30W.

V. Design 1

The aim of the very first design was to choose components and learn from the resulting ripples and power losses. Being my very first design, the aim was to choose components with the correct inductance/capacitance values, voltage ratings, and current ratings without worrying too much about power losses. I planned on learning from the results of this first design to ensure my second design is more optimal.

Using the information calculated in the analysis section of this report, components were selected for design 1. The values used for the basis of this design are listed below.

- A switching frequency of 50kHz.
- A starting duty cycle of 0.1732.
- Minimum inductance values of 11.5mH and 1.98mH for L1 and L2, respectively.
- Minimum capacitance values of 41.3μF and 2.08μF for C1 and C2, respectively.

My initial approach was to allocate about 50% of losses to MOSFET conduction and switching power loss, with the rest of the power loss being relatively evenly distributed among the inductors, capacitors and diodes. A general breakdown of my target power loss allocation going into the design is shown in figure 7.

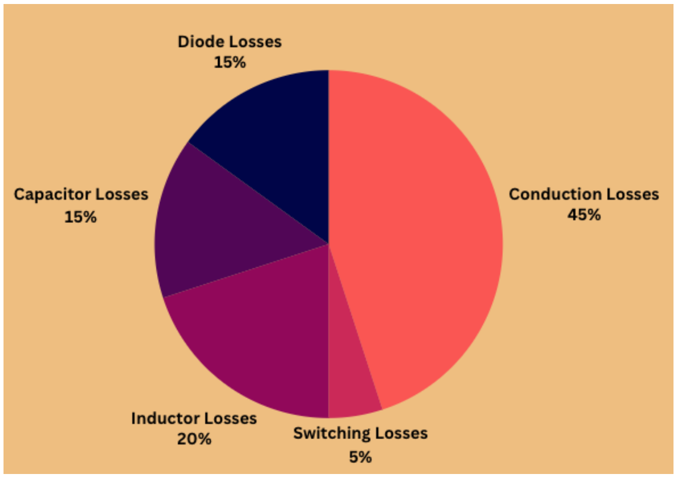


Fig. 7. Design 1 Power Loss Allocation

Throughout this report, the datasheets of each component are referenced next to the component name and can be seen in the appendix.

A. Selection of Power Switches and Diodes

Using the values in table II, the chosen MOSFET and diode ratings are as follows:

- MOSFET Q (Figure 20): 800V and 16A, R_{dson} of $220m\Omega$
- Diode D_1 (Figure 23): 600V and 8A, V_f of 1.2V
- Diode D_2 (Figure 24): 600V and 17A, V_f of 1.05V
- Diode D_o (Figure 25): 120V and 15A, V_f of 0.45V

B. Selection of Inductors

Using the values in Table II, and the calculations made in the ideal circuit analysis, the chosen inductor ratings are as follows:

- Inductor L_1 (Figure 26): $12mH$, blocks 2.8A
- Inductor L_2 (Figure 28): $2mH$, blocks 20A

C. Selection of Capacitors

Using the values in Table II and the calculations made in the ideal circuit analysis, the chosen capacitor ratings are shown below:

- Capacitor C_1 (Figure 30): $47\mu F$, blocks 100V
- Capacitor C_2 (Figure 34): $2.2\mu F$, blocks 25V

D. Power Loss, Efficiency, and Ripple Calculations

From using power loss equations given in Ayachit et al. [1], the initial design with the given ideal values showed power loss distribution as follows:

TABLE III
DESIGN 1 POWER LOSS PER COMPONENT

Component	Power Loss (W)	Percent of Losses
L1	5.0577451	27.43
L2	4.90	26.575
C1	0.0296765	0.161
C2	0.0000075	0.0004
D1	1.82	9.89
D2	1.82	9.867
D0	0.816	4.42
Q cond	3.98695	21.623
Q switch	0.00525	0.028
Total	**18.4380527**	

$$\eta = \frac{P_O}{P_O + P_{losses}} = \frac{99.96}{99.96 + 18.438} = 0.844$$

$$\Delta i_{L1} = \frac{V_g D D'}{L_1 f_s} = \frac{400(0.1732)(1-0.1732)}{(50,000)(12\times10^{-3})} = 0.0955\,\text{A}$$

$$\Delta i_{L2} = \frac{V_g D^2 D'}{L_2 f_s} = \frac{400(0.1732)^2(1-0.1732)}{(2\times10^{-3})(50,000)} = 0.0992\,\text{A}$$

$$\Delta V_{C1} = \frac{I_{o,\text{max}} D^2 D'}{f_s C_1} = \frac{10(0.1732)^2(1-0.1732)}{50,000\cdot 47\times10^{-6}} = 0.1055\,\text{V}$$

$$\Delta V_{C2} = \frac{V_g D^2 D'}{8L_2C_2f_s^2} = \frac{(0.1732^2)*400*(1-0.1732)}{1.2*(50,000^2)*(2\times10^{-3})*(2.2\times10^{-6})}$$

$$\Delta V_{C2} = 0.1127\,\text{V}$$

TABLE IV
DESIGN 1 PERFORMANCE COMPLIANCE (50KHZ)

Specification	Design 1 Value
Input Voltage	**400V**
Output Voltage	**10.925V**
Output Power (full load)	**99.96W**
Output Current Ripple	**0.0992A**
Output Voltage Ripple	**0.1137V**
Efficiency	**0.844**

As seen in these calculations, design 1 meets ripple and efficiency specs, while failing to meet output voltage and power specs.

E. PLECS Simulation of Design 1

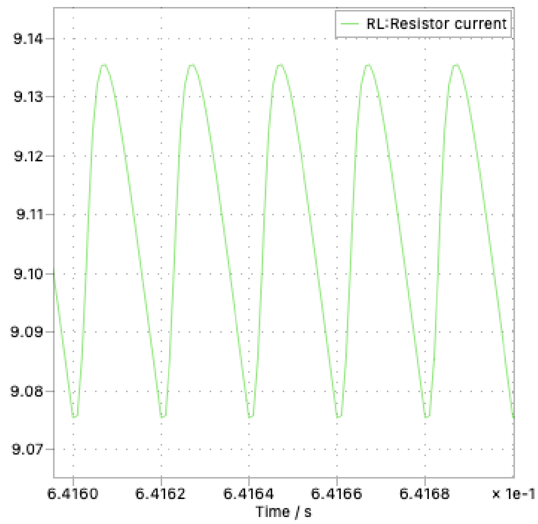


Fig. 8. Design 1 Output Current Ripple

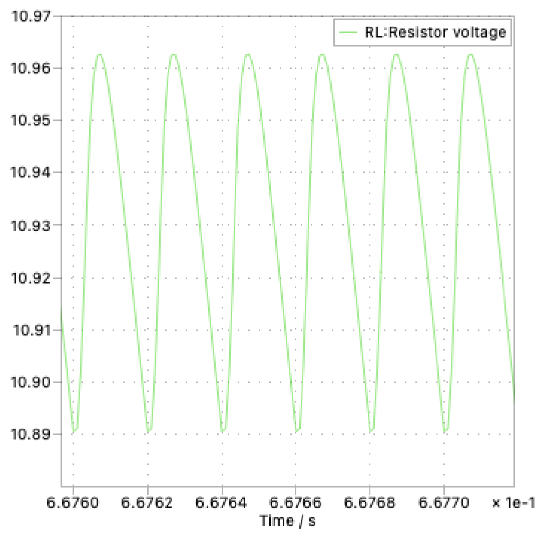


Fig. 9. Design 1 Output Voltage Ripple

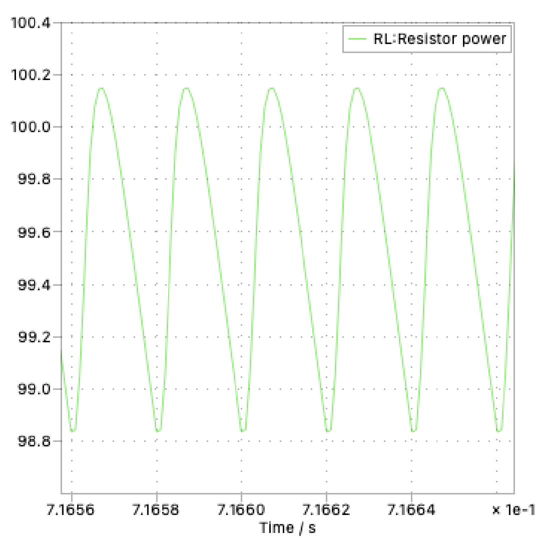


Fig. 10. Design 1 Output Power

F. Key Takeaways from Design 1

As seen in the design 1 power loss distribution table, the target power loss breakdown shown in Figure 7 was not fully met. Passive components accounted for far more losses than the switch itself due to the chosen MOSFET's relatively low R_{dson} value. Additionally, the $L1$, $L2$, $C1$, and $C2$ values were initially calculated for the ideal circuit, neglecting losses throughout the circuit. This in turn resulted in an output voltage and power lower than what was shown in the specifications, failing to meet the specifications of 12V and 120W. The ripple values for the inductors and capacitors were within acceptable limits, however this is expected to change as the output voltage and power is increased. These are all key design flaws to improve upon in a second design.

VI. DESIGN 2

Given what was learned from design 1, I adjusted how I would distribute my power losses in design 2 to more accurately fit the performance of the currently selected components within my quadratic buck converter. Additionally, I focused on more evenly distributing losses in the converter. Design 1 exhibited a majority of losses in it's inductors, and design 2 aims at fixing this. Additionally, design 2 will aim to have significantly more capacitor losses than design 1. Target power distribution of design 2 can be found below:

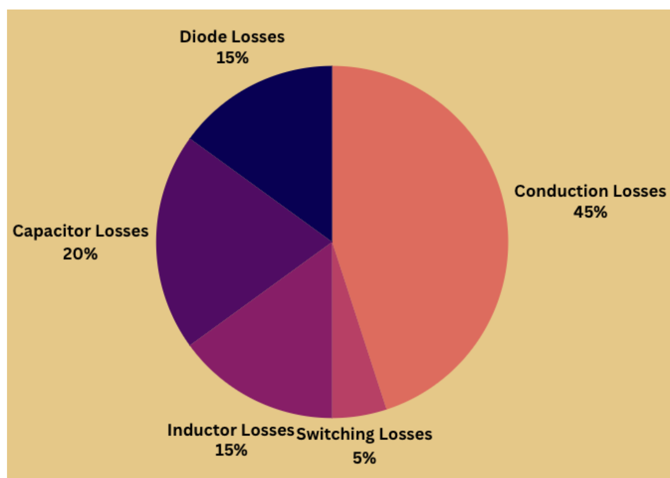


Fig. 11. Design 2 Loss Allocation

To fix some of the flaws from design 1, some potential fixes came to mind:

Proposed Solution	**Results**
Increasing R_L	Marginally increased output voltage but decreased load current and did not change the output power.
Increasing Duty Cycle	Successfully increased output voltage, current, and power.
Increasing L and C Values	Decreased ripple values without affecting average output voltage.

TABLE V
INITIAL DESIGN THOUGHT PROCESS

The first issue to fix was bringing the output voltage up to the specified 12V while taking losses and other non idealities into account. After some experimentation in PLECS, and further calculations, it was determined that increasing the duty cycle to 0.19575 resulted in output voltage, current, and power that aligned with the converter specifications in table I. After this was corrected, inductor and capacitor ripple values need to be increased to compensate for the additional ripple created by increasing the duty cycle. Additionally, given a minimum efficiency of 80%, there is much more room for power losses in this design. In order to adhere to the target power loss allocation shown in Figure **??**, a new MOSFET with a higher R_{dson} value will be selected. New inductors in this design will aim to have lesser winding resistances to lower associated power losses. Last, in an effort to increase capacitor losses, aluminum electrolytic capacitors will be used in this design instead of the multi layer ceramic capacitors (MLCCs) that were used in design 1.

A. Selection of Power Switches and Diodes

In an effort to match the target power loss distribution shown in 7, a new MOSFET with a higher R_{dson} value was chosen. Diode selection remained the same as design 1.

- MOSFET Q (Figure 21): 800V and 16A, R_{dson} of $600m\Omega$
- Diode D_1 (Figure 23): 600V and 8A, V_f of 1.2V
- Diode D_2 (Figure 24): 600V and 17A, V_f of 1.05V
- Diode D_o (Figure 25): 120V and 15A, V_f of 0.45V

B. Selection of Inductors

Due to an increased duty cycle, higher inductance values need to be chosen to compensate for increased current ripple.

- Inductor L_1 (Figure 27): $25mH$, blocks 5A
- Inductor L_2 (Figure 29): $2.5mH$, blocks 20A

Ripple value calculations are shown below to ensure this design meets the appropriate specs.

$$\Delta i_{L1} = \frac{V_g D D'}{L_1 f_s} = \frac{400(0.19575)(1-0.19575)}{(25\times10^{-3})(50,000)}$$

$$\Delta i_{L1} = 0.0504\,\mathrm{A}$$

$$\Delta i_{L2} = \frac{V_g D^2 D'}{L_2 f_s} = \frac{400(0.19575)^2(1-0.19575)}{(2.5\times10^{-3})(50,000)}$$

$$\Delta i_{L2} = 0.0986\,\mathrm{A}$$

C. Selection of Capacitors

Due to an increased duty cycle, higher capacitance values need to be chosen to compensate for increased voltage ripple.

- Capacitor C_1 (Figure 32): $100\mu F$, blocks 100V
- Capacitor C_2 (Figure 36): $2.2\mu F$, blocks 25V

Ripple value calculations are shown below to ensure this design meets the appropriate specs.

$$\Delta V_{C1} = \frac{I_{o,\max} D^2 D'}{f_s C_1}$$

$$\Delta V_{C1} = \frac{10(0.19575)^2(1-0.19575)}{50,000\cdot 100\times10^{-6}} = 0.0616\,\mathrm{V}$$

$$\Delta V_{C2} = \frac{V_g D^2 D'}{8 L_2 C_2 f_s^2}$$

$$\Delta V_{C2} = \frac{(0.19575^2)*400*(1-0.19575)}{8*(50,000^2)*(2.5\times10^{-3})*(2.2\times10^{-6})}$$

$$\Delta V_{C2} = 0.1127\,\mathrm{V}$$

D. Power Loss and Efficiency Calculations

From using power loss equations given in Ayachit et al. [1], the initial design with the given ideal values showed power loss distribution as follows:

TABLE VI
DESIGN 2 POWER LOSS PER COMPONENT

Component	Power Loss (W)	Percent of Losses
L1	1.40	4.79
L2	2.20	7.54
C1	9.85	33.75
C2	0.000096	0.0003
D1	1.86	6.39
D2	1.86	6.36
D0	0.838	2.87
Q cond	11.1702	38.28
Q switch	0.0055	0.02
Total	**29.18**	

$$\eta = \frac{P_O}{P_O + P_{losses}} = \frac{120}{120+29.18} = 0.8044$$

TABLE VII
DESIGN 2 PERFORMANCE COMPLIANCE (50KHZ)

Specification	Design 2 Value
Input Voltage	**400V**
Output Voltage	**12V**
Output Power (full load)	**120W**
Output Current Ripple	**0.0986A**
Output Voltage Ripple	**0.1127V**
Efficiency	**0.8044**

The new power loss allocation better reflects the 80% minimum efficiency, while also displaying the correct output voltage, power, and ripple values. Additionally, the power loss allocation of this design did well to fit the initial planned losses shown in figure 11. The MOSFET accounted for about 40% of the total losses, which was about 10% less than initially planned. To compensate, the capacitors accounted for about 33% of the total losses, which was about 10% more than initially planned. However, all together the loss distribution followed the initial plan shown in figure 11, and this design proved to be successful.

Given that all initial specifications from table I have been met, an efficiency versus output power sweep can be plotted to see how this converter performs at varying load powers within the given range of 40W-120W.

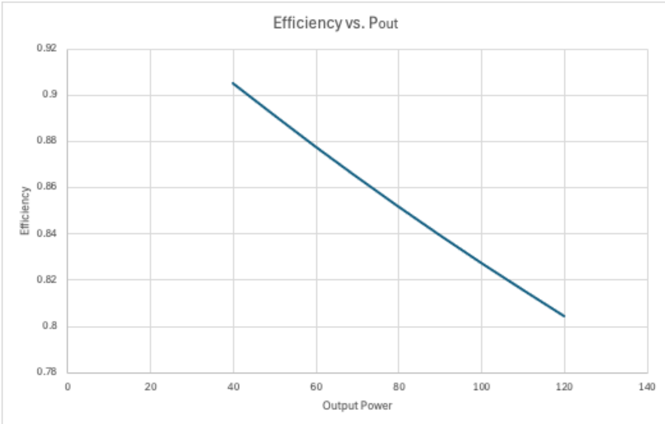


Fig. 12. Efficiency vs. P_{out}

As seen from the graph, converter efficiency and output power exhibit an inverse relationship. Losses increase as the load power becomes more demanding.

E. PLECS Simulation of Design 2

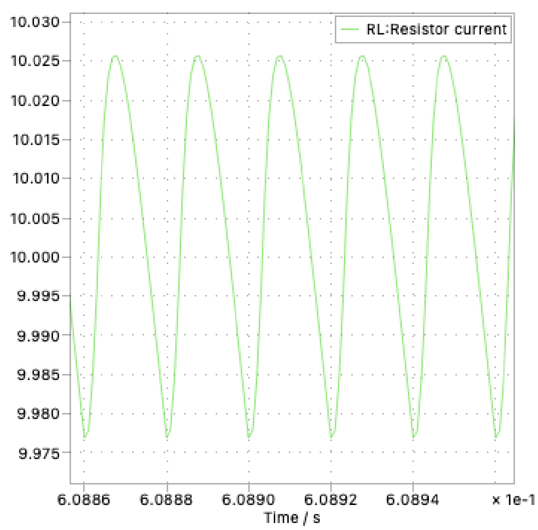


Fig. 13. Design 2 Output Current Ripple

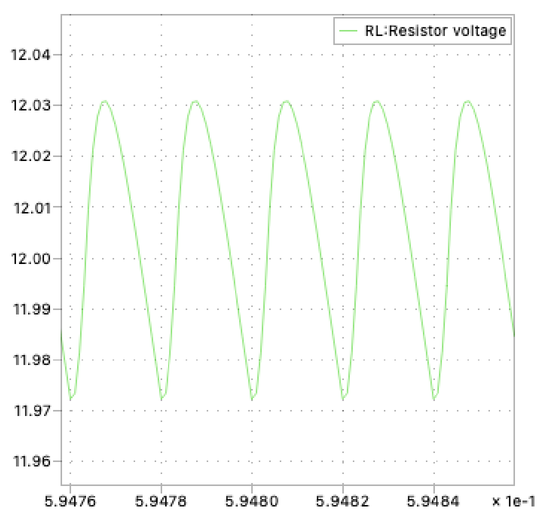


Fig. 14. Design 2 Output Voltage Ripple

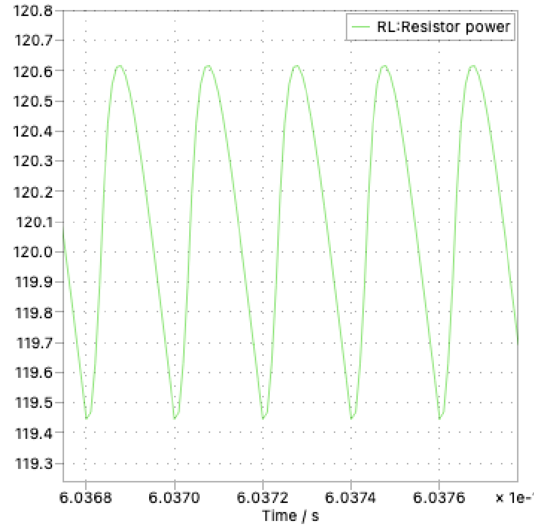


Fig. 15. Design 2 Output Power

As seen in the figures, average current, voltage, and power values align with the initial design specs. Additionally, ripples are within the ranges in the design specs. It is important to note that the simulation ripples do not align with the calculated ripple values due to differences in how PLECS calculates losses.

F. Key Takeaways from Design 2

Fixing the shortcomings of design 1 proved to be more complex than initially anticipated. First, increasing the output voltage and power by adjusting the duty cycle changed the ripple values of the inductors and capacitors. This small iteration created the need for components with higher inductance and capacitance values than initially anticipated. When choosing new inductors, it was important to take losses into account and adhere to my initial power loss allocation in figure 11. This meant finding new inductors with lower dsr values in an effort to avoid the mistakes made in design 1. Second, I aimed at allocating more losses to the capacitors in this design. In order to do so, I switched to using aluminum electrolytic capacitors as opposed to multilayer ceramic capacitors (MLCCs) used in design 1. This is because MLCCs are rated for very high frequencies, and have very low esr values, resulting in minimal losses. On the other hand, electrolytic capacitors have much higher esr values allowing for greater losses.

VII. Design 3

This design aims to analyze how an increase in frequency influences converter operation. Most of the components are unchanged from design 2, and the frequency is increased to $100,000kHz$. This increase in frequency will consequently decrease ripple across the inductors and capacitors and increase switching losses. The decrease in ripple values allows for new inductors and capacitors of lower inductances and capacitances to be chosen. It is important to note that with new inductors and capacitors, the duty cycle was slightly lowered to 0.1934 in order to maintain an output voltage of 12V. Additionally, target power loss allocation will remain the same for this design as it was in design 2.

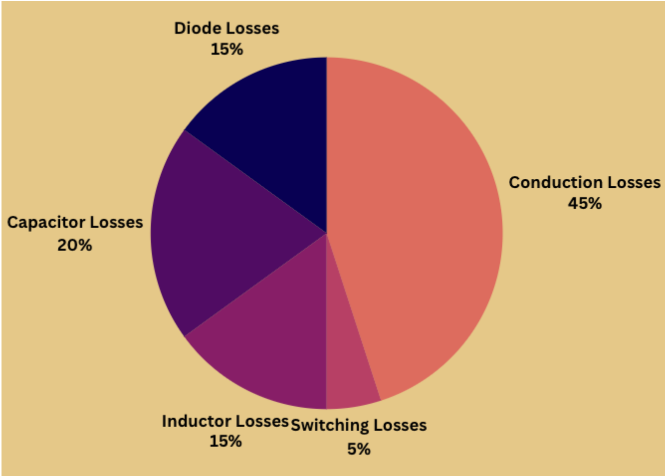


Fig. 16. Design 3 Loss Allocation

A. Selection of Power Switches and Diodes

The MOSFET and diodes used in this design will remain the same as the ones used in design 2.

- MOSFET Q (Figure 21): 800V and 16A, R_{dson} of $600m\Omega$
- Diode D_1 (Figure 23): 600V and 8A, V_f of 1.2V
- Diode D_2 (Figure 24): 600V and 17A, V_f of 1.05V
- Diode D_o (Figure 25): 120V and 15A, V_f of 0.45V

B. Selection of Inductors

As mentioned, lower rated inductors were chosen in this design due to the increase in frequency. Based on the ripple equations from the steady state analysis, inductor values can be roughly halved as the frequency is doubled. The new inductor values are shown below.

- Inductor L_1 (Figure 26): $14mH$, blocks 5A
- Inductor L_2 (Figure 26): $1.35mH$, blocks 15A

Afterwards, the new ripple values can be calculated.

$$\Delta i_{L1} = \frac{V_g D D' T_s}{L_1}$$

$$\Delta i_{L1} = \frac{400(0.1934)(1-0.1934)}{(100,000)(14\times10^{-3})} = 0.0446\,\text{A}$$

$$\Delta i_{L2} = \frac{V_g D^2 D' T_s}{L_2}$$

$$\Delta i_{L2} = \frac{400(0.1934)^2(1-0.1934)}{(100,000)(1.35\times10^{-3})} = 0.0894\,\text{A}$$

C. Selection of Capacitors

Similar to the inductors, lower rated capacitors can be chosen due to the increase in frequency. Based on the ripple equations from the steady state analysis, capacitor values can be roughly halved due to the frequency being doubled. The new capacitor values are shown below.

- Capacitor C_1 (Figure 33): $47\mu F$, blocks 100V
- Capacitor C_2 (Figure 38): $1.5\mu F$, blocks 25V

Afterwards, new ripple values can be calculated.

$$\Delta V_{C1} = \frac{I_{o,\max} D^2 D'}{f_s C_1}$$

$$\Delta V_{C1} = \frac{10(0.1934)^2(1-0.1934)}{100,000\cdot 47\times10^{-6}} = 0.0642\,\text{V}$$

$$\Delta V_{C2} = \frac{V_g D^2 D'}{8 L_2 C_2 f_s^2}$$

$$\Delta V_{C2} = \frac{(0.1934^2)*400*(1-0.1934)}{8*(100,000^2)*(1.35\times10^{-3})*(1.5\times10^{-6})}$$

$$\Delta V_{C2} = 0.0745\,\text{V}$$

D. Calculation of Losses and Efficiencies

Using the equations from Ayachit et al. [1] the power loss per component can be calculated.

TABLE VIII
DESIGN POWER LOSS PER COMPONENT

Component	Power Loss (W)	Percent of Losses
L1	1.096	4.067
L2	2.90	10.751
C1	6.552	24.288
C2	0.1125	0.417
D1	1.92	7.118
D2	1.91	7.075
D0	0.87	3.23
Q cond	11.604	43.017
Q switch	0.012	0.0443
Total	**26.975**	

$$\eta = \frac{P_O}{P_O + P_{losses}} = \frac{120}{120 + 26.975} = 0.8165$$

TABLE IX
DESIGN 3 PERFORMANCE COMPLIANCE (100KHZ)

Specification	Design 3 Value
Input Voltage	**400V**
Output Voltage	**12V**
Output Power (full load)	**120W**
Output Current Ripple	**0.0894A**
Output Voltage Ripple	**0.0745V**
Efficiency	**0.8165**

As seen in table VIII, power loss allocation in this design fits figure 16 very well. Although capacitor losses are about 5% greater than planned, this is compensated by the fact that MOSFET losses are about 5% less than planned. Additionally, all specs were met in this design as shown above in table IX.

E. Simulation in PLECS

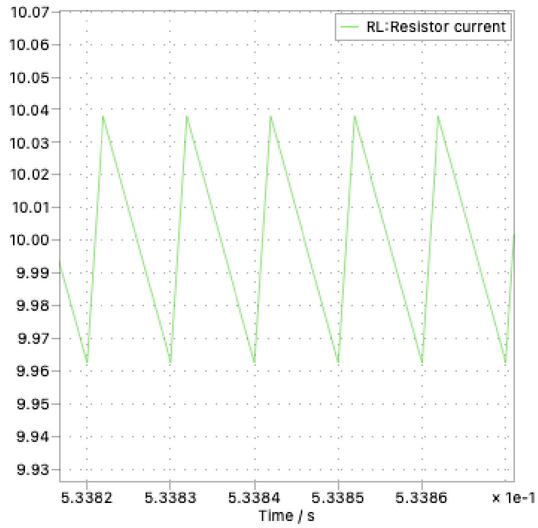


Fig. 17. Design 3 Output Current Ripple

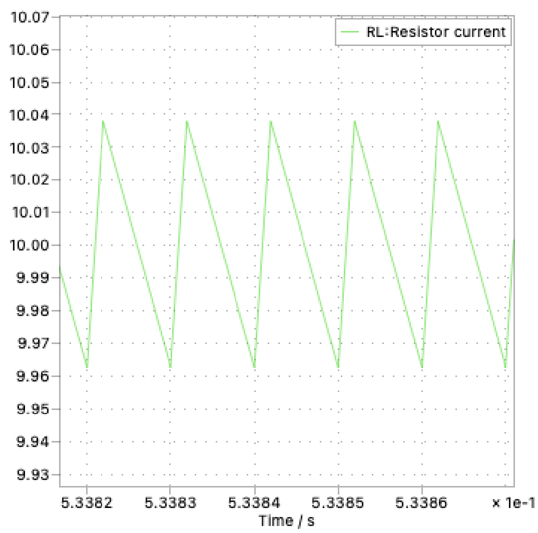


Fig. 18. Design 3 Output Voltage Ripple

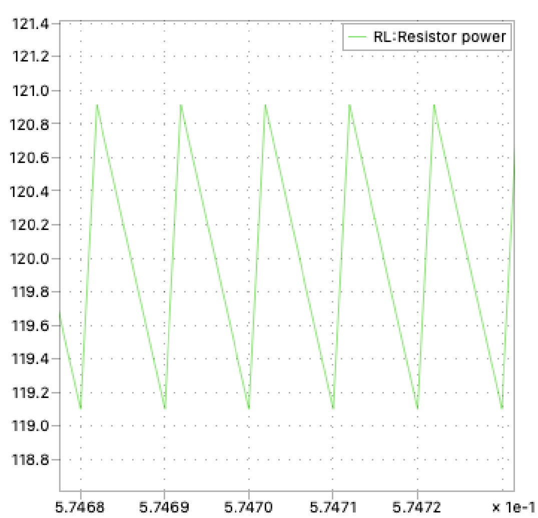


Fig. 19. Design 3 Power

F. Key Takeaways from Design 3

It is important to note that due to different dcr and esr values of the newly chosen inductors and capacitors, the power loss distribution of this design is slightly different from design 2. However, one key takeaway from this design is despite the decrease in capacitor and inductor values, the increase in frequency allowed for current ripple, voltage ripple, and efficiency to remain within the given specs in Table I. As shown in the ripple calculations, an increase in frequency has an inverse relationship with ripple values. In practicality, if the quadratic buck converter circuit were to be consistently operating at a larger frequency, smaller capacitor and inductor values could be used in the design.

VIII. Design 4

This design explores the affect that using a silicon carbide MOSFET has on the circuits losses and efficiency. In all other designs, a silicon MOSFET was used instead in an effort to save costs. In this design, the only component that changes is the MOSFET.

A. MOSFET Selection

As mentioned, a new silicon carbide MOSFET is used in this design to mitigate losses.

- MOSFET Q (Figure 22): 750V and 17A, R_{dson} of $182m\Omega$

As seen from the MOSFET specs, the R_{dson} value is much smaller for this MOSFET than it was in design 3, resulting in much less conduction and switching losses.

B. Calculation of Losses and Efficiency

TABLE X
Design 4 Power Loss per Component

Component	Power Loss (W)	Percent of Losses
L1	1.096	5.80
L2	2.90	15.35
C1	6.552	34.68
C2	0.1125	0.596
D1	1.92	10.165
D2	1.91	10.103
D0	0.87	4.607
Q cond	3.52	18.63
Q switch	0.012	0.063
Total	**18.89**	

$$\eta = \frac{P_O}{P_O + P_{losses}} = \frac{120}{120 + 18.89} = 0.864$$

Compared to design 3, power losses are significantly less when using an SiC MOSFET.

TABLE XI
Iteration II Power Loss per Component

	Si MOSFET	SiC MOSFET
Q cond	11.604 W	3.52 W
Q switch	0.012 W	0.008 W
Efficiency (η)	81.65%	86.40%

C. Key Takeaways from Design 4

SiC MOSFETS generally have lower R_{dson} and C_out values than Si MOSFETs do, resulting in less conduction and switching losses. Additionally, SiC MOSFETS generally operate at higher frequencies than Si MOSFETS. For greater efficiency or designs intended to operate at high frequencies, SiC MOSFETs are generally preferred, although they cost more.

IX. Conclusion

This project examined the design and optimization of a quadratic buck converter through four iterative designs, each addressing specific challenges and inefficiencies. The initial design (Design 1) utilized calculated inductor and capacitor values based on ideal assumptions, neglecting passive losses and non-idealities in components. As a result, the output voltage and power were significantly below design specifications, highlighting the necessity to account for non-ideal component losses during converter design.

Learning from these shortcomings, Design 2 introduced adjustments, including an increased duty cycle and considerations for losses in the MOSFETs and capacitors. The design successfully meets output specifications and achieves efficiency closer to the 80% threshold. One of the bigger challenges of this design was ensuring an efficiency near the specified 80% that also met my personal design target power loss allocation. Finding less efficient components often saves money, but I found that creating a converter with a high efficiency may prove to be much simpler. Additionally, capacitor and inductor adjustments were needed to fix ripple values and compensate for an increased duty cycle during this design.

Building off of this, Design 3 explored the impact of doubling the switching frequency to 100 kHz, in turn reducing ripple values and allowing for the use of smaller inductors and capacitors. This maintained performance within the specified limits, while utilizing new components with smaller inductance and capacitance values. Additionally, an increase in switching frequency consequently increased MOSFET switching losses, creating the need to mitigate power loss in other components in order to maintain an efficiency of around 80%.

Finally, Design 4 replaced the silicon MOSFET with a silicon carbide (SiC) MOSFET, leveraging its lower conduction and switching losses to achieve an efficiency of 86.4%. This highlighted the significant role SiC MOSFETs can play in enhancing performance, marking them as a valuable choice for future high-efficiency power converter applications.

Through this iterative process, the project demonstrated the importance of addressing non-idealities, optimizing component selection, and leveraging advanced materials to meet stringent design specifications. The transition from ideal analyses to practical adjustments highlighted the trade-offs between efficiency, ripple minimization, and material costs.

References

[1] Ayachit, A., and Kazimierczuk, M. K., "Power losses and efficiency analysis of the quadratic buck converter in ccm," in *2014 IEEE 57th International Midwest Symposium on Circuits and Systems (MWSCAS)*, Aug. 2014, pp. 463–466.

[2] Ayachit, A., and Kazimierczuk, M. K., "Steady-state analysis of pwm quadratic buck converter in ccm," in *2013 IEEE 56th International Midwest Symposium on Circuits and Systems (MWSCAS)*, Aug. 2013, pp. 49–52.

[3] Morales-Saldana, J. A., Leyva-Ramos, J., and Carbajal-Gutierrez, E. E., "Modeling of switch-mode dc-dc cascade converters," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 38, no. 1, pp. 295–299, Jan. 2002.

[4] Middlebrook, R. D., "Transformerless dc-to-dc converters with large conversion ratios," in *Proceedings of the IEEE/INTELEC Conference*, 1984, pp. 455–460.

[5] Matsuo, H., and Harada, K., "The cascade connection of switching regulators," *IEEE Transactions on Industry Applications*, vol. 12, no. 2, pp. 192–198, Mar./Apr. 1976.

[6] Maksimovic, D., and Čuk, S., "Switching converters with wide dc conversion range," *IEEE Transactions on Power Electronics*, vol. 6, no. 1, pp. 151–157, Jan. 1991.

[7] Erickson, R. W., and Maksimovic, D., *Fundamentals of Power Electronics*, 2nd ed., Springer, 2001.

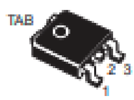
APPENDIX

life.augmented

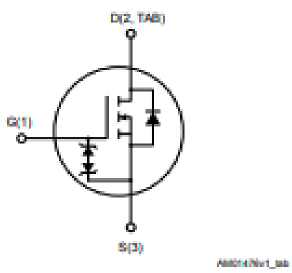
STD80N240K6

Datasheet

N-channel 800 V, 197 mΩ typ., 16 A MDmesh K6 Power MOSFET in a DPAK package



DPAK



STPOWER

Product status link
STD80N240K6

Product summary	
Order code	STD80N240K6
Marking	80N240K6
Package	DPAK
Packing	Tape and reel

Features

Order code	V_{DS}	$R_{DS(on)}$ max.	I_D
STD80N240K6	800 V	220 mΩ	16 A

- Worldwide best $R_{DS(on)}$ x area
- Worldwide best FOM (figure of merit)
- Ultra low gate charge
- 100% avalanche tested
- Zener-protected

Applications

- Flyback converter
- Adapters for tablets, notebook and AIO
- LED lighting

Description

This very high voltage N-channel Power MOSFET is designed using the ultimate MDmesh K6 technology based on 20 years STMicroelectronics experience on super junction technology. The result is the best-in-class on-resistance per area and gate charge for applications requiring superior power density and high efficiency.

Fig. 20. Initial MOSFET Datasheet - STD80N240K6 on Digikey

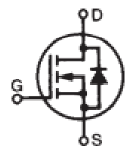
IXYS

PolarHV™ Power MOSFET

N-Channel Enhancement Mode
Fast Recovery Diode
Avalanche Rated

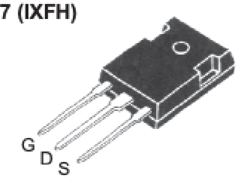
IXFH 16N80P
IXFT 16N80P
IXFV 16N80P
IXFV 16N80PS

V_{DSS} = 800 V
I_{D25} = 16 A
$R_{DS(on)} \leq 600$ mΩ
$t_{rr} \leq 250$ ns

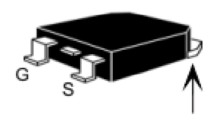


Symbol	Test Conditions	Maximum Ratings	
V_{DSS}	T_J = 25°C to 150°C	800	V
V_{DGR}	T_J = 25°C to 150°C; R_{GS} = 1 MΩ	800	V
V_{GSS}	Continuous	±30	V
V_{GSM}	Transient	±40	V
I_{D25}	T_C = 25°C	16	A
I_{DM}	T_C = 25°C, pulse width limited by T_{JM}	40	A
I_{AR}	T_C = 25°C	8	A
E_{AR}	T_C = 25°C	30	mJ
E_{AS}	T_C = 25°C	1.0	J
dv/dt	$I_S \leq I_{DM}$, di/dt ≤ 100 A/µs, $V_{DD} \leq V_{DSS}$ $T_J \leq$ 150°C, R_G = 5 Ω	10	V/ns
P_D	T_C = 25°C	460	W
T_J		-55 ... +150	°C
T_{JM}		150	°C
T_{stg}		-55 ... +150	°C
T_L	1.6 mm (0.062 in.) from case for 10 s	300	°C
T_{SOLD}	Plastic body for 10 s	260	°C
M_d	Mounting torque (TO-247)	1.13/10	Nm/lb.in.
F_C	Mounting force (PLUS220)	11..65/2.5..15	N/lb
Weight	TO-247	6.0	g
	TO-268	5.0	g
	PLUS220 & PLUS220SMD	4.0	g

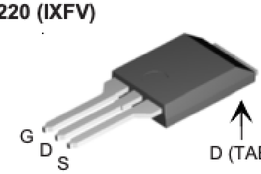
TO-247 (IXFH)



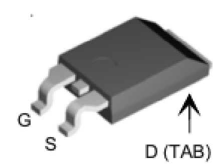
TO-268 (IXFT)



PLUS220 (IXFV)



PLUS220SMD (IXFV...S)



G = Gate D = Drain
S = Source TAB = Drain

Symbol	Test Conditions (T_J = 25°C, unless otherwise specified)		Characteristic Values Min.	Typ.	Max.	
BV_{DSS}	V_{GS} = 0 V, I_D = 250 µA		800			V
$V_{GS(th)}$	$V_{DS} = V_{GS}$, I_D = 4 mA		3.0		5.0	V
I_{GSS}	V_{GS} = ±30 V, V_{DS} = 0 V				±100	nA
I_{DSS}	$V_{DS} = V_{DSS}$				25	µA
	V_{GS} = 0 V	T_J = 125°C			250	µA
$R_{DS(on)}$	V_{GS} = 10 V, I_D = 0.5 I_{D25} Pulse test, t ≤ 300 µs, duty cycle d ≤ 2 %				600	mΩ

Features
- Fast Recovery diode
- Unclamped Inductive Switching (UIS) rated
- International standard packages
- Low package inductance
  - easy to drive and to protect

Advantages
- Easy to mount
- Space savings
- High power density

 DS99599E(07/06)

Fig. 21. MOSFET with Higher R_{dson} Datasheet

IMDQ75R140M1H

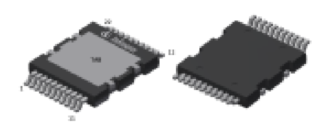
Infineon

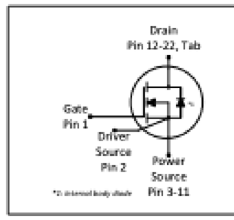
MOSFET

CoolSiC™ Power Device 750 V G1

The 750 V CoolSiC™ is built over the solid silicon carbide technology developed in Infineon in more than 20 years. Leveraging the wide bandgap SiC material characteristics, the 750V CoolSiC™ MOSFET offers a unique combination of performance, reliability and ease of use. Suitable for high temperature and harsh operations, it enables the simplified and cost effective deployment of the highest system efficiency.

PG-HDSOP-22





Features

- Highly robust 750V technology, 100% avalanche tested
- Best-in-class $R_{DS(on)}$ x Q_{fr}
- Excellent $R_{DS(on)}$ x Q_{oss} and $R_{DS(on)}$ x Q_G
- Unique combination of low C_{rss}/C_{iss} and high $V_{GS(th)}$
- Infineon proprietary die attach technology
- Cutting edge top side cooling package (QDPAK)
- Driver source pin available

Benefits

- Enhanced robustness to withstand bus voltages beyond 500 V
- Superior efficiency in hard switching
- Higher switching frequency in soft switching topologies
- Robustness against parasitic turn on for unipolar gate driving
- Best-in-class thermal dissipation
- Reduced switching losses through improved gate control

Potential applications

- EV charging infrastructure
- Solar PV inverters
- UPS (uninterruptable power supplies)
- Energy storage and battery formation
- Telecom and Server SMPS

RoHS

Product validation

Fully qualified according to JEDEC for Industrial Applications

Please note: The source and driver source pins are not exchangeable. Their exchange might lead to malfunction.

Table 1 Key Performance Parameters

Parameter	Value	Unit
V_{DSS} over full $T_{j,range}$	750	V
$R_{DS(on),typ}$	140	mΩ
$R_{DS(on),max}$	182	mΩ
$Q_{G,typ}$	12	nC
$I_{DM,max}$	38	A
$Q_{oss,typ}$ @ 500 V	28	nC
$E_{oss,typ}$ @ 500 V	5.1	µJ

Type / Ordering Code	Package	Marking	Related Links
IMDQ75R140M1H	PG-HDSOP-22	75R140M1	see Appendix A

Final Data Sheet 1 Rev. 2.1, 2023-10-10

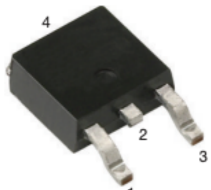
Fig. 22. Design 3 SiC MOSFET Datasheet

VS-8EWF02S-M3, VS-8EWF04S-M3, VS-8EWF06S-M3

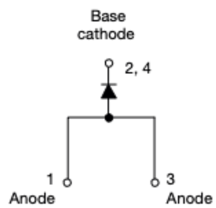
www.vishay.com

Vishay Semiconductors

Surface Mount Fast Soft Recovery Rectifier Diode, 8 A



DPAK (TO-252AA)



FEATURES

- Glass passivated pellet chip junction
- Meets MSL level 1, per J-STD-020, LF maximum peak of 260 °C
- Material categorization: for definitions of compliance please see www.vishay.com/doc?99912

RoHS COMPLIANT
HALOGEN FREE

APPLICATIONS

- Output rectification and freewheeling diode in inverters, choppers and converters
- Input rectifications where severe restrictions on conducted EMI should be met

DESCRIPTION

The VS-8EWF..S-M3 fast soft recovery rectifier series has been optimized for combined short reverse recovery time, low forward voltage drop and low leakage current.

The glass passivation ensures stable reliable operation in the most severe temperature and power cycling conditions.

PRIMARY CHARACTERISTICS	
$I_{F(AV)}$	8 A
V_R	200 V, 400 V, 600 V
V_F at I_F	1.2 V
I_{FSM}	150 A
t_{rr}	55 ns
T_J max.	150 °C
Snap factor	0.5
Package	DPAK (TO-252AA)
Circuit configuration	Single

MAJOR RATINGS AND CHARACTERISTICS

SYMBOL	CHARACTERISTICS	VALUES	UNITS
$I_{F(AV)}$	Sinusoidal waveform	8	A
V_{RRM}		200 to 600	V
I_{FSM}		150	A
V_F	8 A, T_J = 25 °C	1.2	V
t_{rr}	1 A, 100 A/µs	55	ns
T_J	Range	-40 to +150	°C

VOLTAGE RATINGS

PART NUMBER	V_{RRM}, MAXIMUM PEAK REVERSE VOLTAGE V	V_{RSM}, MAXIMUM NON-REPETITIVE PEAK REVERSE VOLTAGE V	I_{RRM} AT 150 °C mA
VS-8EWF02S-M3	200	300	3
VS-8EWF04S-M3	400	500	
VS-8EWF06S-M3	600	700	

ABSOLUTE MAXIMUM RATINGS

PARAMETER	SYMBOL	TEST CONDITIONS	VALUES	UNITS
Maximum average forward current	$I_{F(AV)}$	T_C = 96 °C, 180° conduction half sine wave	8	A
Maximum peak one cycle non-repetitive surge current	I_{FSM}	10 ms sine pulse, rated V_{RRM} applied	125	
		10 ms sine pulse, no voltage reapplied	150	
Maximum I^2t for fusing	I^2t	10 ms sine pulse, rated V_{RRM} applied	78	A^2s
		10 ms sine pulse, no voltage reapplied	110	
Maximum $I^2\sqrt{t}$ for fusing	$I^2\sqrt{t}$	t = 0.1 ms to 10 ms, no voltage reapplied	1100	$A^2\sqrt{s}$

Revision: 22-Jul-2024 1 Document Number: 93375

For technical questions within your region: DiodesAmericas@vishay.com, DiodesAsia@vishay.com, DiodesEurope@vishay.com

Fig. 23. Diode D_1 Datasheet

IXYS A Littelfuse Technology

DSS17-06CR

Schottky				Ratings			
Symbol	**Definition**	**Conditions**		**min.**	**typ.**	**max.**	**Unit**
V_{RSM}	*max. non-repetitive reverse blocking voltage*		T_{VJ} = 25°C			600	V
V_{RRM}	*max. repetitive reverse blocking voltage*		T_{VJ} = 25°C			600	V
I_R	*reverse current, drain current*	V_R = 600 V	T_{VJ} = 25°C			500	µA
		V_R = 600 V	T_{VJ} = 125°C			5	mA
V_F	*forward voltage drop*	I_F = 15 A	T_{VJ} = 25°C			3.17	V
		I_F = 30 A				3.46	V
		I_F = 15 A	T_{VJ} = 125°C			2.54	V
		I_F = 30 A				2.90	V
I_{FAV}	*average forward current*	T_C = 95°C rectangular d = 0.5	T_{VJ} = 175°C			17	A
V_{F0}	*threshold voltage*	*for power loss calculation only*	T_{VJ} = 175°C			1.91	V
r_F	*slope resistance*	*for power loss calculation only*				21.5	mΩ
R_{thJC}	*thermal resistance junction to case*					1.4	K/W
R_{thCH}	*thermal resistance case to heatsink*				0.3		K/W
P_{tot}	*total power dissipation*		T_C = 25°C			105	W
I_{FSM}	*max. forward surge current*	t = 10 ms; (50 Hz), sine; V_R = 0 V	T_{VJ} = 45°C			200	A
C_J	*junction capacitance*	V_R = 400 V f = 1 MHz	T_{VJ} = 25°C		20		pF

Fig. 24. Diode D_2 Datasheet

VISHAY.

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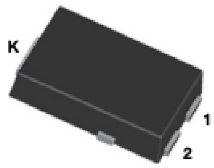
V15P12

Vishay General Semiconductor

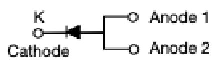
High Current Density Surface-Mount TMBS® (Trench MOS Barrier Schottky) Rectifier

Ultra Low V_F = 0.45 V at I_F = 5 A

eSMP® Series



SMPC (TO-277A)



FEATURES

AUTOMOTIVE GRADE Available

RoHS COMPLIANT

HALOGEN FREE

- Very low profile - typical height of 1.1 mm
- Ideal for automated placement
- Trench MOS Schottky technology
- Low forward voltage drop, low power losses
- High efficiency operation
- Meets MSL level 1, per J-STD-020, LF maximum peak of 260 °C
- AEC-Q101 qualified available
  - Automotive ordering code; base P/NHM3
- Material categorization: for definitions of compliance please see www.vishay.com/doc?99912

ADDITIONAL RESOURCES

3D Models

PRIMARY CHARACTERISTICS	
$I_{F(AV)}$	15 A
V_{RRM}	120 V
I_{FSM}	220 A
V_F at I_F = 15 A (125 °C)	0.63 V
T_J max.	150 °C
Package	SMPC (TO-277A)
Circuit configuration	Single

TYPICAL APPLICATIONS

For use in low voltage high frequency inverters, freewheeling, DC/DC converters, and polarity protection applications.

MECHANICAL DATA

Case: SMPC (TO-277A)
Molding compound meets UL 94 V-0 flammability rating
Base P/N-M3 - halogen-free, RoHS-compliant, and commercial grade
Base P/NHM3 - halogen-free, RoHS-compliant and AEC-Q101 qualified

Terminals: matte tin plated leads, solderable per J-STD-002 and JESD 22-B102
M3 and HM3 suffix meets JESD 201 class 2 whisker test

MAXIMUM RATINGS (T_A = 25 °C unless otherwise noted)

PARAMETER	SYMBOL	V15P12	UNIT
Device marking code		V1512	
Maximum repetitive peak reverse voltage	V_{RRM}	120	V
Maximum DC forward current	$I_{F(AV)}$ (1)	15	A
	$I_{F(AV)}$ (2)	3.7	
Peak forward surge current 10 ms single half sine-wave superimposed on rated load	I_{FSM}	220	A
Operating junction and storage temperature range	T_J, T_{STG}	-40 to +150	°C

Notes

(1) Mounted on 30 mm x 30 mm pad areas aluminum PCB
(2) Free air, mounted on recommended pad area

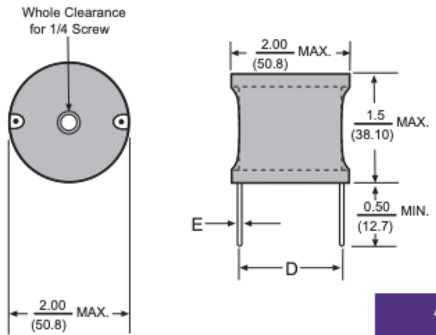
Revision: 11-Dec-2019 1 Document Number: 87625

For technical questions within your region: DiodesAmericas@vishay.com, DiodesAsia@vishay.com, DiodesEurope@vishay.com

Fig. 25. Diode D_o Datasheet

RoHS

RDC60 Radial Drum Core Inductors



Dimensions: Inches / (mm)

Features

- High Current / Radial Power Line Choke
- Drum Core Design
- Hole Clearance for 1/4 Screw
- UL VW-1 Shrink Tube Cover

Electrical

Inductance Range: 4.7µH to 47,000µH

Tolerance: 20% for 4.7µH to 8.2µH and 10% for 10µH to 47,000µH

Operating Temp: -55ºC ~ +125ºC

Saturation Current: Lowers Inductance by 5%

Test Equipment

(L): HP 4263A @ 1Khz

(DCR): HP 4263A

Physical

Packaging: Box Trays
Marking: EIA Inductance Code

Allied Part Number	(L) (µh) @ 1Khz	Tolerance	DCR Max. (Ω)	Saturation Current (A) DC	Rated Current (A)	Dimension (E)	Dimension (D)
RDC60-4R7M-RC	4.7	20	.002	149.9	35.0	0.105	1.40
RDC60-5R6M-RC	5.6	20	.002	122.7	35.0	0.105	1.40
RDC60-6R8M-RC	6.8	20	.003	103.8	35.0	0.105	1.40
RDC60-8R2M-RC	8.2	20	.003	90.0	35.0	0.105	1.40
RDC60-100K-RC	10	10	.003	79.4	35.0	0.105	1.48
RDC60-120K-RC	12	10	.004	71.0	35.0	0.105	1.48
RDC60-150K-RC	15	10	.004	64.3	35.0	0.105	1.48
RDC60-180K-RC	18	10	.005	58.7	35.0	0.105	1.48
RDC60-220K-RC	22	10	.005	54.0	35.0	0.105	1.48
RDC60-270K-RC	27	10	.006	50.0	35.0	0.105	1.48
RDC60-330K-RC	33	10	.006	46.5	35.0	0.105	1.48
RDC60-390K-RC	39	10	.006	43.5	35.0	0.105	1.48
RDC60-470K-RC	47	10	.008	40.9	35.0	0.105	1.48
RDC60-560K-RC	56	10	.009	36.5	35.0	0.105	1.48
RDC60-680K-RC	68	10	.009	32.9	35.0.	0.105	1.48
RDC60-820K-RC	82	10	.010	30.0	35.0	0.105	1.48
RDC60-101K-RC	100	10	.014	26.5	27.0	0.094	1.53
RDC60-121K-RC	120	10	.015	24.5	27.0	0.094	1.53
RDC60-151K-RC	150	10	.023	21.4	21.0	0.084	1.49
RDC60-181K-RC	180	10	.025	19.5	21.0	0.084	1.49
RDC60-221K-RC	220	10	.028	18.0	21.0	0.084	1.49
RDC60-271K-RC	270	10	.030	16.2	21.0	0.084	1.49
RDC60-331K-RC	330	10	.040	14.8	17.0	0.075	1.31
RDC60-391K-RC	390	10	.055	13.6	13.5	0.068	1.31
RDC60-471K-RC	470	10	.061	12.3	13.5	0.068	1.31
RDC60-561K-RC	560	10	.068	11.3	13.5	0.068	1.40
RDC60-681K-RC	680	10	.094	10.3	11.4	0.060	1.42
RDC60-821K-RC	820	10	.104	9.4	11.4	0.060	1.42
RDC60-102K-RC	1000	10	.143	8.5	9.0	0.054	1.36
RDC60-122K-RC	1200	10	.156	7.7	9.0	0.054	1.36
RDC60-152K-RC	1500	10	.219	6.8	7.2	0.048	1.31
RDC60-182K-RC	1800	10	.241	6.3	7.2	0.048	1.31
RDC60-222K-RC	2200	10	.270	5.7	7.2	0.048	1.40
RDC60-272K-RC	2700	10	.364	5.1	5.5	0.043	1.36
RDC60-332K-RC	3300	10	.498	4.6	4.5	0.039	1.24
RDC60-392K-RC	3900	10	.548	4.2	4.5	0.039	1.32
RDC60-472K-RC	4700	10	.608	4.5	4.5	0.039	1.32
RDC60-562K-RC	5600	10	.671	4.5	4.5	0.039	1.36
RDC60-682K-RC	6800	10	.750	3.2	4.5	0.039	1.40
RDC60-822K-RC	8200	10	1.03	2.9	4.0	0.035	1.45
RDC60-103K-RC	10000	10	1.16	2.6	4.0	0.035	1.45
RDC60-123K-RC	12000	10	1.54	2.4	2.8	0.031	1.40
RDC60-153K-RC	15000	10	1.75	2.2	2.8	0.031	1.40
RDC60-183K-RC	18000	10	1.94	2.0	2.8	0.028	1.45
RDC60-223K-RC	22000	10	2.74	1.8	2.0	0.028	1.37
RDC60-273K-RC	27000	10	3.71	1.6	1.7	0.025	1.37
RDC60-333K-RC	33000	10	4.16	1.5	1.7	0.025	1.37
RDC60-393K-RC	39000	10	5.56	1.4	1.4	0.025	1.35
RDC60-473K-RC	47000	10	6.19	1.2	1.4	0.022	1.35

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4/23/12

Fig. 26. Design 1 Inductor L_1 Datasheet

High Frequency Reactors *197 Series*

Home / Transformers / Chokes & Reactors /

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[+] ZOOM

RoHS

Features:

- Perfect for high frequency filtering applications.
- High self-resonant frequency values
- Operating Frequency: 60Hz - 10kHz
- Some models feature universal channel mount packaging with flexible insulated leads (6" min.).
- Some models feature rugged construction with aluminum base and stainless steel band along with open-style terminals for maximum versatility.
- Consult datasheets for further design details.
- For DC applications try out 195-196 Series

PRODUCT RESOURCES

Specification Sheet

Print Page

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Part Details

Click Part No, below, for details (e.g., Product drawings, assembly instructions, ship weight)

Part No.	Inductance (mH)	DC Current (A)	Self-Resonant Frequency (kHz)	DC Resistance (mOhm)	Dimensions A	B	C	Mounting Hole Pattern			Weight (lbs.)
197AC25	0.075	25	272.3	18	2.00	3.25	1.60	2.81	x		0.875
197AB20	0.12	20	1246.4	25	2.00	3.25	1.65	2.81	x		0.875
197AB25	0.15	25	1452.0	10	3.31	3.40	2.50	2.50	x	2.00	2.5
197AA15	0.24	15	739.5	38	2.00	3.25	1.60	2.81	x		0.875
197AA20	0.25	20	1185.3	14	3.31	3.05	2.50	2.50	x	2.00	2.5
197A25	0.48	25	504	11	4.50	3.95	3.12	4.00	x	2.75	6
197B10	0.5	10	471.6	67	2.00	3.25	1.60	2.81	x		0.875
197B15	0.5	15	812.3	39	3.31	3.40	2.50	2.50	x	2.00	2.5
197B20	0.8	20	333.0	23	3.86	4.50	3.37	4.00	x	2.75	6
197C10	1	10	514.2	75	3.31	3.40	2.50	2.50	x	2.00	2.5
197C5	1.25	5	314.9	126	2.00	3.25	1.60	2.81	x		0.875
197C15	1.35	15	289.05	29	3.86	4.50	3.37	4.00	x	2.75	6
197C25	1.4	25	272.3	30	6.40	6.10	4.38	5.00	x	3.50	16
197D20	2	20	218.0	49	6.40	6.10	4.38	5.00	x	3.50	16
197E10	3.5	10	129.55	96	3.86	4.50	3.37	4.00	x	2.75	6
197E15	3.5	15	152.9	80	6.40	6.10	4.38	5.00	x	3.50	16
197E5	4	5	250.5	232	3.31	3.40	2.50	2.50	x	2.00	2.5
197H10	7.5	10	123.3	143	6.40	6.10	4.38	5.00	x	3.50	16
197J5	14	5	74.35	293	3.86	4.50	3.37	4.00	x	2.75	6
197M5	25	5	72.4	403	6.40	6.10	4.38	5.00	x	3.50	16

Need Assistance? Contact Us.

Tags: reactor, high frequency, filtering, self-resonant

Data subject to change without notice.

Fig. 27. Design 2 Inductor L_1 Datasheet

HAMMOND *Quality Products. Service Excellence.*

High Frequency Reactors *197 Series*

Features:

- Perfect for high frequency filtering applications.
- High self-resonant frequency values
- Operating Frequency: 60Hz - 10kHz
- Some models feature universal channel mount packaging with flexible insulated leads (6" min.).
- Some models feature rugged construction with aluminum base and stainless steel band along with open-style terminals for maximum versatility.
- Consult datasheets for further design details.
- For DC applications try out **195-196 Series**

RoHS

Part No.	Inductance (mH)	DC Current (A)	Self-Resonant Frequency (kHz)	DC Resistance (mOhm)	Dimensions A	B	C	Mounting Hole Pattern			Weight (lbs.)
197AC25	0.075	25	272.3	18	2.00	3.25	1.60	2.81	x		0.875
197AB20	0.12	20	1246.4	25	2.00	3.25	1.65	2.81	x		0.875
197AB25	0.15	25	1452.0	10	3.31	3.40	2.50	2.50	x	2.00	2.5
197AA15	0.24	15	739.5	38	2.00	3.25	1.60	2.81	x		0.875
197AA20	0.25	20	1185.3	14	3.31	3.05	2.50	2.50	x	2.00	2.5
197A25	0.48	25	504	11	4.50	3.95	3.12	4.00	x	2.75	6
197B10	0.5	10	471.6	67	2.00	3.25	1.60	2.81	x		0.875
197B15	0.5	15	812.3	39	3.31	3.40	2.50	2.50	x	2.00	2.5
197B20	0.8	20	333.0	23	3.86	4.50	3.37	4.00	x	2.75	6
197C10	1	10	514.2	75	3.31	3.40	2.50	2.50	x	2.00	2.5
197C5	1.25	5	314.9	126	2.00	3.25	1.60	2.81	x		0.875
197C15	1.35	15	289.05	29	3.86	4.50	3.37	4.00	x	2.75	6
197C25	1.4	25	272.3	30	6.40	6.10	4.38	5.00	x	3.50	16
197D20	2	20	218.0	49	6.40	6.10	4.38	5.00	x	3.50	16
197E10	3.5	10	129.55	96	3.86	4.50	3.37	4.00	x	2.75	6
197E15	3.5	15	152.9	80	6.40	6.10	4.38	5.00	x	3.50	16
197E5	4	5	250.5	232	3.31	3.40	2.50	2.50	x	2.00	2.5
197H10	7.5	10	123.3	143	6.40	6.10	4.38	5.00	x	3.50	16
197J5	14	5	74.35	293	3.86	4.50	3.37	4.00	x	2.75	6
197M5	25	5	72.4	403	6.40	6.10	4.38	5.00	x	3.50	16

Tags: **reactor**, **high frequency**, **filtering**, **self-resonant**

Data subject to change without notice

Fig. 28. Design 1 Inductor L_2 Datasheet

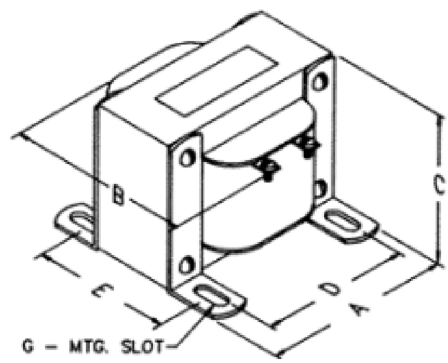
HAMMOND

Quality Products. Service Excellence.

Heavy Current Chassis Mount *195-196 Series*

Features

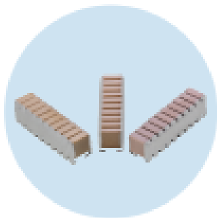
- Open core & coil, 4-slot bracket mounting chokes
- Tolerance of 15% on both inductance & resistance
- Storage: -40C to 105C temperature range
- Operating: -40C to 85C temperature range
- Inductances measured at rated D.C. current
- The "195" series is single coil
- The "196" series is dual coil - allowing more versatility
- Recommended maximum operating voltage 600 VAC (winding to core)
- Hipot tested at 2,500 VAC
- Connections are made to a screw terminal or heavy copper tabs with holes
- Perfect for high current power supply filtering
- All chokes are UL approved under Type 3AH, E207860, 30V7
- For AC applications 60 Hz to 10,000 Hz try our **197 Series**



195 Series

Part No.	Inductance mH (Millihenries)	D.C. Current (Amps)	Resistance (Ohms)	Insulation Class	A	B	C	D	E	Mounting Slot G			Weight (lbs.)
195A200	0.3	200	0.0012	-	7.50	7.00	6.50	6.00	5.25	0.28	x	0.56	46
195B100	0.5	100	0.002	-	6.38	6.25	5.38	5.25	4.13	0.28	x	0.56	31
195B150	0.5	150	0.0018	B	5.25	5.50	4.47	4.38	4.13	0.28	x	0.56	26
195C20	1	20	0.013	A	3.00	3.06	2.50	2.50	2.25	0.20	x	0.38	3
195C30	1	30	0.010	A	3.75	3.85	3.13	3.13	2.50	0.20	x	0.38	6
195C50	1	50	0.006	A	4.50	5.25	3.75	3.75	3.50	0.20	x	0.38	14.5
195C75	1	75	0.004	A	5.25	6.00	4.47	4.38	4.63	0.28	x	0.56	23
195C100	1	100	0.0036	B	5.25	6.50	4.47	4.38	5.13	0.28	x	0.56	26
195D50	1.4	50	0.005	-	6.38	5.50	5.38	5.25	3.88	0.28	x	0.56	28
195E20	2.5	20	0.022	A	3.75	4.20	3.13	3.13	2.75	0.20	x	0.38	6.5
195E30	2.5	30	0.013	A	4.50	5.25	3.75	3.75	3.50	0.20	x	0.38	12.5
195E50	2.5	50	0.008	A	5.25	6.00	4.47	4.38	4.63	0.28	x	0.56	23.5

Fig. 29. Design 2 Inductor L_2 Datasheet



Applications	• Input and output stages of switch mode power supplies and DC-DC converters
Benefits	• Reduces the overall circuit board footprint • Low ESR and low ESL • High capacitance to volume ratio • Superior performance over aluminum or tantalum capacitors

		Capacitance (µF)						
		14	22	27	47	68	100	220
Voltage	25V					-3	-5	-10
	50V			-3	-5		-10	
	100V	-3	-5		-10			

Note: Dash number denotes number of capacitors and leads per side.

Typical ESR (Ohms)					
	22µF	27µF	47µF	100µF	220µF
ESR @ 1kHz	0.0830	0.0680	0.0400	0.0240	0.0110
ESR @ 10kHz	0.0086	0.0070	0.0040	0.0033	0.0015
ESR @ 50kHz	0.0044	0.0031	0.0020	0.0013	0.0006
ESR @ 100kHz	0.0032	0.0022	0.0015	0.0009	0.0004

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Fig. 30. Design 1 Capacitor C_1 Datasheet

SMD Aluminum Electrolytic Capacitors

AEK Series

KYOCERA AVX

TECHNICAL SPECIFICATIONS

Category Temperature Range:	-55ºC to + 105°C (6.3 - 100V), -40°C to +105°C (160 - 400V)		
Capacitance Range:	At 25°C,120Hz	1.0µF to 1000µF	
Capacitance Tolerance:	At 25°C,120Hz	±20%	
Dissipation Factor (%)	Measurement Frequency: 120Hz at 25°C	Please see the Ratings and Part Number Reference Table below	
Leakage Current	Rated voltage at 25°C*	6.3 - 100V	160 - 400V
		I ≦ 0.01CV or 3µA, whichever is greater (2min)	I ≦ 0.04CV + 100µA (1min)

* Note: In the case of an anomalous reading, re-measure the leakage current after following voltage treatment:
Voltage treatment: DC rated voltage to be applied to the capacitors for 120 minutes at 105°C.

CAPACITANCE AND RATED VOLTAGE RANGE (FIGURE DENOTES CASE SIZE)

Capacitance		Rated Voltage DC (V_R)												
µF	Code	6.3V	10V	16V	25V	35V	50V	63V	80V	100V	160V	200V	250V	400V
1.0	1R0													0608*
1.5	1R5													0610
2.2	2R2												0608*	0610
3.3	3R3												0608*	0810
4.7	4R7												0810	0812
5.6	5R6													0812
6.8	6R8													0813
8.2	8R2													0815
10	100								0608	0608	1010	0810	0812	1013
15	150										0812	0813		1016
22	220						0608	0608	0810	0810	1012		1016	
33	330						0608	0810	0810	1010	1013			
47	470				0608	0608	0810	1010	1010	1010	1016			
100	101		0608	0608	0608	0810	1010	1010	1012	1213				
150	151			0608					1213					
220	221	0608	0608	0810	0810	1010		1213	1216					
330	331	0810	0810	0810	1010	1012	1216							
470	471		0810	1010	1012									
820	821		1010											
1000	102	1010												

Released ratings
* L dimensions (height) reduced to 7.70±0.50mm

RATINGS & PART NUMBER REFERENCE

Part No.	Case Size	Capacitance (µF)	Rated Voltage (V)	DF Max. (%)	ESR Max. @100kHz (Ω)	100kHz RMS Current (mA)
			6.3 Volt			
AEK0608221M006R	0608	220	6.3	30	0.68	160
AEK0810331M006R	0810	330	6.3	40	0.3	340
AEK1010102M006R	1010	1000	6.3	40	0.28	860
			10 Volt			
AEK0608101M010R	0608	100	10	24	0.68	175
AEK0608221M010R	0608	220	10	24	0.68	180
AEK0810331M010R	0810	330	10	30	0.3	340
AEK0810471M010R	0810	470	10	30	0.3	360
AEK1010821M010R	1010	820	10	30	0.28	860
			16 Volt			
AEK0608101M016R	0608	100	16	20	0.68	175
AEK0608151M016R	0608	150	16	20	0.68	190
AEK0810221M016R	0810	220	16	26	0.3	500
AEK0810331M016R	0810	330	16	26	0.3	545
AEK1010471M016R	1010	470	16	26	0.28	800

All technical data relates to an ambient temperature of +25C. Capacitance and DF are measured at 120Hz, 0.5RMS with DC bias of 2.2 volts. DCL is measured at rated voltage after 5 minutes.
* L dimension (height) reduced to 7.70±0.50mm

KYOCERA AVX | The Important Information/Disclaimer is incorporated in the catalog where these specifications came from or available online at www.kyocera-avx.com/disclaimer/ by reference and should be reviewed in full before placing any order.

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TDS-ALUM-0007 | Rev 6

Fig. 31. Design 2 Capacitor C_1 Datasheet

SMD Aluminum Electrolytic Capacitors

AEK Series

KYOCERA AVX

Part No.	Case Size	Capacitance (µF)	Rated Voltage (V)	DF Max. (%)	ESR Max. @100kHz (Ω)	100kHz RMS Current (mA)
			25 Volt			
AEK0608470M025R	0608	47	25	16	0.68	180
AEK0608101M025R	0608	100	25	16	0.68	205
AEK0810221M025R	0810	220	25	16	0.3	550
AEK1010331M025R	1010	330	25	16	0.28	780
AEK1012471M025R	1012	470	25	16	0.15	875
			35 Volt			
AEK0608470M035R	0608	47	35	14	0.68	210
AEK0810101M035R	0810	100	35	14	0.3	575
AEK1010221M035R	1010	220	35	14	0.28	835
AEK1012331M035R	1012	330	35	14	0.15	900
			50 Volt			
AEK0608220M050R	0608	22	50	12	1.36	175
AEK0608330M050R	0608	33	50	12	1.36	180
AEK0810470M050R	0810	47	50	12	0.6	540
AEK1010101M050R	1010	100	50	12	0.45	700
AEK1216331M050R	1216	330	50	12	0.15	1180
			63 Volt			
AEK0608220M063R	0608	22	63	12	4.2	150
AEK0810330M063R	0810	33	63	12	1.16	375
AEK0810470M063R	0810	47	63	12	1.16	450
AEK1010101M063R	1010	100	63	12	0.67	575
AEK1213221M063R	1213	220	63	12	0.28	890
			80 Volt			
AEK0608100M080R	0608	10	80	12	4.8	140
AEK0810220M080R	0810	22	80	12	1.95	375
AEK0810330M080R	0810	33	80	12	1.95	450
AEK1010470M080R	1010	47	80	12	1.24	575
AEK1012101M080R	1012	100	80	12	1.24	600
AEK1213151M080R	1213	150	80	12	0.54	800
AEK1216221M080R	1216	220	80	12	0.46	960
			100 Volt			
AEK0608100M100R	0608	10	100	12	5	135
AEK0810220M100R	0810	22	100	12	2.5	345
AEK1010330M100R	1010	33	100	12	1.6	560
AEK1010470M100R	1010	47	100	12	1.6	575
AEK1213101M100R	1213	100	100	12	0.65	680

Fig. 32. Design 2 Capacitor C_1 ESR

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High Frequency Reactors *197 Series*

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RoHS

Features:

- Perfect for high frequency filtering applications.
- High self-resonant frequency values
- Operating Frequency: 60Hz - 10kHz
- Some models feature universal channel mount packaging with flexible insulated leads (6" min.).
- Some models feature rugged construction with aluminum base and stainless steel band along with open-style terminals for maximum versatility.
- Consult datasheets for further design details.
- For DC applications try out 195-196 Series

PRODUCT RESOURCES

Specification Sheet

Print Page

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Part Details

Click Part No, below, for details (e.g., Product drawings, assembly instructions, ship weight)

Part No.	Inductance (mH)	DC Current (A)	Self-Resonant Frequency (kHz)	DC Resistance (mOhm)	Dimensions A	B	C	Mounting Hole Pattern			Weight (lbs.)
197AC25	0.075	25	272.3	18	2.00	3.25	1.60	2.81	x		0.875
197AB20	0.12	20	1246.4	25	2.00	3.25	1.65	2.81	x		0.875
197AB25	0.15	25	1452.0	10	3.31	3.40	2.50	2.50	x	2.00	2.5
197AA15	0.24	15	739.5	38	2.00	3.25	1.60	2.81	x		0.875
197AA20	0.25	20	1185.3	14	3.31	3.05	2.50	2.50	x	2.00	2.5
197A25	0.48	25	504	11	4.50	3.95	3.12	4.00	x	2.75	6
197B10	0.5	10	471.6	67	2.00	3.25	1.60	2.81	x		0.875
197B15	0.5	15	812.3	39	3.31	3.40	2.50	2.50	x	2.00	2.5
197B20	0.8	20	333.0	23	3.86	4.50	3.37	4.00	x	2.75	6
197C10	1	10	514.2	75	3.31	3.40	2.50	2.50	x	2.00	2.5
197C5	1.25	5	314.9	126	2.00	3.25	1.60	2.81	x		0.875
197C15	1.35	15	289.05	29	3.86	4.50	3.37	4.00	x	2.75	6
197C25	1.4	25	272.3	30	6.40	6.10	4.38	5.00	x	3.50	16
197D20	2	20	218.0	49	6.40	6.10	4.38	5.00	x	3.50	16
197E10	3.5	10	129.55	96	3.86	4.50	3.37	4.00	x	2.75	6
197E15	3.5	15	152.9	80	6.40	6.10	4.38	5.00	x	3.50	16
197E5	4	5	250.5	232	3.31	3.40	2.50	2.50	x	2.00	2.5
197H10	7.5	10	123.3	143	6.40	6.10	4.38	5.00	x	3.50	16
197J5	14	5	74.35	293	3.86	4.50	3.37	4.00	x	2.75	6
197M5	25	5	72.4	403	6.40	6.10	4.38	5.00	x	3.50	16

Need Assistance? Contact Us.

Tags: reactor, high frequency, filtering, self-resonant

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Fig. 33. Design 3 Capacitor C_1 Datasheet

SAMSUNG ELECTRO-MECHANICS

RoHS+Halogen Compliant Ecoparts

SPECIFICATION (Reference sheet)

· **Supplier : Samsung electro-mechanics**
· **Product : Multi-layer Ceramic Capacitor**
· **Samsung P/N :** **CL05A225MA5NUNC**
· **Description :** **CAP, 2.2㎌, 25V, ±20%, X5R, 0402**

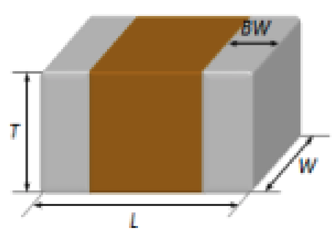
General | Standard | Normal | 85℃ | 2T | Normal | Reflow OK

A. Samsung Part Number

CL	05	A	225	M	A	5	N	U	N	C
①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪

① **Series**	Samsung Multi-layer Ceramic Capacitor			
② **Size**	0402 (inch code) L : 1.00±0.20㎜		W :	0.50±0.20㎜
③ **Dielectric**	X5R	⑧ **Inner electrode**	Ni	
④ **Capacitance**	2.2㎌	**Termination**	Cu	
⑤ **Capacitance tolerance**	±20%	**Plating**	Ni/Sn 100%	(Pb Free)
⑥ **Rated Voltage**	25V	⑨ **Product**	Size control code	
⑦ **Thickness**	0.50±0.20㎜	⑩ **Special**	Reserved for future use	
		⑪ **Packaging**	Cardboard Type, 7" Reel / Quantity : 10K	

B. Structure & Dimension



Samsung P/N	Dimension(㎜)			
	L	W	T	BW
CL05A225MA5NUNC	1.00±0.20	0.50±0.20	0.50±0.20	0.25±0.10

Fig. 34. Design 1 Capacitor C_2 Datasheet

VISHAY. www.vishay.com

013 RLC

Vishay BCcomponents

Aluminum Electrolytic Capacitors Radial Low Leakage Current

Fig. 1

FEATURES

- Useful life at +85 °C: 3000 h
- Low leakage current, low energy consumption
- Miniaturized, high CV-product per unit volume
- Natural pitch 5 mm
- Polarized aluminum electrolytic capacitors, non-solid electrolyte
- Radial leads, cylindrical aluminum case, all-insulated (light blue)
- Charge and discharge proof
- Material categorization: for definitions of compliance please see www.vishay.com/doc?99912

RoHS COMPLIANT

APPLICATIONS

- Telecommunication, automotive, audio-video, EDP and industrial
- Coupling, decoupling, buffering, timing, energy storage
- Portable and mobile equipment
- Low surface demand on printed-circuit board

MARKING

The capacitors are marked (where possible) with the following information:

- Rated capacitance (in µF)
- Tolerance on rated capacitance, code letter in accordance with IEC 60062 (M for ± 20 %)
- Rated voltage (in V)
- Date code in accordance with IEC 60062
- Code indicating factory of origin
- Name of manufacturer
- "-"-sign on top to identify the negative terminal
- Series number (013)

QUICK REFERENCE DATA

DESCRIPTION	VALUE
Nominal case sizes (Ø D x L in mm)	8.2 x 11
Rated capacitance range, C_R	33 µF to 470 µF
Tolerance on C_R	± 20 %; ± 10 % on request
Rated voltage range, U_R	6.3 V to 50 V
Category temperature range	-40 °C to +85 °C
Leakage current after 2 min:	
U_R = 6.3 V to 25 V	0.002 C_R x U_R or 0.7 µA, whichever is greater
U_R = 35 V and 50 V	0.002 C_R x U_R + 1 µA
Endurance test at 85 °C	2000 h
Useful life at 105 °C	750 h
Useful life at 85 °C	3000 h
Useful life at 40 °C, 1.4 x I_R applied	80 000 h
Shelf life at 0 V, 85 °C	500 h
Based on sectional specification	IEC 60384-4 / EN 130300
Climatic category IEC 60068	40 / 085 / 56

SELECTION CHART FOR C_R, U_R, AND RELEVANT NOMINAL CASE SIZES (Ø D x L in mm)

C_R (µF)	U_R (V)					
	6.3	10	16	25	35	50
33	-	-	-	-	-	8.2 x 11
47	-	-	-	8.2 x 11	-	8.2 x 11
68	-	-	-	-	-	8.2 x 11
100	-	-	8.2 x 11	-	8.2 x 11	-
220	-	8.2 x 11	-	-	-	-
330	8.2 x 11	-	-	-	-	-
470	8.2 x 11	-	-	-	-	-

Revision: 03-Jul-2024 1 Document Number: 28313

For technical questions, contact: aluminumcaps1@vishay.com

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Fig. 35. Design 2 Capacitor C_2 Datasheet

Table 1

ELECTRICAL DATA AND ORDERING INFORMATION

U_R (V)	C_R 100 Hz (µF)	NOMINAL CASE SIZE Ø D x L (mm)	I_R 100 Hz 85 °C (mA)	I_{L2} 2 min (µA)	tan δ 100 Hz	Z 10 kHz (Ω)	ORDERING CODE MAL2013....... BULK PACKAGING LONG LEADS FORM CA	F (mm)	CUT LEADS FORM CB	F (mm)	TAPED AMMOPACK FORM TFA	F (mm)
6.3	330	8.2 x 11	210	4.2	0.2	0.9	53331E3	5.0	63331E3	5.0	33331E3	5.0
	470	8.2 x 11	250	5.9	0.2	0.64	53471E3	5.0	63471E3	5.0	33471E3	5.0
10	220	8.2 x 11	190	4.4	0.16	0.9	54221E3	5.0	64221E3	5.0	34221E3	5.0
16	100	8.2 x 11	150	3.2	0.13	1.0	55101E3	5.0	65101E3	5.0	35101E3	5.0
25	47	8.2 x 11	130	2.4	0.08	1.3	56479E3	5.0	66479E3	5.0	36479E3	5.0
35	100	8.2 x 11	150	8.0	0.13	1.0	50101E3	5.0	60101E3	5.0	30101E3	5.0
50	33	8.2 x 11	110	4.3	0.06	1.4	51339E3	5.0	61339E3	5.0	31339E3	5.0
	47	8.2 x 11	130	5.7	0.08	1.3	51479E3	5.0	61479E3	5.0	31479E3	5.0
	68	8.2 x 11	150	7.8	0.08	1.2	51689E3	5.0	61689E3	5.0	31689E3	5.0

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For technical questions, contact: aluminumcaps1@vishay.com

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Fig. 36. Design 2 Capacitor C_2 ESR

VISHAY. www.vishay.com

128 SAL-RPM

Vishay BCcomponents

Aluminum Capacitors Solid Al, Radial Pearl Miniature

123 SAL-A ← axial version — 128 SAL-RPM

Fig. 1

QUICK REFERENCE DATA	
DESCRIPTION	**VALUE**
Maximum case sizes (H x W x T in mm)	10 x 7 x 3.5 to 10 x 8 x 6
Rated capacitance range (E6 series), C_R	0.22 µF to 68 µF
Tolerance on C_R	± 20 %
Rated voltage range, U_R	6.3 V to 40 V
Category temperature range:	
U_R = 6.3 V to 40 V	-55 °C to +85 °C
U_C = 6.3 V to 25 V	-55 °C to +125 °C
Endurance test at 125 °C	10 000 h
Useful life at 125 °C	20 000 h
Useful life at 175 °C	2000 h
Useful life at 40 °C, I_R applied	> 300 000 h
Shelf life at 0 V, 125 °C	500 h
Based on sectional specification	IEC 60384-4/EN 130300
Climatic category IEC 60068	55/125/56

FEATURES

- Polarized aluminum electrolytic capacitors, solid electrolyte MnO_2
- Radial leads, max. height 10 mm, resin dipped, orange colored
- Extremely long useful life: 20 000 h at 125 °C
- Extended high temperature range up to 175 °C
- Excellent low temperature, impedance and ESR behavior
- Charge and discharge proof, application with 0 Ω resistance allowed
- Reverse DC voltage up to 0.3 x U_R allowed
- AC voltage up to 0.8 x U_R allowed
- Material categorization: for definitions of compliance please see www.vishay.com/doc?99912

RoHS COMPLIANT

APPLICATIONS

- Audio-video, automotive, industrial high temperature and telecommunication
- Smoothing, filtering and buffering
- For small power supplies, DC/DC converters

MARKING

The capacitors are marked (where possible) with the following information:

- Rated capacitance (in µF)
- Tolerance on rated capacitance, code letter in accordance with IEC 60062 (M for ± 20 %)
- Rated voltage (in V) and category voltage if applicable
- Date code in accordance with IEC 60062
- Name of manufacturer
- "I" sign to indicate the negative terminal
- "+" sign to identify the positive terminal
- Series number

MOUNTING

When bending, cutting or straightening the leads, ensure that the capacitor body is relieved of stress.

Bending after soldering must be avoided.

Completely sealing the component's body or use in an oxygen-free environment has a negative impact on useful life.

SELECTION CHART FOR C_R, U_R, U_C, AND RELEVANT MAXIMUM CASE SIZES (H x W x T in mm)

C_R (µF)	U_R (V) AT T_{amb} = 85 °C				
	6.3	10	16	25	40
	U_C (V) AT T_{amb} = 125 °C				
	6.3	10	16	25	25
0.22	-	-	-	-	10 x 7 x 3.5
0.33	-	-	-	-	10 x 7 x 4
0.47	-	-	-	-	10 x 7 x 5
0.68	-	-	-	10 x 7 x 3.5	10 x 7 x 5
1.0	-	-	-	10 x 7 x 3.5	10 x 7 x 5
1.5	-	-	-	10 x 7 x 3.5	10 x 8 x 6
2.2	-	-	10 x 7 x 3.5	10 x 7 x 4	10 x 8 x 6

Revision: 14-Aug-15 1 Document Number: 28354

For technical questions, contact: aluminumcaps2@vishay.com

Fig. 37. Design 3 Capacitor C_2 Datasheet

Table 2

ELECTRICAL DATA AND ORDERING INFORMATION

U_C (V)	U_R (V)	C_R 100 Hz (µF)	MAXIMUM CASE SIZE H x W x T (mm)	I_R 100 Hz 125 °C (mA)	I_R 10 kHz 85 °C (mA)	I_R 100 kHz 40 °C (mA)	I_{L5} 5 min (µA)	MAX. ESR 100 Hz (Ω)	TYP. ESR 100 Hz (Ω)	Z 100 kHz (Ω)	ORDERING CODE MAL2128....... FORM CB	FORM CA	FORM TR+ REEL	FORM TFA AMMO
6.3	6.3	10	10 x 7 x 3.5	22.4	320	595	2	20	8	2.0	53109E3	73109E3	23109E3	33109E3
		22	10 x 7 x 4	32.9	470	870	4	9	3.5	1.0	53229E3	73229E3	23229E3	33229E3
		33	10 x 7 x 5	65.4	595	1100	5	6.1	2	0.70	53339E3	73339E3	23339E3	33339E3
		47	10 x 8 x 5	118.4	740	1360	7	4.3	2	0.50	53479E3	73479E3	23479E3	33479E3
		68	10 x 8 x 6	153.0	800	1650	11	3.0	1.5	0.40	53689E3	73689E3	23689E3	33689E3
10	10	4.7	10 x 7 x 3.5	16.1	230	425	2	43	16	3.00	54478E3	74478E3	24478E3	34478E3
		6.8	10 x 7 x 3.5	18.9	270	500	2	30	12	2.20	54688E3	74688E3	24688E3	34688E3
		10	10 x 7 x 4	21.7	310	573	3	20	9	1.70	54109E3	74109E3	24109E3	34109E3
		15	10 x 7 x 4	27.3	390	720	4	14	7	1.20	54159E3	74159E3	24159E3	34159E3
		22	10 x 7 x 5	51.7	470	870	6	9	3.5	0.90	54229E3	74229E3	24229E3	34229E3
		33	10 x 8 x 5	81.6	510	940	8	6.1	2	0.60	54339E3	74339E3	24339E3	34339E3
		47	10 x 8 x 6	105.4	620	1140	12	4.3	1.5	0.40	54479E3	74479E3	24479E3	34479E3
16	16	2.2	10 x 7 x 3.5	14.0	200	370	2	91	25	4.50	55228E3	75228E3	25228E3	35228E3
		3.3	10 x 7 x 3.5	16.1	230	425	2	61	26	3.30	55338E3	75338E3	25338E3	35338E3
		4.7	10 x 7 x 4	18.9	270	500	2	43	14	2.30	55478E3	75478E3	25478E3	35478E3
		6.8	10 x 7 x 4	22.4	320	590	3	30	11	1.65	55688E3	75688E3	25688E3	35688E3
		10	10 x 7 x 5	42.9	390	720	4	20	6	1.10	55109E3	75109E3	25109E3	35109E3
		15	10 x 8 x 5	71.2	445	820	6	14	5	0.85	55159E3	75159E3	25159E3	35159E3
		22	10 x 8 x 6	86.7	510	940	9	9	3.5	0.65	55229E3	75229E3	25229E3	35229E3
25	25	0.68	10 x 7 x 3.5	7.7	110	200	2	295	85	17.00	56687E3	76687E3	26687E3	36687E3
		1.0	10 x 7 x 3.5	9.1	130	240	2	200	71	12.50	56108E3	76108E3	26108E3	36108E3
		1.5	10 x 7 x 3.5	10.8	155	285	2	135	48	10.00	56158E3	76158E3	26158E3	36158E3
		2.2	10 x 7 x 4	13.6	195	360	2	91	34	7.00	56228E3	76228E3	26228E3	36228E3
		3.3	10 x 7 x 5	16.1	230	425	2	61	19	5.20	56338E3	76338E3	26338E3	36338E3
		4.7	10 x 8 x 5	25.3	270	500	3	43	14	3.50	56478E3	76478E3	26478E3	36478E3
		6.8	10 x 8 x 6	52.7	310	570	4	30	11	2.70	56688E3	76688E3	26688E3	36688E3
		10	10 x 8 x 6	64.8	360	660	6	20	9	2.00	56109E3	76109E3	26109E3	36109E3

Fig. 38. Design 3 Capacitor C_2 ESR