Component Design Challenges
Part 1

Introduction

Electronic component designs are driven by requirements. Form, fit and function are the fundamental elements. Truly good designs meet these needs and incorporate reliability and manufacturability. Reliability includes performance over the life of the application as well as consistency from part to part, lot to lot and year to year. Manufacturability includes simplicity, clarity, control and efficiency. Both reliability and manufacturability have a large impact on yield which in turn influences cost, delivery and user satisfaction. Then there’s the impact of design requirements and preferences. All of these factors must be considered when facing a design challenge.

Requirements vs. Preferences

Requirements are firm and it is critical that they be met. Preferences are desired characteristics that may not appear on the priority list. Knowing the design’s priorities is important because trade-offs may need to be made at times to ensure the design is realistic, reliable and repeatable.

For example, a customer request was made for an inductor with the following requirements:

Size:	1”L X 1”W X 1”H Maximum
Inductance:	54 mH Minimum
DCR:	0.50 Ω Maximum
Configuration:	Surface Mount

Communication with the customer determined the priorities were as follows in order of importance:

1. Size
2. Resistance
3. SMD Package
4. Inductance

The list of priorities identifies where trade-offs can be made, if they are deemed necessary.

The first effort to develop a design solution is based on inductance, to determine if any compromises are needed. We refer to that result as Design 1:

Design 1: 57 mH, 0.55 Ω, surface mount inductor, in a 1”L X 1”W X 1.5”H package

Note that the package size is larger than the customer requirement and the DC Resistance is above the maximum specified. However, when we incorporate the design priorities from the customer (above), a design solution is attained by lowering the inductance until the size and resistance in an SMD footprint is achieved.

This second effort yields the following final design, Design 2:

Design 2: 50 mH, 0.45 Ω, surface mount inductor, in a 1”L X 1”W X 1”H package

In this case a design is achieved that best suits the application since its characteristics are aligned with the order of priorities. While meeting all characteristics of a customer request is ideal, it is important to know the design priorities and to make appropriate trade-offs when necessary. Some priorities could be mechanical requirements, electrical performance, environmental conditions or even economics. The table below includes some examples of mechanical, electrical and environmental characteristics.

Possible Design Priorities

Mechanical	Electrical	Environmental
Existing Foot Print	Maximum Resistance	Temperature Stability
Maximum Height from PCB	Current Handling	Moisture Resistance
Surface Mount or Thru-Hole	Frequency Range of Use	Outgassing Compliance
Molded or Potted	Inductance or Impedance Requirement	Operating Temperature Range

Manufacturability & Reliability

The previous example considered the importance of design priorities. The next example will expand upon this to include a focus on manufacturability and reliability by design. Considerations will be made throughout the design process in order to avoid future concerns in the manufacturing processes and in the component's performance over time. In other words, manufacturability and reliability will be designed into the component, in addition to following design priorities.

The following requirements were provided for an autotransformer in order of design priority:

1. Inductance: L (1-5) = 180 mH ± 10% @ 1 kHz, 1 V_{rms}
2. Voltage Ratios: (1-5 to 1-2) 1:10
(1-5 to 2-3) 1:3.5
(1-5 to 3-4) 1:3.5
(1-5 to 4-5) 1:3
3. DCR: (1-5) 90 Ω Maximum @ 20°C
4. Size: 2.25"L X 2.25"W – reduce by 50% if possible
5. Height: 0.75" Maximum
6. Configuration: Thru-Hole, 0.025" to 0.028" leads
7. Fastening: Mechanical Fastening to PCB Required
8. Environmental: Environmental Seal Required

Design Process

An autotransformer is a transformer with only one winding. Sections of the same winding are used as both the primary and secondary windings by taps being formed within the winding to make electrical connections. The key advantage of autotransformers is that they can be smaller, lighter and more cost efficient than their multi-winding counterparts.

The first step in the design process is to determine the smaller area requested.

Existing: 2.25"L X 2.25"W = 5 in^2

Target: 5 in^2 X 50% = 2.5 in^2

Final: 2.5 in^2 = 1.58"L X 1.58"W

Determining the core requires looking at many factors. Operating frequency, flux density, geometry, temperature stability and cost are some factors that need to be considered to determine the most suitable core. In this case a toroid has many benefits for this design. Toroidal transformers are smaller, lighter and more efficient than other shapes. Also, mechanical fastening can be done at a single point through the center of the toroid. The medium frequency (1 kHz) and required permeability help to determine the core material. Some common materials and their recommended operating frequencies are shown below.

Core Material Options

Material	Operating Frequency
Permalloy Powder	10 kHz to 1 MHz
High Flux Powder	10 kHz to 1 MHz
Kool Mu™ / Sendust Powder	Up To 10 MHz
Iron Powder	100 kHz to 100 MHz
Ferrite - MnZn	10 kHz to 2 MHz
Ferrite - NiZn	200 kHz to 100 MHz

There are many suppliers of soft magnetic cores. Cost, lead times and reliability are important aspects of a design and these need to be considered for both raw materials and the finished component. The Kool Mu™ core has a relatively low cost as well as an operating frequency that is suited to the customer's application. Using the mechanical and electrical requirements of the application to evaluate Magnetics Kool Mu™ Toroid core offerings, core 548 (specifically Part Number 0077548-A7) was chosen. The selected core has a specified A_L of 127 nH/N^2 ± 8% (116 nH/N^2 to 137 nH/N^2). The inductance of the entire winding is specified as 180 mH ± 10% (162 mH to 198 mH).

The total number of turns (N) required is calculated to be 1190, using the following formula:

$$N = \sqrt{\frac{180 \cdot 10^6}{127}} = 1190$$

To avoid issues in meeting the customer's inductance specification, the variation in the core's A_L value should be evaluated.

$$L_{min} = (A_L - 8\%) \cdot 1190^2 = 116 \cdot 1190^2 = 164 \text{ mH}$$
$$L_{max} = (A_L + 8\%) \cdot 1190^2 = 137 \cdot 1190^2 = 194 \text{ mH}$$

Those calculations confirm that the design is within the specified inductance tolerance.

Using the provided voltage ratios, the number of turns between taps can be determined.

1-2: 1190 / 10 = 119 Turns
2-3: 1190 / 3.5 = 340 Turns
3-4: 1190 / 3.5 = 340 Turns
4-5: 1190 / 3 = 391 Turns

The inductance of each section of the winding can be determined using $L = A_L \cdot N^2$

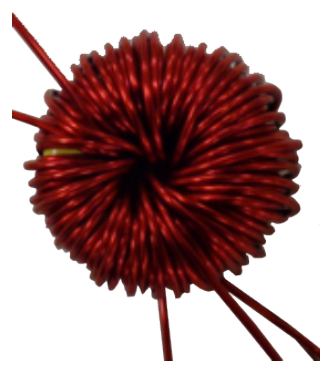
1-2:	1.798 mH
2-3:	14.681 mH
3-4:	15.681 mH
4-5:	19.415 mH

Of note, these inductances are based on the nominal A_L value of the core. Although inductance limits are not specified on the individual windings, if they were, calculations would be made at the minimum and maximum specified A_L values of the core to ensure these would be in specification over the entire range of the material tolerance. Good design practice is to use a core and number of turns that allow for the variation in A_L value.

The Maximum DC Resistance helps to determine the minimum wire size that can be used electrically. The winding area size helps to determine the maximum wire size that is allowed physically.

Note: Fill factor is a function of manufacturability; it is important to avoid over fill and tight fits that will inhibit winding capability. A full winding is considered 30% to 45% fill factor. This is a good utilization of the space available and maintains reliability and manufacturability. Higher percentage fills can be achieved, but often require intensive labor and additional costs.

To demonstrate, the image on the left (below) represents approximately a 30% fill factor; this design allows for consistent machine winding, which is preferred. On the right is a fully filled toroid that cannot be machine wound and requires additional inefficient steps for completion; this design also leaves room for error such as miscounted turns or wire damage, which is not preferred. So a 40% fill factor is a good starting target to utilize the winding area and avoid costly manufacturing operations.



The Mean Length per Turn can be found on the Magnetics core datasheet. For the chosen core at a 40% fill factor the Mean Length per Turn will be 1.86”. Therefore 1190 turns at 1.86” per turn equates to needing 2213” (184.5 feet) of wire.

Magnet wire resistance is specified as Ohms per Foot of wire. Using the 90 Ω maximum resistance specification and dividing it by the required feet of wire will result in the Maximum Ohms per Foot (below). That value helps to determine the minimum wire size that can be used to remain within specification for resistance.

Max. Ω/ft = 90 Ω / 184.5 ft = 0.488 Ohms of resistance per foot maximum

A wire chart (below) is used to determine that 36 AWG is the finest wire that can be used to remain below the required resistance.

Selected Portion of Industry Standard Wire Chart *

Size (AWG)	BARE COPPER								
	DIAMETER (Inches)			RESISTANCE (OHMS PER 1000 FT AT 20°C)			FEET PER POUND	POUNDS PER 1000 FT	CIRCULAR MILS NOM
	MIN	NOM	MAX	MIN	NOM	MAX			
26	0.0157	0.0159	0.0161	40.01	41.02	42.07	1310	0.7650	252.8
27	0.0141	0.0142	0.0143	50.72	51.43	52.17	1640	0.6100	201.6
28	0.0125	0.0126	0.0127	64.30	65.33	66.37	2080	0.4810	158.8
29	0.0112	0.0113	0.0114	79.80	81.22	82.68	2590	0.3870	127.7
30	0.0099	0.0100	0.0101	101.7	103.7	105.8	3300	0.3030	100.0
31	0.0088	0.0089	0.0090	128.0	130.9	133.9	4170	0.2400	79.21
32	0.0079	0.0080	0.0081	158.1	162.0	166.2	5160	0.1940	64.00
33	0.0070	0.0071	0.0072	200.1	205.7	211.7	6550	0.1530	50.41
34	0.0062	0.0063	0.0064	253.2	261.3	269.8	8320	0.1200	39.69
35	0.0055	0.0056	0.0057	319.2	330.7	342.8	10500	0.0949	31.36
36	0.0049	0.0050	0.0051	398.7	414.8	431.9	13200	0.0757	25.00
37	0.0044	0.0045	0.0046	490.1	512.1	535.7	16300	0.0613	20.25
38	0.0039	0.0040	0.0041	617.0	648.2	681.9	20600	0.0484	16.00
39	0.0034	0.0035	0.0036	800.2	846.6	897.1	27000	0.0371	12.25
40	0.0030	0.0031	0.0032	1013	1079	1152	34400	0.0291	9.61

* MWS Wire Industries

The chosen core provides a window area of 0.460 in^2. Using a target of a 40% fill factor, the usable winding area is calculated to be 0.184 in^2:

$$\text{Winding Area} = 0.460\ \text{in}^2 \cdot 40\% = 0.184\ \text{in}^2$$

The related wire diameter can be calculated as follows:

$$\text{Wire Diameter} = \sqrt{\frac{\text{Winding Area}}{\text{Number of Turns}}}$$

$$\text{Wire Diameter} = \sqrt{\frac{0.184}{1190}} = 0.0123\ \text{in}$$

From the wire chart above, 0.0123" diameter maximum means the heaviest wire desired is 29 AWG. From a manufacturability standpoint, the shuttle of the winder utilized to build the toroid can only hold so much wire. As the diameter of the wire increases the length of the wire that can be held decreases. It is important to consider the capability of the equipment that will be used. On the other hand, too fine a wire may lead to reliability issues due to its inherent fragility. Winding speed may need to be reduced to avoid breaking the wire during the winding process. In this case 32 AWG wire is selected since there is enough room on the shuttle to hold the entire 184.5 feet of wire and the wire will be durable enough to wind at optimized speeds without any additional yield losses. So 32 AWG wire will provide the best balance between physical size limitations and electrical requirements.

From the chart it is defined that the maximum DC Resistance per foot of 32 AWG at 20°C is 0.1662 Ω. Previously it was determined that 184.5 feet of wire would be needed to wind 1190 turns. In using those values to calculate the design's DCR (below) we determine that we are below the specified 90 Ω max.

$$DCR_{32\ AWG} = 184.5 \cdot 0.1662 = 30.65\ \Omega$$

Next, to verify the physical fit and fill factor for 32 AWG wire, we must first determine the area of the winding using its diameter of 0.008" from the chart and the number of turns:

$$\text{Winding Area} = \text{Diameter}^2 \cdot N = 0.008^2 \cdot 1190 = 0.076\ in^2$$

The fill factor is the ratio of winding area utilized to the winding area available:

$$\text{Fill Factor} = 0.076\ in^2 / 0.460\ in^2 = 16.5\%$$

This confirms that physical fit is achievable and fill factor is appropriate to coincide with manufacturing practices. In addition, the first three design priorities, 1.) Inductance, 2.) Voltage Ratios, and 3.) DCR have been met without needing any trade-offs. The winding requirements are also defined in a way that will be manufacturing friendly and provide reliability in the field.

In Part 2 we will cover the mechanical assembly of this autotransformer. This will include defining the terminations, evaluating potting materials for the environmental seal and preparing the final package to be easily mounted to a PCB.

IN CONCLUSION

Electronic component designs are driven by customer requirements and preferences. It is also important to consider component manufacturability and reliability during the design process. Evaluating all of these factors and maintaining a balance in trade-offs delivers the optimum design solution.

HELPFUL INFORMATION

Gowanda Electronics, an affiliate of GCG, provides additional information on Custom Inductors & Transformers here: https://www.gowanda.com/custom-products/

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