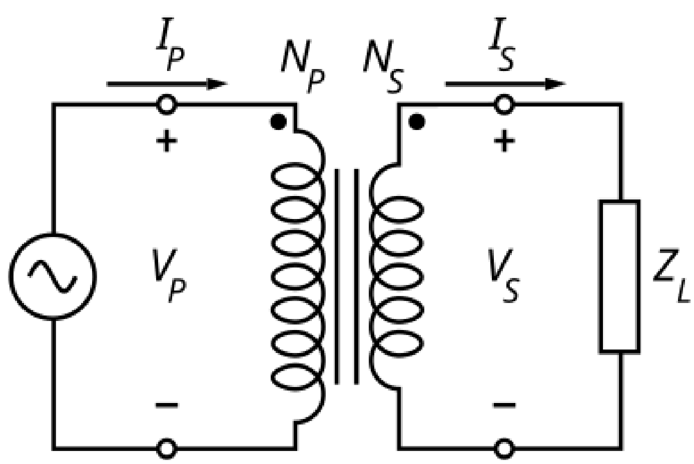
Introduction

The issue of having a desired voltage that differs from available voltage sources can be solved with transformers. Although they can be purchased, it may be challenging to find one that meets your specific needs. Thankfully, they are simple enough to make. This guide focuses specifically on powdered micrometal toroidal transformers with resonant frequencies from 1 MHz to 8 MHz.

What is a Transformer?

A transformer is a device that transfers electrical energy between circuits. They take in a primary voltage and output a secondary voltage, each one passing through its respective wire and windings. They are used to change AC voltage levels, either increasing or decreasing a secondary voltage.

Transformers use the law of the conservation of energy, which states that energy cannot be created or destroyed. Therefore, the total power output is equal to the power input. Real transformers experience losses in output power due to factors like winding resistance, eddy currents, and heat.



Basic circuit schematic of a transformer

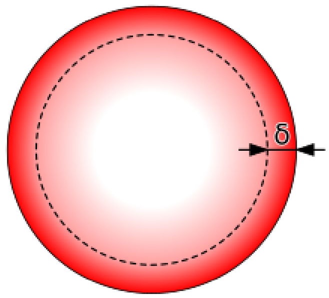
Design Considerations

Wire Gauge

When choosing what wire gauge to use, you must take into account the expected maximum current that may pass through the wire and the wire's current capacity.

At higher alternating current frequencies, the skin effect occurs, which increases the current density near the surface of the conductor and decreases it towards the center of the conductor. It effectively reduces the conductive area of the wire, making it so that only the ‘skin,’ a region which extends a certain depth into the wire, conducts electricity. The area of the conductive ‘skin’ decreases as the frequency increases, which results in an increased AC resistance throughout the wire, causing a loss in energy efficiency.

The gauge of the wire only affects the frequency at which the skin effect starts to affect the wire, since higher-gauge wires begin experiencing the skin effect at high frequencies when compared to lower-gauge wires.



The skin effect in a conductive wire

In general, the wire gauge does not significantly affect the performance of the transformer if it is operating safely within the wire’s current capacity. At high frequencies, the difference in skin depth between wire gauges that are close in size (e.g., 20-gauge and 24-gauge) is negligible. To effectively mitigate the skin effect, Litz wire is recommended.

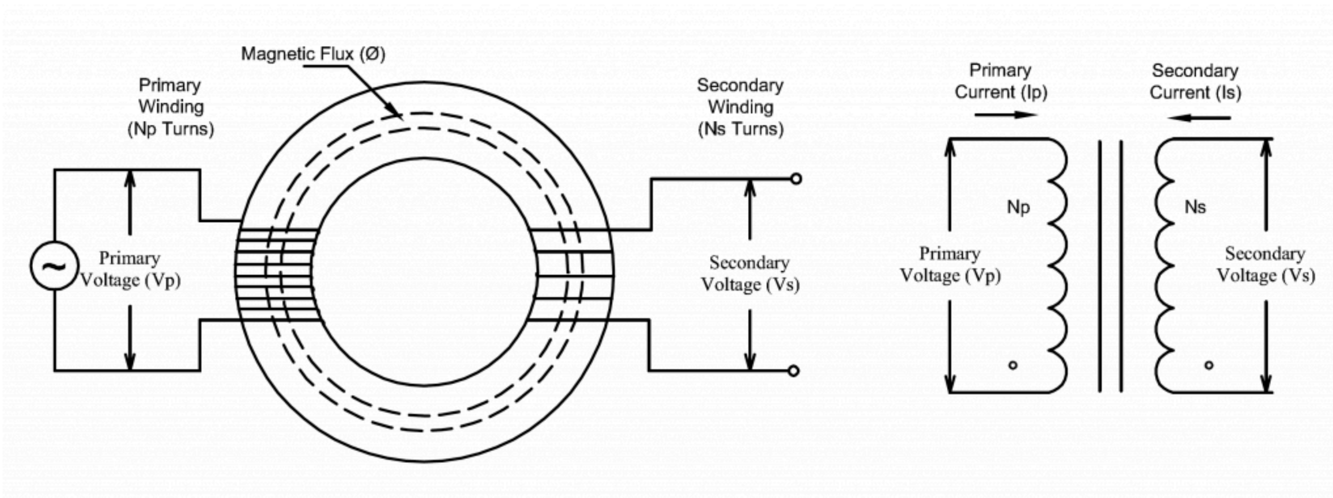
Core Material

Different core materials operate at different frequencies and can withstand different strengths of magnetic fields before becoming magnetically saturated.

Magnetic saturation occurs when the externally applied magnetic field cannot increase the magnetization of the material further. Magnetic remanence is the material's tendency to maintain a magnetic field after an external magnetic field that was applied to it has dissipated. When combined, these effects can create a permanent magnet. If these fields are unwanted, they result in decreased power efficiency.

The core material that will be used in this guide is a micrometal powdered iron, which demonstrates high saturation values and a frequency range between kHz and MHz. Thanks to the properties of the material, magnetic remanence and saturation are not a concern.

Toroidal Transformers



Transformer cores come in different shapes according to the required functionality of the transformer. For our purposes, a toroidal core will be used, as it has high energy efficiency and makes construction simple.

Significant Parameters in a Toroidal Transformer

Number of Windings

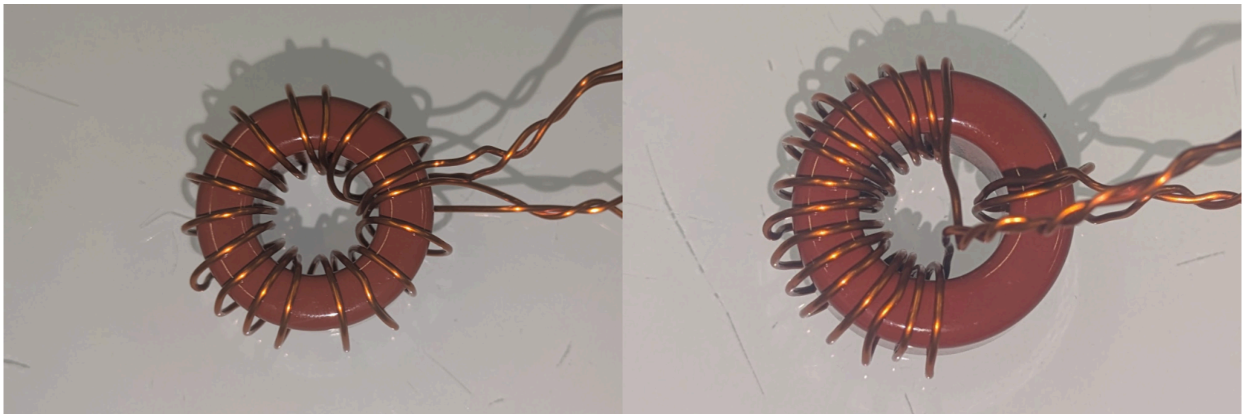
The ratio of the number of secondary and primary windings affects the secondary voltage, the resonant frequency, and the quality factor. The change in secondary voltage is predicted by:

$$V_s = V_p * \frac{N_s}{N_p}.$$

32 secondary windings (left) and 16 secondary windings (right)

Secondary Windings Coverage

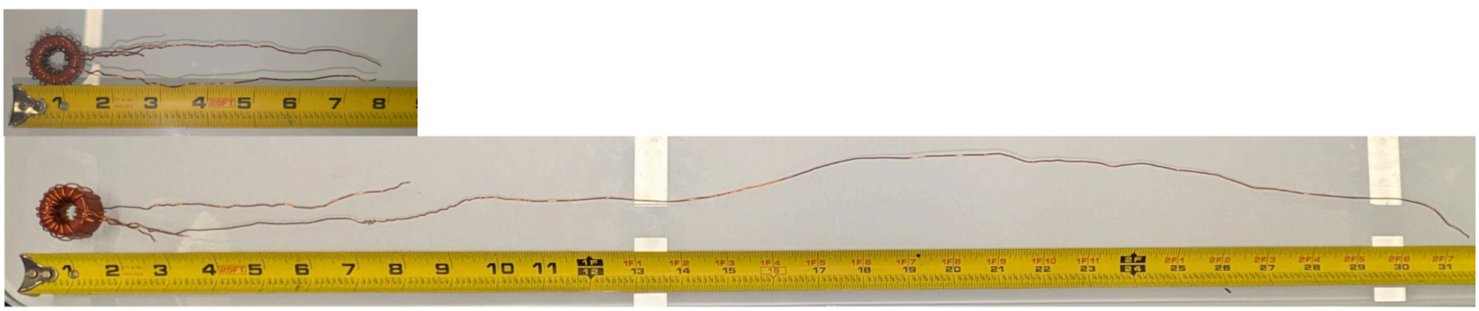
The angle covered by the secondary windings affects the resonant frequency, the quality factor, and energy efficiency.



Maximum secondary winding coverage (left) and 180° of secondary winding coverage (right)

Length of Wire

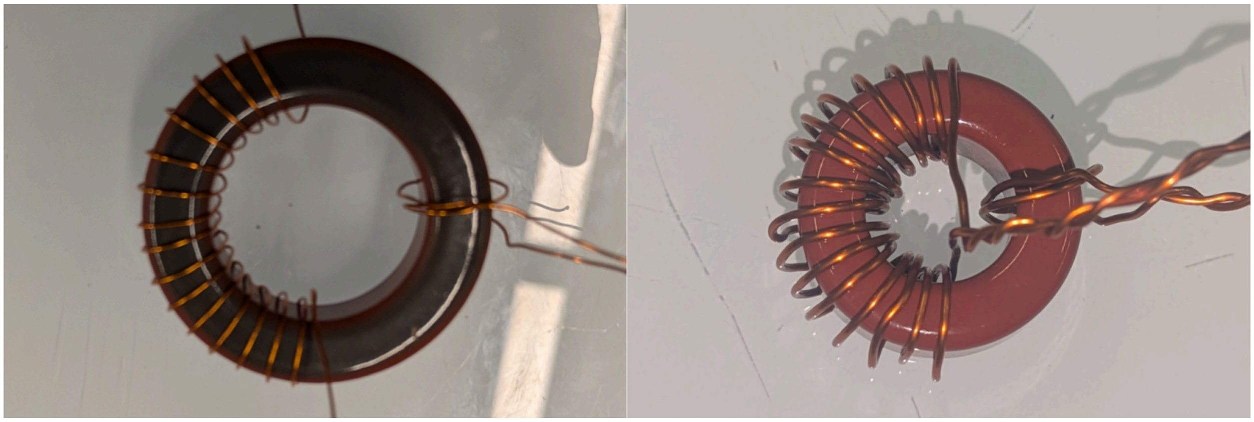
The length of the wire, which includes the wire in the windings, affects the resonant frequency, quality factor, and energy efficiency.



Shorter secondary wire (top) and longer secondary wire (bottom)

Toroid Size

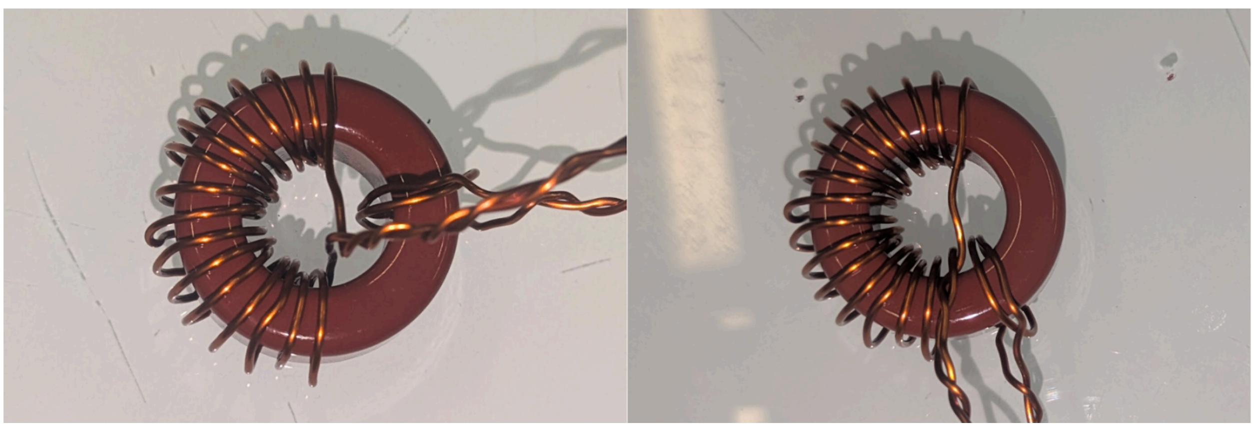
Toroid size affects the resonant frequency and the efficiency.



Large toroid core (left) and smaller toroid core (right)

Distance Between Primary and Secondary Windings

The distance between the primary and secondary windings affects the energy efficiency.



Large (left) and small (right) distances between primary and secondary windings

Relationships Between Parameters and Qualities of Transformer

	Increasing				
	Secondary Windings	Length of Secondary Wire	Secondary Windings Coverage	Toroid Size	Distance Between Primary and Secondary Windings
Resonant Frequency	Decreases	Decreases	Increases	Increases	None
Quality Factor	Increases	Decreases	Decreases	Decreases	None
Secondary Voltage	Increases	None	None	None	None
Efficiency	None	Decreases	Increases	Decreases	Decreases

	Decreasing				
	Secondary Windings	Length of Secondary Wire	Secondary Windings Coverage	Toroid Size	Distance Between Primary and Secondary Windings
Resonant Frequency	Increases	Increases	Decreases	Decreases	None
Quality Factor	Decreases	Increases	Increases	Increases	None
Secondary Voltage	Decreases	None	None	None	None
Efficiency	None	Increases	Decreases	Increases	Increases

Data of Different Transformers

Resonant Frequencies and Quality Factors for Different Numbers of Secondary Windings (Toroid with inner radius 1.2 in. and outer radius 2 in., 2 primary windings)

101.25 in. Secondary Wire					
32 Windings			48 Windings		
Secondary Winding Coverage	Resonant Frequency (MHz)	Quality Factor	Secondary Winding Coverage	Resonant Frequency (MHz)	Quality Factor
Maximum (>340°)	4.580	39.48	Maximum (>340°)	2.850	42.54
Half (180°)	3.679	89.73	Half (180°)	2.507	118.82
One-third (120°)	3.116	97.37	One-third (120°)	2.274	111.47

69.75 in. Secondary Wire					
16 Windings			32 Windings		
Secondary Winding Coverage	Resonant Frequency (MHz)	Quality Factor	Secondary Winding Coverage	Resonant Frequency (MHz)	Quality Factor
Maximum (>340°)	7.050	24.31	Maximum (>340°)	4.250	35.42
Half (180°)	6.380	44.93	Half (180°)	3.517	109.91
One-third (120°)	5.660	65.06	One-third (120°)	3.331	107.45

38.25 in. Secondary Wire		
16 Windings		
Secondary Winding Coverage	Resonant Frequency (MHz)	Quality Factor
Maximum (>340°)	8.020	20.56
Half (180°)	6.893	73.33
One-third (120°)	6.068	83.12

Resonant Frequencies and Quality Factors for Different Lengths of Secondary Wire
(Toroid with inner radius 0.55 in. and outer radius 1.05 in., 2 primary windings)

32 Windings					
69.75 in. Secondary Windings			101.25 in. Secondary Windings		
Secondary Winding Coverage	Resonant Frequency (MHz)	Quality Factor	Secondary Winding Coverage	Resonant Frequency (MHz)	Quality Factor
Maximum (>340°)	4.03	32.34	Maximum (>340°)	3.73	34.86
Two-thirds (240°)	3.889	53.27	Two-thirds (240°)	3.65	57.03
One-third (120°)			One-third (120°)		

Voltage and Efficiency for Different Numbers of Secondary Windings (Toroid with inner radius 1.2 in. and outer radius 2 in., 2 primary windings)

32 Windings					
69.75 in. Secondary Windings			101.25 in. Secondary Windings		
Secondary Winding Coverage	Measured Secondary Voltage (V) (Pk-Pk)	Efficiency (%)	Secondary Winding Coverage	Measured Secondary Voltage (V) (Pk-Pk)	Efficiency (%)
Maximum (>340°)	13.3	83.13	Maximum (>340°)	13.5	84.38
Two-thirds (240°)	12	75.00	Two-thirds (240°)	12.5	78.13
One-third (120°)	10.3	64.38	One-third (120°)	9.4	58.75

16 Windings					
38.25 in. Secondary Windings			69.75 in. Secondary Windings		
Secondary Winding Coverage	Measured Secondary Voltage (V) (Pk-Pk)	Efficiency (%)	Secondary Winding Coverage	Measured Secondary Voltage (V) (Pk-Pk)	Efficiency (%)
Maximum (>340°)	8	100	Maximum (>340°)	8.5	106.25
Two-thirds (240°)	8	100	Two-thirds (240°)	6	75
One-third (120°)	7	87.5	One-third (120°)	4.7	58.75

48 Windings		
101.25 in. Secondary Wire		
Secondary Winding Coverage	Measured Secondary Voltage (V) (Pk-Pk)	Efficiency (%)
Maximum (>340°)	17.2	71.67
Half (180°)	15.5	64.58
One-third (120°)	10	41.67

Voltage and Efficiency for Different Numbers of Secondary Windings (Toroid with inner radius 0.55 in. and outer radius 1.05 in., 2 primary windings)

32 Windings					
69.75 in. Secondary Windings			101.25 in. Secondary Windings		
Secondary Winding Coverage	Measured Secondary Voltage (V) (Pk-Pk)	Efficiency (%)	Secondary Winding Coverage	Measured Secondary Voltage (V) (Pk-Pk)	Efficiency (%)
Maximum (>340°)	13	81.25	Maximum (>340°)	13	81.25
Two-thirds (240°)	14.9	93.13	Two-thirds (240°)	14.2	88.75
One-third (120°)			One-third (120°)		

How to Make a Step-Up Toroidal Transformer

Materials Needed

- Micrometal Powdered Iron Toroid core
- Insulated copper wire
- Wire cutter
- Object to peel insulation off of wire

Designing Process

Before making the transformer, you must know what it is you desire:

- What do you want your secondary voltage to be?
- Do you want a high resonant frequency?
- Do you want a high Q value?

If you want a specific secondary voltage, then you need to choose the right ratio of secondary to primary windings by using

$$V_s = V_p * \frac{N_s}{N_p}.$$

If you want a high resonant frequency, you will want to maximize the secondary winding coverage as well as minimize your number of secondary windings.

To achieve a low resonant frequency, you will want to minimize the secondary winding coverage as well as maximize the number of secondary windings.

To achieve large quality factors, a high number of secondary windings and a low area coverage by the windings are desirable.

Low quality factors are achieved with a low amount of secondary windings, as well as high area coverage by the windings.

Example: Building a Toroid Step-Up Transformer

For this guide, I will walk through the process of making a step-up toroidal transformer. I will try to achieve these qualities:

- Secondary voltage is ten times greater than the primary voltage.
- Resonant Frequency at 1 MHz
- Q value around 100

Since the secondary voltage will be ten times greater than the primary voltage, this means the ratio of secondary windings to primary windings should equal ten. This is given by:

$$V_s = V_p * \frac{N_s}{N_p}.$$

However, because the transformer will most likely not be operating at 100% energy efficiency, the ratio of secondary to primary windings will need to be higher than 10. I will account for this design consideration at the end, since adjusting the number of windings affects the secondary voltage more than anything else.

Since the specifications call for a low resonant frequency, I will recall the following trends to make decisions in my design:

- Resonant frequency decreases as:
  - Toroid size decreases
  - Secondary wire length increases
  - Winding coverage decreases
  - The number of secondary windings increases
- The quality factor increases as:
  - Toroid size decreases
  - Secondary wire length decreases
  - Winding coverage decreases
  - The number of secondary windings increases

The ideal design would therefore have a small toroid, a long secondary wire length, low winding coverage, and a large number of secondary windings. However, you can only condense a finite amount of windings into one area, so we will have to use the large toroid. Additionally, while wire length does play a role in the resonant frequency and quality factor, it is not as effective as the number of windings.

To keep things simple, I'll focus on the number of secondary windings and their coverage. I'll also only use a primary voltage of 1 volt (peak to peak).

First Iteration

Wire Gauge	Primary Windings	Secondary Windings	Secondary Winding coverage
20-gauge wire	2	68	360°

Results		
Resonant Frequency (MHz)	Quality Factor	Secondary Voltage (Peak-to-peak) (V)
2.014	57.54	21

The resonant frequency is a bit too high, so I'll try decreasing the secondary windings' coverage.

Second Iteration

Wire Gauge	Primary Windings	Secondary Windings	Secondary Winding coverage
20-gauge wire	2	68	300°

Results		
Resonant Frequency (MHz)	Quality Factor	Secondary Voltage (Peak-to-peak) (V)
1.94	92.38	20.5

Due to the thickness of the wire and the space on the toroid, 300° was the least amount of coverage I could achieve on the windings. Next, I'll increase the number of secondary windings

Third Iteration

Wire Gauge	Primary Windings	Secondary Windings	Secondary Winding coverage
20-gauge wire	2	84	360°

Results		
Resonant Frequency (MHz)	Quality Factor	Secondary Voltage (Peak-to-peak) (V)
1.668	72.52	22.5

This appears to be the maximum amount of winding I can fit onto the toroid with 20-gauge wire. At this point, I can decrease the resonant frequency by increasing the length of the wire. However, this will likely not have a significant enough effect to get the resonant frequency down to 1 MHz. For this reason, I will construct another toroidal transformer using 24-gauge wire with the hopes that more windings can fit onto it.

Fourth Iteration

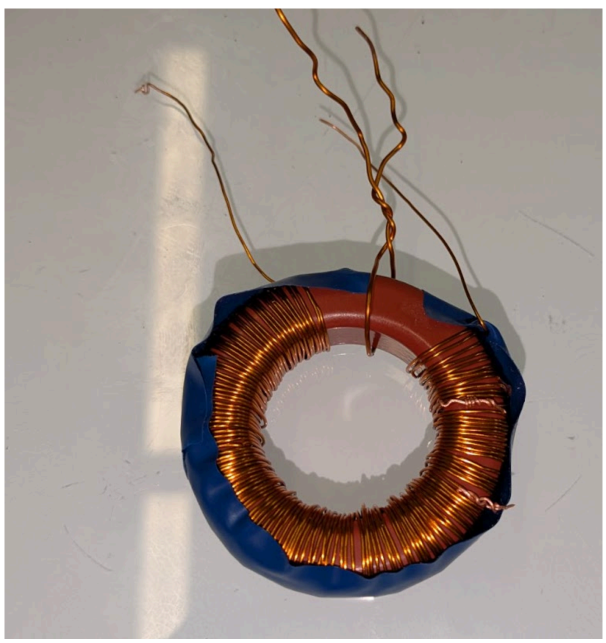
Wire Gauge	Primary Windings	Secondary Windings	Secondary Winding coverage
24-gauge wire	2	104	360°

Results		
Resonant Frequency (MHz)	Quality Factor	Secondary Voltage (Peak-to-peak) (V)
1.335	66.75	20

We're getting closer to our desired qualities! Next, I'll increase the number of secondary windings.

Fifth Iteration

In this design, I used tape to keep the windings in place.



Wire Gauge	Primary Windings	Secondary Windings	Secondary Winding coverage
24-gauge wire	2	Time to count	300°

Results		
Resonant Frequency (MHz)	Quality Factor	Secondary Voltage (Peak-to-peak) (V)
1.0037	104.55	10

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