Laminated Transformer Core.

Description

This Grain Aligned laminated magnetic core can be used to construct a power transformer for 50 Hz or 60Hz line frequency, with a power capability of 200 to 2000VA, depending on model. 50 Hz operation will require all power rating values to be adjusted by a factor of 5/6.

Specifications

Max core loss at 60Hz:
0.970 W/Kg @ 1.5 Tesla
1.39 W/Kg @ 1.8 Tesla

Saturation flux density: 2.035 Tesla (20350 Gauss)

Curie Temperature: 730C (1350F)

Permeability:

Induction, Tesla	Permeability
0.4	31100
0.6	34300
0.8	37300
1.0	40380
1.2	42400
1.4	39400
1.6	34040
1.8	24200
1.9	16300

Turns per Volt
50Hz: 34 / A (cm sq)
60Hz: 28 / A (cm sq)

The cross sectional area (A) for your particular core is provided separately.

The core is covered with a 6 mil layer of modified Mylar film, heat-shrunk onto the core. If this film is cut or removed, it will not be possible to re-apply it.

A primary winding will be wound on the core, after which a layer of insulating tape should be placed over the primary, followed by one or more secondary windings. A final layer of insulating tape should be added to protect the windings in the application.

If the gauge of the wire used in the primary winding is larger than 20 AWG (smaller numbers than 20), it will be necessary to add another layer of tape on the core before winding the primary. This is because the edges of the core are sharp (90 degree corners) . Thin wire can take sharp turns - meaning it can form small radii with ease. Thick wire cannot easily form small radii, and the tightening force needed to wind thick wire around the core could cause the wire to dig into the insulation layer at the corners, and touch the core metal, thus causing a short circuit.

The recommended number of turns for a 120V primary winding is:
T = TPV x 120V
where TPV is the Turns per Volt for a specific core. It will be twice that for a 240 Volt line voltage.
TPV is roughly equal to 28/A for 60 Hz line frequency, and 34/A for 50Hz line frequency, where A is the cross sectional area of the core in square cm.

Note that transformer design formulas relating TPV, A, and power capacity exist from many sources, and can provide results which vary widely. Some formulas have their origins in the 1930's , others in the 1950, 1970, and 1990's. A formula published in the 1957 Engineer's Handbook can find its way into online documentation, and later be quoted, and re-quoted, ultimately achieving immortality.

We may have a tendency to believe that, since the laws of physics do not change, design formulas from decades ago must still be valid today.
Such design information has very good longevity, especially since the current author of a web document may not know where the original source was. Here is the problem: A transformer in 1930" may have used mild steel for laminations. In 1950, newer , better steels were introduced, then alloys with silicon , then phosphorus. Later, more refinements were brought to the steel used in transformer laminations, until grain aligned alloy was perfected only recently. Grain alignment allows a material to have better magnetic properties in one direction, at the expense of properties in other directions. You then design for a magnetic field which occurs only in the direction in which the material is at its best. Take just one quantity for example: Saturation Flux density (Bsat). all pre-1980 transformers, and many of the more recent ones, this value was considered to be around 1.2 Tesla, so engineers designed transformers to run at about 1 Tesla. The current material has a B(sat) of 2.02 Tesla, and can be designed to run a 1.6-1.7 Tesla. The immediate implication of this is a lower TPV, than if using more traditional materials.
Many other benefits exist. Keep in mind however, that less performant transformer steels still exist and are used today, in many transformers that do not require the best performance. Legacy steels are less expensive, and cost often dictates design choices. So, if you find other transformer design formulas, do expect results to vary.

VA, Volt-Amperes

The Volt Amperes (VA) rating of a transformer core is a very arbitrary specification. The same core can be used to build transformers which drive very different size loads in the final application.

An arithmetic analysis of transformer efficiency is provided on the last page, and should be read before taking any design decisions.

Note that power handling capacity of a transformer is ***not*** directly related to the value of A, despite what some sources state. The maximum power obtained from a transformer occurs when the load impedance is equal to the source impedance (impedance of the secondary winding). Under this condition, the output voltage drops to one half its unloaded value. This may seem like very poor regulation, but it really does provide the greatest power available from any transformer. The impedance of the secondary winding is almost entirely caused by copper wire resistance. If you now wish to reduce the secondary voltage drop, you need to reduce the resistance of the secondary wire. So you use larger wire. You may continue to use larger and larger wire, and try to draw larger and larger currents from the secondary, ad infinitum, limited only by the available space in which to wind the thicker wire. Thicker wire will result in better regulation in any transformer, under all conditions. Some applications, however may neither require, nor benefit from better regulation. Loads which always draw the same power, do not care whether a transformer with poor regulation is powering them. Having a 20% output voltage sag, while selecting a 20% higher nominal secondary voltage will be no different than using a transformer of the required output voltage, having 0% sag under load (a possibly expensive proposition).

If a linear series voltage regulator is used to power the load, then voltage sag is desirable in the transformer, as it affords less voltage stresses on the regulator pass transistors as load current increases.

So the VA rating of a transformer is highly dependent on the regulation (or amount of voltage sag under full load) that you expect from that transformer. Transformers are specifically NOT regulating devices, since they are a voltage source in series with a resistor. Since the thicker the wire used, the lower the internal resistance of the transformer, and the better the regulation, it makes sense to use the largest wire practical. This also reduces the power wasted in the windings, and reduces the amount of heat you have to remove.
Your ability to remove heat from the transformer will have a significant effect on the VA (the power you can afford to deliver to the load).

So then VA rating is somewhat related to window area - the area in which to place as thick a wire as practical.
It is then also indirectly related to the cross sectional area, A, because A determines the minimum number of turns per volt required to keep the magnetic flux density below saturation. A determines TPV.
And the fewer TPV you need, the less copper you have to use, and the lower the copper losses.

So ultimately, the VA rating of the transformer will depend on 4 factors:
window area, cross section, required regulation, and heat removal.

The last two factors are entirely managed by the designer. Understanding your load, and not designing for greater regulation then necessary for the load is a crucial factor in efficient transformer design.
Once you decide the amount of voltage sag you can allow, you need to determine what will happen with the heat generated.
Every watt of power not delivered to the load is a watt of heat you'll need to remove.

Enclosure design must thus be established at this point. All ventilation slots in the enclosure, as well as the intended positioning of the enclosure in its final deployment must be considered. Will it be placed on a bookshelf, with books and other objects cluttering the air flow around the unit? If so, convection air flow alone may not sufficiently cool the unit. Forced air cooling (a fan) is typically very effective at increasing heat removal, if properly designed.

An important thing to note is that fans can be operated at 30-70% lower speed then their specification, and still provide much better heat removal then convection alone. A 12V brushless DC fan supplied from 7 volts , for example, may be completely inaudible , and still provide a very useful air flow. Lower speeds also dramatically extend the fan's life by reducing bearing wear. A resistor or diodes in series with the fan supply will reduce the voltage to a desired level. Find the lowest voltage at which the fan will start reliably, and then operate the fan at least 1 volt above that point.

Another important point about fans, is that they provide a more effective air flow if used as exhaust fans rather than inflow fans. Make them push air out of the enclosure rather than blow it in. This allows air to take on a laminar flow rather than a turbulent flow, and increases the velocity of the air stream, while keeping noise low.

Construction

Number of turns on secondary windings will follow the equation:

$$\frac{v_1}{n_1} = \frac{v_2}{n_2}$$

where v1 and v2 are primary and secondary voltages, and n1 and n2 are primary and secondary turns.

For a 120V primary, the wire size will be 20 AWG, and for a 220V it will be 22 AWG.

A high reliability design could use 10% larger number of turns and 1 or 2 wire sizes larger wire for all windings.

Each winding should be wound in such a way so that its turns are evenly distributed around the core. At least one layer of insulating tape should be used between the primary and secondary windings, and between each secondary winding, if these are designed to carry more than 20V.

Best coupling between 2 windings is achieved, when the 2 windings physically occupy "same space". This is not possible in practice, but one can attempt to come quite close to that ideal.

Tape used for insulation should be approved for electrical use. Tapes not designed for electrical purposes can have adhesives that are slightly acidic or alkaline, which over time can degrade the enamel coating of the wire, and corrode the wire. A high reliability design may use uncoated tape (no adhesive). The inner end of the tape can be held in place by successive tape layers applying pressure on the first turn, while the outer end of the tape can be held in place with a piece of adhesive tape, which is only touching other tape layers, but not the enamel wire itself.

If you are sure that your design is final and no future disassembly would be needed, You can coat each layer of wire with a clear coat of varnish or enamel, to keep the windings in place. The varnish chosen should be a good quality urethane or epoxy base coating. Epoxy is safest in terms of solvent emissions. The coating should be thin enough to be easily brushed on or sprayed on evenly.

Enamel coating of the windings is not necessary, but it will eliminate any noise the transformer could produce. Any electrical coil combined with a magnetic core will exhibit magnetomotive forces (magnetic forces which cause motion), and in turn, this is the very construction of a loudspeaker. It goes without saying that the wire windings will have a tendency to vibrate to the frequency of the applied voltage. Normally, a transformer wound "dry" (without any varnish on the windings) would exhibit a 60 Hz "hum" sound that is only audible when putting your ear very close to the transformer. A rubber or soft material pad installed between the transformer and the chassis in the final application, would ensure that this sound is not transmitted to the chassis.

The current expected in each winding will be governed by the power equation.

$$V1 \ I1 = P1 = P2 = V2 \ I2$$

$$V1 \ I1 = (V2 \ I2)+(V3 \ I3)+(V3 \ I3)$$

where V1 and I1 are the primary voltage and current, P1 is the primary power, and the suffix "2" refers to the secondary side quantities. Where there are multiple secondaries, suffixes 3, 4, and higher are used to refer to those quantities.
This above equation refers to an ideal transformer, one with no losses. In practice, the power available to the secondaries will be reduced by about 2% - 3% depending on copper losses.

Wire size chosen for each secondary should depend on the current expected in that winding. A 500VA secondary which produces 50V would be expected to carry 10A. In practice, if a transformer will be used for audio amplification applications, wire size would be calculated very differently than if it is used to deliver power to a constant load.
Music power density varies greatly in time, and the peak-to-average ratio tends to be high. Peak power is the power required when the sound is at its loudest points, and average power is that obtained when averaging the loudest and quietest sound levels over time.

Peak-to-Average power ratio tends to vary greatly with the type of sound amplified. It is generally around 2 for some Rock-n-Roll and Country, 4 for Disco and Pop, 4.5 for modern Rock, 5 for jazz, 5-6 for classical, and 7-9 for speech and some voice-over announcements.

Wire gauge is chosen with two factors in mind:
1. copper losses, and
2. temperature rise.

Temperature rise is greatly alleviated as a problem, in applications with high Peak-to-Average ratio, since heat and temperature rise are integrating by nature, so they reflect average power over a long time.
Copper losses can be calculated by determining the resistance of the wire chosen (from any wire gauge table)

Wire gauge tables specify resistance per 100ft or 1000ft, so the net resistance of the length of wire used in your application needs to be calculated.

From Ohm's Law, if a transformer secondary delivers 50V at 10 Amps, the effective impedance of the load would have to be 5 Ohms. If the secondary wire resistance is 0.5 Ohm, then, at full power, roughly 10% of the power will be dissipated across the 0.5 Ohm internal wire resistance, and 90% across the load. The output voltage will drop by 10%. This is called voltage sag, and a 10% sag under maximum load is generally accepted from an unregulated power supply. Many supplies operate with a sag of 20%. Using a larger wire size on the secondary, will result in a lower internal resistance, less copper losses, and less sag.
These parameters can be known in advance, before a single turn of wire is wound, by calculating the length of wire needed and determining resistance.

STARTING TO WIND

First step is to prepare a work sheet. This will be a piece of paper on which you will write information about what you are doing. Trust me, this will one day become VERY important information. Keep this work sheet next to you at all times while working and a pen always ready.
Measure all dimensions of the unwound laminated core, and write them on the work sheet.

To wind wire on the toroid, you will first need to calculate the total length of wire needed for the entire winding. This length of wire will need to be cut from the spool and wound on a "shuttle". The shuttle is a homemade device simply consisting of a rectangular piece of corrugated or stiff cardboard. It is cut in approximately the shape below, and should measure about 2 inches wide by 5 inches long.

Theoretically, if the original spool holding the wire you are using could fit through the opening in the toroid core, then you can use that spool to thread the wire around. But in most cases the wire will be on a spool too large to fit through the core. So a smaller, elongated, temporary spool must be made - the shuttle. You will wind the wire loosely on the shuttle- without forcing the wire to make a tight radius at the two ends of the cardboard form. The shape of the wire windings around this cardboard piece will approximate an oval.

You then pass this shuttle through the center opening of the toroid, and you wind the required number of turns around the core. You will rotate the core slightly so each winding will be applied next to the previous winding in such a way that the wire is RADIALLY oriented (always pointing towards the center of the core). Do not allow the wire to skew in either direction away from the radial direction. This will use up more wire than you calculated. The windings will naturally be more bunched together on the inner diameter and more spaced out on the outer diameter. You should use the inner diameter to determine wire spacing. Space them so they are sitting next to each other - without gaps and without overlapping - on the inner diameter. It is best to keep the toroid standing upright on a solid surface, and cradled between 2 cogs to prevent it rolling away.
You may need to wind more than one layer, in which case you will make more than a 360 degree sweep around the core while winding. For the primary of this core, this is a certainty.

To calculate the length of wire needed, you must first get the perimeter of one turn.

You add up the height of the core and its thickness and multiply by 2. To that quantity you must add an adjustment for radius compensation.

The center of the wire will not be sitting ON the core, but will be (at least) one wire radius away from the core. The wire will also make radii at the corners. For the core provided the following approximations can be used:

Add 3% for wire gauges above 24.
Add 4% for wire gauges 22-23.
Add 5% for wire gauges 20-21.
Add 6% for wire gauge 19.
Add 8% for wire gauge 18.
Add 10% for wire gauge 17.
Add 12% for wire gauge 16.
Add 15% for wire gauge 15.
Add 18% for wire gauge 14.

The above applies only to layer 1, the first layer on the core. For subsequent layers, you need to correct the height and width used to calculate the perimeter, to new values, measured on the part itself. You will then add 1% to all adjustments in the above table, to compensate for increased corner radius with each layer.
For any layer after the first, add a further 3% to the total length to allow for mis-placed turns, crossed turns, and lead-in/ lead-out humps
.
Once you obtained your required length, add another 12-24 inches, to allow ample length for lead-out.

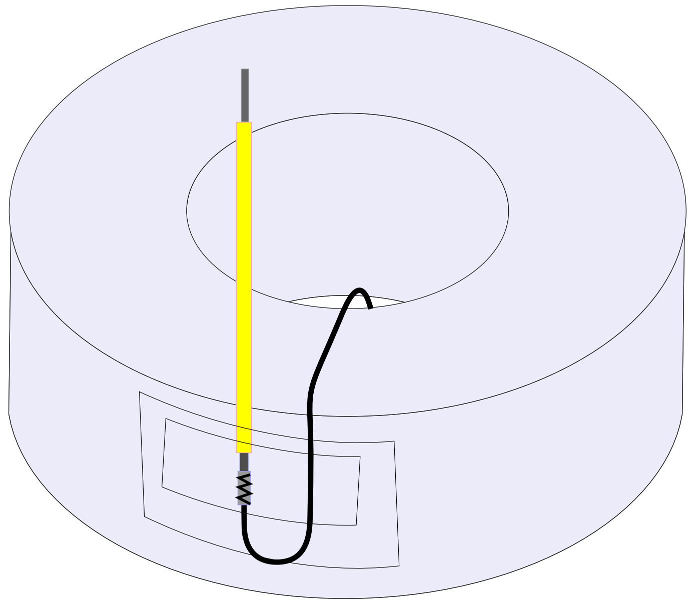
Prepare lead-out wires. These should be pieces of insulated stranded copper wire 6-12" long, of a gauge greater than that needed to carry the respective currents for each winding. Ideally they should be color -coded and you must write down on your work sheet what color is assigned to which winding start and end positions. Strip, twist and tin the ends of all pieces of wire. If you cannot color-code, attach small pieces of tape to each wire with markings (letters, numbers, whatever) to allow you to tell the wires apart. Write down the makings and their meaning on your work sheet.

Then, before you begin winding, solder the lead-out wire to the START of your winding. Make a good , twisted solder joint over a length of about 1.4 inch, and insulate this joint with good quality electrical tape or heat-shrink tubing. Do not add more than 2-3 layers of tape, to keep the overall joint small. Position this joint on the OUTER surface of the core and tape it to the core with electrical tape. Make a U turn with the enamel wire , and start going in the opposite direction. Tape again with a short length of tape, over both the first leg and the second leg of the "U". The resulting direction of the enameled wire will be the winding direction for the entire core. Wind one turn of wire, and apply another piece of insulating tape (again on the outer face of the toroid) over both legs of the "U" AND the first turn of wire. You are now ready to start winding. During all subsequent work, remember that the direction in which this first lead-in wire points is the direction of winding. Simply imagine an arrow pointing in the direction of the only remaining visible stripped end of this wire.

Keep count of the number of turns and work in an area where you will be free from any distractions.
Counting errors of 2-3 turns in the primary have no real consequence, however no error would be permitted for the count of two identical secondaries that must be part of a dual-rail power supply. You can always measure the voltages after winding, but before snipping off the final lead-out and soldering the lead-out wire. If you see any voltage difference between 2 secondaries that need to be identical, this is the time to add another turn here or there to compensate.

Lead-outs:

Solder joint is first covered with heat-shrink tubing. The first piece of adhesive tape goes OVER the joint, UNDER the enamel wire. You form a U turn with the enamel wire. The second (larger) piece of adhesive tape goes OVER both joint and enamel wire. Wire is then wound over the joint applying positive pressure over it.



Problems:

If you should realize that your wire will end before completing all the needed turns for a winding, don't sweat it. Just strip 1/4 inch of enamel from the end of the wire, splice another length of enameled wire to it, solder, insulate with heat-shrink, and continue winding. Just make sure you put the splice on the outer face of the toroid. Adjust wire lengths as needed to make sure the splice ends up there. Why the outer face? The inner face is space constrained, so that's out of the question. You do not want any lumps or bumps there. The two sides determine the final height of the transformer, and it is generally preferred to be kept to a minimum. Furthermore, the transformer will rest on its side in the final application, and any lumps there will prevent horizontal placement. It may furthermore receive a hold-down plate on the top side, which again would make poor contact if lumps were present there.

So the only place left to safely host all lumps and bumps is the outer face.

If you should determine that the entire length of wire wound on a shuttle will not fit through the central opening of the core, do not despair. Large gauge wire does not tolerate well being bent to small radii so it should not be pressed hard against the shuttle to make it fit. Instead, you could wind the wire on two shuttles, one starting at each end, and build wire on both shuttles until they meet in the middle. Then start winding in the middle. Tape one shuttle temporarily so it will not unwind. Then proceed to wind normally with one shuttle in one direction. When done, wind with the second shuttle in the opposite direction. This should help to keep down the size of the shuttle in cases where very heavy gauge wire needs to be wound. It may also be practical to cut and wind half of the winding at one time, then splice and solder another length of wire and wind the second half.

Calculating power losses and regulation

Assume a toroid with ID = 3" or 4.5cm. OD = 5.2" or 13cm. Height = 1.75" or 4.38cm.
Sectional width = 1.1" or 2.75cm. Cross section area (A) will be $12cm^2$.
For this type of material, Turns/Volt (TPV) = 28 / A, or 2.3 in this case.

Determine length per turn.
section height= 4.38cm.
section width = 2.75cm.
section perimeter = (4.38 x 2) + (2.75 x 2) = 14.26cm
Multiply this number by 1.15 to get a rough estimate of the average length of wire per turn. This is 16.4 cm here.
So for a 115V winding, wire length = 2.3 TPV x 16.4cm per turn, x 115V = 4337.8cm, or 43.38m.
Assume the use of 16 AWG wire (a good starting point for this size transformer).
16 AWG wire has 0.0132 Ohms per meter. The winding would have 43.38 x 0.0132 = 0.573 Ohms.
Assume you connect a load which attempts to draw 500W (it will get 500W - losses) . The primary current will be:
500W / 115V = 4.35A.
Voltage drop across the winding will be 4.35A x 0.573 Ohms = 2.5V
2.5V / 115V = 2.2% drop under full load.
2.5V x 4.35A = 10.875W power wasted.

The above figures are for the primary only. The same analysis will be done for the secondary winding. Assuming the losses allowed on the secondary will be equal to the losses on the primary (which is the optimal situation), then total loss = 10.875W + 10.875W + core losses.
The core loss is 1.39W/kg x 3kg = 4.17W. Total loss = 25.92W
25.92W / 500W = 5.18%
So voltage sag may be 5.2% under full load.
This can also be stated as the transformer having a regulation of 5.2% at full rated load, which is rather good for most transformers.
Total power loss will be 25.9W, which leads to an efficiency of 94.8%.
It means that 25.9W of heat will have to be removed from the device, by convection, forced air cooling, or otherwise, if a power of 500W will be drawn by the load continuously. Most loads, especially audio loads, will have an average power that is only a fraction of the peak power demand.
Now this is an iterative process. If you do not like the values you obtained for loss and regulation, you can now go back and increase (or decrease) the size of wire and re-calculate new values.

Calculating space taken by copper windings in the transformer window

Assume a core with ID = 2.75"
Wire size 16 AWG dia. = 0.05" uncoated, 0.06" coated.
Net ID at first layer = 2.75 - 0.06 = 2.69". Circumference = 2.69 x pi = 8.45"
Assuming best-practice winding with all turns of wire perfectly seated next to one another, allow 0.01 air space between turns (you won't be able to seat them all touching each other molecule-to-molecule). Total wire diameter now becomes 0.07"

8.45" / 0.07" = 120 turns can fit on one layer. Reduce this number by 10 turns , to allow for lead-in / lead-out, wire deviations, etc. you have 110 turns.
115V x 2.3 TPV = 265 turns total for this winding. 265 - 110 = 155 turns will go to a second and third layer. A layer of 10 mil insulating tape will cover the first layer. The tape will overlap itself by some fraction under 50% so effectively its thickness will be doubled. Therefore 0.04" tape thickness total. Also add 2 x the thickness of the first layer of wire.

Second layer starts at an ID of: 2.69" - (0.06" x2) -0.04" = 2.53"
Circumference = 2.53 x pi = 7.94"
7.94 / 0.07 = 113 turns can fit on this layer. Reduce this number by 5 turns , to allow for wire deviations, (there are no lead-in / lead-outs in this layer). you have 108 turns.

You now know how to repeat the process for each additional layer, and each additional (secondary) winding.