Comparing the designs of different transformers

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The purpose of this construction project was to analyze the characteristics of several types of transformers. The four types that were built consist of a toroidal ferrite core, a laminated steel EI core, as well as a cylindrical core and a rectangular core; both nearly equal in size and made from ten high-strength neodymium magnets. I then planned on being able to connect the transformers to a wall outlet power supply, run the voltage through the transformer then a rectifier, and finally power a .18 Amp, 12 VDC computer fan. Also, I will explain the processes of what happens within the transformer as well as the circuit that is necessary to provide a source and load on each transformer.

Ultimately, the transformers, if reliable and capable, were to be used to step-down voltage coming from the wall, which is about 115V to 125V, to a lesser voltage. This current would then be rectified, then used to power a motor for visual confirmation of the transformers' success. However, when each transformer underwent its final test, or directly being electrically connected to the wall outlet, each and every transformer failed and melted the enamel right off the wire. It is quite obvious afterwards that there was too much current running than the wires could possibly hold safely. Within seconds, smoke rose from each and damaged them beyond repair.

Before explaining what exactly happened and what I could've done to improve the circuit, I will explain the technical aspects of the transformer and the rectifier. A transformer is a device that converts electrical power in an a-c system from one voltage or current into electrical power at a different voltage or current through inductively coupled conductors. Simple transformers typically consist of three parts: the primary coil which contains the alternating current from the power supply, the core of magnetic material which holds an alternating magnetic flux, and the secondary coil which depends on the alternating flux and changing magnetic field to generate an EMF through the core and thereby inducing a current in the secondary coil. The current and voltage induced into the secondary coil is dependant upon the ratio of the number of turns in the secondary to the number of turns in the primary as follows: $V_s / V_p = N_s / N_p$. These values are interchangeable in that the voltage can either be “stepped up” by making this ratio of turns greater than one or “stepped down” by making the ratio less than one. While the voltage ratio is equal to the ratio of the turns, the current ratio of these constant-potential transformers is approximately equal to the inverse ratio of the windings’ turns. This experiment deals only with step-down transformers since the power supply holds a high voltage and the transformer must supply a lower voltage in order to power the small motor.

When an alternating voltage is applied to the primary winding, a counter voltage or electromotive force is generated due to the changing magnetic field that equals the applied voltage. Since the primary and secondary windings are on the same core, the magnetic flux generated by the magnetizing current flowing in the primary coil generates an EMF in the secondary. According to Lenz’s Law, this EMF will be opposite to the direction put through the primary to prevent the change in the magnetic field. The current running through the secondary then is proportional to the impedance of the secondary circuit, and this current will flow so that the magnetic flux produced in the core will oppose the flux due to the primary winding because of the direction of the EMF generated. Restated, there is an induced EMF and current in the secondary winding due to the change in current in the primary winding. This property is called mutual inductance in which the secondary coil will oppose any change in current from the primary coil by generating a current opposite to it. For instance, when an alternating current is approaching its positive peak, Lenz Law says that the induced EMF will flow opposite to the current’s direction. When the current is reversed, the EMF will flow positive to aid the field and retain its strength. Thereby, inductance behaves in electronics just as inertia behaves in mechanics.

Larger transformers are generally more efficient. Mine are relatively small with a large amount of wasted space between wire turns: strike one. The efficiency loss in a transformer may typically be determined by the copper loss of the windings and the iron loss within the core. The copper loss is due to the natural resistance of the wire and may be found by loss equals the square of the current flowing times the resistance of the wire. Both losses seem fairly feasible reasons for the transformers’ failure. Iron loss consists of the sum of the losses due to eddy currents, hysteresis, and magnetostriction. Eddy currents are small currents generated by the changing flux of the alternating current flowing within each part of the core. These eddy currents are proportional to the voltage induced in the core material and also limited by the resistivity of the core. The magnitude of an eddy current within an isolated lamination is primarily dependent on width, thickness, and volume resistivity. As width and thickness increases, or as the frequency or applied magnetic field increases, the eddy currents also increase. The smaller the lamination thickness, the greater chance at reducing eddy currents. The eddy currents induce magnetic fields that oppose change in the original magnetic field due to Lenz’s law, causing a drag force on the field. This generates losses because some energy that could aid the inductance of the transformer is being converted into heat. Friction creates heat when two surfaces rub, just as eddy currents cause heat when it’s opposing the original current. Hysteresis is the ability of magnetic and ferromagnetic materials to "remember," or hold momentarily its field. This can cause a lag in the varying electric field. Magnetostriction is a property of ferromagnetic materials to stretch and shrink their cores when subject to a magnetic field. This property is what causes a transformer to hum, and it causes loss due to frictional heating.

It was very plain to see that both eddy currents and magnetostriction may contribute to a significant amount of power loss. The EI core was obtained by burning the insulation off of a malfunctioning transformer, retrieving only the core. During the length of the scorching, the varnish very possibly could've melted between the laminates and allow the eddy currents to flow within the core as a whole due to insufficient insulation. As I have calculated, copper loss also counts for over 1000 watts of power wasted in the wire. Also, all of the transformers hummed like a chorus when connected to the wall outlet.

I inquired an experienced source at the beginning about what size wire would be suggested for this project. The recommended wire sizes are as follows: 24 gauge for the primary windings, and 38 gauge for the secondary windings. I then looked for core types. The EI core was salvaged from an old desk lamp by removing the actual transformer in the base, burning the insulation, unwinding the wire, then winding it again with my own wire. The ferrite ring core was provided thanks to Dr. Penhallegon from a toroidal kit. I then selected two almost identical sets of magnets with the only extreme difference being their shapes-one set of cylinders and another of rectangular block shapes. The magnets were purchased from eBay due to my curiosity of how a magnetic core would affect the flux of the transformer. I figured that a strong, static magnetic field within a fluctuating field would possibly increase the size of the alternating field, and thereby increasing the core’s effectiveness. As will be explained later, this hypothesis proved very untrue.

The set number of windings for the transformers was decided foremost by the voltage ratio needed-approximately a 10:1 ratio, because it was planned to power a 12V motor from the wall- then according to inefficiencies from thin wire and heat loss, the gaps of air between turns due to circular wire wrapping around itself, and kinks formed in the wire from an impatient undergraduate. Finally, by observing professional transformers and seeing that they could easily contain thousands of windings that would require weeks of labor by hand, realistically, it was decided to use about 240 turns on the primary winding and forty turns on the secondary winding.

The transformers were then constructed with each following the chosen turn number. The following table shows the amount of turns on each winding and the voltage input and output measured using a 1000-ohm resistor and a signal generator.

Table 1

Number of windings-	Primary	Secondary	Voltage Input	Output
EI core	241	38	.25V	.07V
Cylinder	245	42	.43V	.03V
Toroid	240	40	7V	1.1V
Block	243	38	.47V	.05V

Next, the transformers were each measured for their impedance. Table 2 holds these figures.

Table 2

Impedance through transformers			
	Input	Output	Z ratio (approx.)
Commercial Transformer (EI)	1230 mH	13.4 mH	90:1
Toroidal	495 mH	10mH	50:1
EI Core	104 μH	61 μH	2:1
Block Magnet Core	166 μH	10.3 μH	16:1
Cylindrical Magnet Core	99 μH	6.7 μH	15:1

So far it wasn't looking good. All of the transformers besides the toroidal weren't providing near enough voltage or impedance. It seemed as though they all had a short in them. This though could be a strong possibility as the wire may have been slightly stripped during the winding process of the EI core and the magnets themselves seem prone to eddy currents. There's no lamination hardly within the magnetic cores, leaving eddy currents free to circulate throughout a large thickness. That combined with the strong static magnetic field and the low resistivity of copper gives these transformers a relatively low efficiency. In order to step up the voltage and give them a chance, the experiment proceeded to connecting to the wall outlet. With 15-20 Amps coming from the wall, it seemed wise to place a fuse in the circuit. The rest of the story will follow later.

I consulted the American Wire Gauge Tables after the experiment, unfortunately, and found that for approximately 150 feet of 24-gauge wire used in the primary coil of the toroidal design, it held about 3.85 ohms of copper resistance and carries safely about .6 Amps. This obviously is a drastic difference from about 31 Amps it carried from its 120-volt power source, according to Ohm's Law. Approximately seven feet of 38-gauge wire was used in each secondary coil with a total copper resistance of 4.6 ohms and carrying .02 amps safely. Ohm's Law grants that this wire would be carrying 2.6 amps accompanying the 12-volts needed to power the desired motor: strike two. Note: The amount of wire used for the other transformers is uncertain, but they do contain same wire with an insignificant difference in the number of turns, i.e. equal turn ratio.

The momentary value of the induced EMF through the wire may be found in the equation: $i = (E – e) / R$, Where i = momentary value of increasing current flowing after the circuit is closed,

E = impressed voltage,

e = momentary value of induced EMF,

R = resistance of circuit.

Since transformers are inductors and inductance doesn't reach a certain current instantaneously, the curve of increasing amperage by time is found by the equation $I_L (t) = I_f [1 - \exp (-t/\tau)]$. This logarithmic function shows the induced EMF is greatest when the current changes at the greatest rate. It does the same for discharging. Given that the transformers had lasted long enough to get an accurate ammeter reading, one could find the actual induced EMF in the secondary coil using 120-volts for E and 3.85 ohms for R.

If two long coils are wound interlaced on the same high-permeability core such as in these transformers, one may equate the magnetic flux per ampere of the primary coil by: $\phi / I_p = (N_p \mu A) / l$. Given that each primary coil has 17 amps from the wall and approximately 250 turns, the EI core, and the cylindrical and block magnet cores' flux may be calculated with this formula. The flux, therefore, of the EI core is 7.5 E^{-3} Tm^2 with an area of .03 m^2 and length 2.3 cm. Dividing this number by the area then gives the magnetic field produced by the primary coil of .232 Teslas. The flux of the cylindrical transformer's primary coil is 8.54 E^{-6} Tm^2 with an area of 1.27 m^2 and length 7.9 cm. The flux of the rectangular magnet's primary coil is 1.32 E^{-5} Tm^2 with an area of 1.61 m^2 and length 6.5 cm. The magnetic field given by cylindrical and rectangular primary coils are 6.74 E^{-2} T and 8.18 E^{-2} T, respectively.

Using Ampere's Law, one can find the magnetic field of the toroidal solenoid by the equation: $B = (N_p\mu_0I_p) / 2\pi r$. Using the same values of N and I as above and a radius of .005m, the magnetic field within the toroidal solenoid is .17 T. Multiplying the field by its cross sectional area of .01 sq. meters gives a flux of 1.7 E^{-3} Tm^2.

The inductance of the EI core, cylindrical solenoid, rectangular solenoid, and toroidal solenoid may be found by dividing flux by amperage and is 44.12 mH, 50.23 μH, 77.65 μH, and 10 mH respectively. The flux and inductance of the secondary coils can be inferred to be insignificant since the amperage running through them would immediately singe the coils, create a short, and be useless, granted the current had successfully flowed through the primary coil. Knowing this, as well as the final measurements of impedance as shown in Table 2, their effect on the overall flux and inductance may be disregarded.

The magnetic orientation of the neodymium magnets reflected little difference in inductance between the cylindrical and rectangular transformer. The cylindrical magnets are each axially polarized through their flat surfaces, following the same direction, as the magnetic field of the solenoid. The rectangular magnets are each polarized in such a way that if the solenoid's magnetic field pointed in the x direction, the magnets' field would point in the y direction. Note: both magnet types are rated grade N42 with a Gauss Rating of over 13,200 and are both nearly the same size.

One would think that the similar magnetic fields between the magnets and coils of the cylinder transformer would multiply its overall inductance and impedance based on magnet strength and the efficiency of the wire coiling. Also, one might assume that the opposing magnetic fields of the rectangular magnets and the wire coiling would diminish the transformer's effectiveness. Oddly enough, in this experiment, the polar orientation of the magnetic core made seemingly no difference, and if anything, the magnetic cores proved greatly unsurpassed by the EI core and toroidal transformers even though magnets are known to have a high permeability and should, therefore, be excellent cores. The answer to this predicament can very well be the limit to how much magnetic flux can be generated before the core becomes saturated. There is a point for every magnetized core where the flux density levels off at the point where the core material has saturated. Past that point, the coil behaves as if it had an air-core with a very low permeability. This may clearly explain the low inductance and the very low voltage seen from both the primary and secondary coils with the signal generator as well as the noisy sine wave produced when connected to an oscilloscope. One method to fix this could be to place air gaps within the cores to reduce the effects of saturation. Also, because the rectangular and cylindrical rods had open ends, the magnetic path length had an equivalency of an air core conductor since the magnetic field has to travel back through the air to complete the path. So, with that knowledge, I've learned I have successfully developed a fairly expensive air core transformer that is dangerous to bring near ferromagnetic materials.

Reluctance, which is similar to electrical resistance, explains the problem with the EI core construction. A poor conductor of flux has a high magnetic resistance. The greater the reluctance, the higher the EMF required for obtaining a given magnetic field. Air has a high reluctance, while iron has a generally lower reluctance. During construction, the wires slipped off the end of the E configuration of the core. A couple of the turns were slightly nicked when trying to put them back on the core, possibly creating a small short. In the end, a couple turns refused to stay on the core, causing a small air gap between the E and the I configurations. Although it's a very small gap, the reluctance is greatly increased from the large reluctance of air. This requires more flux and greatly reduces the laminated iron’s permeability, ultimately sabotaging the entire transformer.

For all the transformers, the secondary coil was fit to supply plenty of power to the load, granted the current isn’t too high. The turn ratio seemed like it might work after observing a correct output with the toroidal transformer. But in the end, I didn’t consider that seventeen amps would be too much for the primary coil. As bad as that sounds, even more amperage was running through the secondary coil. Since the current running through the transformer is inversely proportional to the voltage ratio, one can use the voltage tables from above to approximate the amount of current that would flow in the secondary winding. This puts an overwhelming 61 Amps in the EI secondary, 108 Amps in the toroid secondary, 160 Amps in the rectangular secondary, and a ridiculous 244 Amps in the cylindrical secondary coil. Had the current somehow made it through the primary coil, there’d be no hope for the secondary winding, which was underneath the primary windings in each transformer.

After frying the cylindrical transformer from the wall outlet in the first test, I was still confused about the current and voltage ratio ordeal. Oblivious to the problem, a Variable transformer was obtained and placed in the circuit between the wall outlet and the toroidal transformer. Thinking voltage may still be the problem; the variable transformer was set to 40 volts output, which seemed like it should step down the voltage enough to get a manageable voltage reading from my transformers without any major problems. This wasn’t the case, and the toroidal transformer started smoking. I then placed the EI core in the circuit with a 1 MΩ resistor. According to Ohm’s Law, one can increase both the voltage and the resistance to keep the current the same. So, if resistance is increased, amperage decreases. With 40 volts divided by 1 MΩ, that gives 400 mA.

The winding melted. Finally, the rectangular core was used with a 10 MΩ resistor, and nothing happened. I never got a reading of anything, but I concluded that by the time you configure the current to a level the wire can handle, the voltage is too low and the transformer is too inefficient to provide enough power for the motor. At that point, it was decided that there was too much current from the outlet than could possibly be detained and these four transformers were not up to the task of handling the objective that was set.

After all is said and done, and all my homemade transformers were crispy, I simply made the planned circuit with a commercial transformer to ensure that it could possibly work. So, a replacement plug cord was electrically connected to the input of the transformer. The output was then connected to a rectifier board to convert the current from alternating to direct current. Full-wave rectification works by converting the input waveform to one of constant polarity so that the input may be used to power a dc motor. In other words, it flips the negative crests of AC power to the positive polarity so that the waves simply have positive crests flowing. The rectifier board was checked for functionality by testing the resistance of the diodes. A diode has a low resistance for current traveling from the cathode to the anode (in this case, well call the current positive). The diode then holds a high resistance for any current traveling in the reverse direction (or negative). So, one can conclude that if the rectifier properly works, then the current can easily flow through the diodes because there is no reversing current once the current has been converted to direct current. The rectifier did work properly so then the current is directly sent to the 12 VDC motor where it effectively powers the computer cooling fan with LED lights. The circuit schematic is shown below, and the real circuit will be displayed in lab for the demonstration.

QuickTime™ and a
decompressor
are needed to see this picture.

So, a summary of all the failing components of this project: 1. I didn't do the complete math beforehand because I had little knowledge of the laws and concepts that govern the functionality of transformers. 2. Small wire diameters are able to hold less current and lose heat more easily due to the excess of current traveling through it. More current leads to more wasted current by heat. That was a big mistake. 3. Conservation of energy applies to electricity. Work = voltage X current. If voltage is reduced, then current must increase to conserve energy. This also applies in Ohm's Law. 4. After looking at several commercial transformers, they all had thousands of windings with minimal wasted space. A transformer of that caliber would've cost me weeks of work to produce one, but there's probably that many turns for a reason.

Given that the transformers could handle the current and had the right winding and impedance ratio as reflected in commercial transformers, these four transformers might've had a chance. Unfortunately, there were too many constraints that I was unaware of while constructing them that acted against my favor. Transformers can be a simple construction, but in order for one to power anything practical, there are many complex concepts that are involved. These problems can prove disastrous for anyone not fully aware of what is going on, and can easily be dangerous if applied to a large power supply. It will require some more research and a lot more experience for me to successfully develop a very efficient transformer.

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