DENT #001 | Planar Transformer - core saturation

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Planar magnetics have become very common in DC/DC converters and other power conversion devices. Except for the wall warts, magnetics in every modern converter I either acquired for my projects or reverse engineered to see how it is made and works, had this type of core. Advantages and shortcomings of inductors and transformers implemented using planar technology vs. traditional wire wound are well known and described in many articles published by ferrite core manufacturers. My recent quest advancing automotive battery management systems was to deploy active balancing concept, and all practical designs of such systems make use of inductive components for storing and moving energy. While other techniques for moving charge from one place to another have been tried, nothing beats moving charge by magnetics. Why? There are several unique properties of magnetic field and components taking advantage of it, especially relevant in this application field:

- You can step current or voltage up or down
- You can easily isolate circuits with several thousand volts dielectric barriers
- You can split energy into several paths using multiple windings in common core
- Planar transformers usually cost less as you only buy the core - the windings etched on PCB come "for free"
- These are the only electronic components you can design and make yourself, which gives you flexibility to get exactly what you want.

None of this advantages exist with capacitor based or any other charge transfer techniques.

But, for not very clear to me reasons, many people try to avoid use of magnetics - you see many publications with transformerless power supplies or inductorless converters using other techniques such as voltage multipliers, charge pumps, flying capacitors etc. The notion perhaps comes from old days when magnetics were heavy, large and expensive. I think the other reason for disliking coils and inductors is more "mysterious" behavior compared to other passive components that are better understood "on intuitive level". This might be because proper design, selection or use requires some level of understanding of basic physics of what's going on in the component as it operates, and with magnetics, and especially non-linear cores, it is the most complex to grasp, let alone to calculate. But understanding basics of inductors, transformers and their coils and cores is very rewarding for circuit designers and you don't need a PhD in math or material science to successfully deploy your own magnetics.

Countless transistors and transformers are being blown up by misapplication of inductive components used by beginners or young and inexperienced engineers. In this mini app note I'll highlight probably the main reason why this happens. And this reason is unique to inductors in electrical circuits - no other type of passive or active components exhibit it. What happens is that in "right conditions" your inductor simply stops being an inductor and almost becomes a piece of copper wire. (That does not apply to air coils without magnetic core used in RF applications; we'll focus here on power transferring applications such as DC/DC converters or power supplies). To understand what's going on, brief refreshment of the fundamentals of inductors is in order. I will avoid using math, and will concentrate just on the principles relevant for understanding of the phenomena. If you want to dig deeper, remember - Wikipedia and Google are your best friends.

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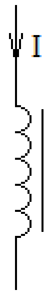

Any time electric current flows through a conductor it creates magnetic field around it. Forming conductor into a coil concentrates flux of the field such that it usually passes through the center of the coil and closes magnetic circuit outside the coil - fig.2. However, open space has very high "resistance" as a medium to conduct magnetic field, or we say low permeability for it. Therefore it takes a lot of current to create more-less strong magnetic field in a coil. As shown on fig.2 all the flux lines located inside coil must close the magnetic path in a loop outside the coil to have net field through any crossection plane equal to zero. The flux lines are spread out in the space around coil - more dense near it and with quickly diminishing density as you move away.

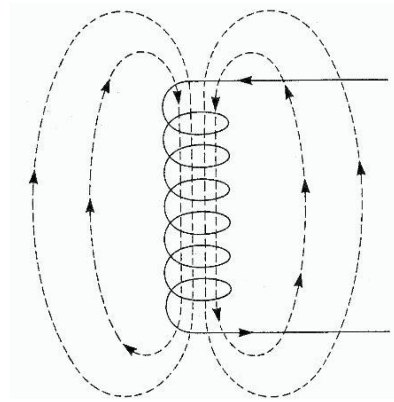

Fig.2.

Magnetic field is a form of stored energy. In our magnetics we want to store as much energy in as little volume as possible, e.g. increase flux lines density. Obviously, if resistance of the matter for the flux lines would be lower, more of them would go through the path of least resistance, similar to electric current always concentrating on the path of lowest resistance, and it will take less current to achieve the same flux density. So to reduce resistance for the flux lines and concentrate them in lower volume we use materials with low magnetic resistance (high permeability) as a core for coils (fig.3). Now flux lines will not go through the open air at all, and will all be concentrated inside the core which "shorts" magnetic path for the field conducting it along the core and making it much stronger for given current. The core is typically made of iron alloy for low frequencies (<1kHz) and ferrite for higher frequencies.

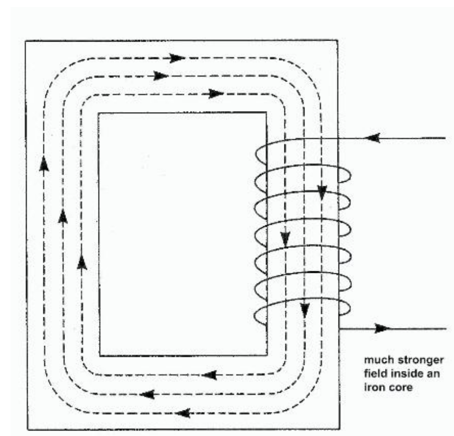

Fig.3.

How exactly a magnetic field "propagates" around the core and why do we care? This is relevant to grasp in order to understand the core saturation phenomena. And that, in turn will allow you to be in control of the coil behavior and prevent blowing up semiconductors.

A magnetic core material is formulated such that it consists of magnetic "domains", you can think of them as randomly oriented tiny magnets which are able to rotate. While nothing physically rotates in the core material, visualization using magnets analogy is enough to understand saturation phenomena without complicating the concept.

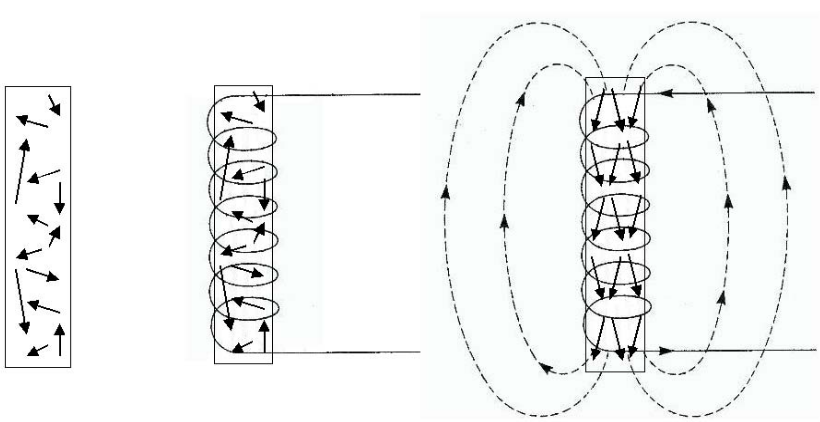

Fig. 4.

Consider fragment of the ferrite core as shown on the fig. 4. The arrows represent magnetic domains - tiny magnets pointing their north and south poles in all directions so that overall magnetic field created by each of them locally, cancels out. However as soon as the current is supplied through the coil and thus its magnetic field is created, this field

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will interact with small local field existing around each domain.

As we know, opposite poles of magnets create force attracting poles and same type poles create repelling force. So this very force re-aligns domains in the core making them point their poles such that their magnetic field begins to coincide with the field created by the current in the coil. The higher current, the stronger the field and higher force aligning domains. Each domain will try to re-orient its nearest neighbor, this is how the field (flux lines) propagate along the path in material where domains exist. So how high can we crank up the current (provided, the wire can dissipate the heat) and expect the flux density to keep proportionally increasing? Well, as you can imagine, at some point magnetic field in the core created by the current will become so strong, that all the domains along magnetic path will get oriented strictly along the field flux lines. This is the condition where the code is magnetized as good as it can possibly be - further increase of the current will no longer increase the field - there are simply no "mis-oriented" domains left to rotate - they are all already pointing in one direction, thus collectively creating the strongest possible field in the core. This is the *core saturation*.

Now it is good time to introduce concept of inductance (more precisely - self-inductance). Without complicating the matter, just know that it is simply a measure of degree to which a coil resists changes in current through it. Without inductance the current would instantaneously change from zero to the maximum value, according to the Ohm's law - the voltage on the coil divided by the wire resistance. But the current through the coil can never change instantly. So how can coil prevent current from changes without affecting resistance of the wire? How come a 100V across the coil of 1 Ohm resistance does not produce 100 amps of the current as soon as the voltage is applied? Well the only way to influence the current through a conductor (wire) with fixed resistance is to change voltage across it, right?

So what happens is when you apply 100V across the coil, the current start flowing, creating increasing magnetic field in the coil proportional to current value. But it works in reverse just as well - the very field crossing the coil induce voltage across the coil which happens to be the opposite polarity of the applied voltage. Thus voltages subtract and initial current is less than 100 V/1 Ohm. This induced voltage is famous "back EMF" ("electro motive force"), and in fact at first instant it is exactly equal to externally applied voltage, therefore total voltage across the coil becomes zero and so is the current per Ohm's law. How much of this back EMF the coil produces for given change in the current *is* the property of the coil called inductance. What happens next? Rising magnetic field starts re-orienting domains in the core. "Rotating" of each of them creates their tiny EMFs. Combined EMF, fighting the voltage on the coil from external source, is equal to sum of EMFs induced by each small "moving magnet". As time goes by, more and more domains line up along the field and thus stop rotating e.g. drop out of their EMF production. So as less and less domains remain that were grossly mis-oriented at the beginning and thus still keep rotating, the total "collective" back EMF keeps diminishing accordingly as well. This means less and less voltage is being subtracted from fixed 100V source, so more and more is appears across the coil terminals and thus the current gradually increase. This linear increase will last for as long as there are any domains left that can still move and thus induce this back EMF. Once all the domains in the core get lined up, back EMF induction will cease and entire source voltage appear across the coil. So now the only thing that restricts the current is Ohmic value of the coil wire. Nothing to induce back EMF anymore: the coil property quantified by its inductance makes zero back EMF. Since back EMF = $L*dI/dt$ we must conclude that $L*dI/dt = 0$ and the only way this can happen is if $L = 0$. In other words, inductor has lost its inductance, it no longer is able to produce any back EMF fighting the voltage on the coil while the current still changes (e.g. dI/dt is not zero). That is very dangerous situation! You think that you've got an inductor to your circuit, but at some [saturation] point inductor looses all its L value and becomes nothing more than piece of wire!

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Except for a few specific applications, the core saturation is very undesirable phenomena, at least in power conversion world. So how to avoid this? You need to make sure you stay within flux densities lower that those capable of creating such strong magnetic fields in the core that all magnetic domains get oriented along it and thus no more flux (as current still changes) and so back EMF can be produced. There are several ways: you can increase amount of core material - physically more magnetic domains available meaning more of them to turn and it will take much higher current to re-orient them all. You can also introduce a gap in the core path - this is akin introducing a resistor in the electric wire restricting the current. The field will have difficulty jumping across the gap so its density for given current will be lower. That means saturation will occur at higher currents, but remember, that diminishing ability to effectively rotate all the domains means lower back EMF production for the same current changes, meaning lower inductance. So the rate of the current increase with the same voltage applied will be higher and everything else being equal means such an inductor will reach its saturation point sooner in time.

One more interesting consequence of the inductor resisting to changes in current - it prevents decreasing the current the same way as increasing it. As soon as the supply voltage reduces or collapses to zero, the coil current starts diminishing. This will reverse polarity of back EMF which now will add to the supply voltage thus increasing it in attempt to maintain the current at the same value. The faster current changes (drops), the quicker all the magnetic domains return to their random state, the more back EMF gets generated resisting these changes.

This phenomena is analogous to a mechanical mass, such as pendulum. The mass is inductance, the velocity is current and the mechanical force applied to it is voltage. Initially it is hard to get the pendulum moving, especially heavy one. You apply continuous force to it and it linearly gains velocity. You feel resistance of it as if someone pushes it back ("back EMF"). But as soon as you change direction of your force trying to stop it from the opposite side, now it resists of slowing it down - the back EMF force changed direction now keeps pushing it in the direction it was going, trying to maintain its velocity. The higher the mass (inductance) - the harder it is to change velocity with the same force. Just like you can't instantly start or stop the pendulum (you will need infinite force to do it), you cannot start or stop the current through an inductor (it will either take infinite voltage to do it, or it will try to generate infinite back EMF voltage to prevent abrupt stop of the flowing current. This effect can instantly zap transistors operating relays or solenoids if you try to abrupt the current instantly - nasty inductive kick back should never be underestimated!

Now, how to apply all this in practice when you build a DC/DC converter? Most core manufacturers will publish maximum flux densities for their cores of different materials and temperatures. But typical electronics lab will not have instrumentation to measure magnetic fields. Calculations are difficult. You can easily measure inductance of your inductors and transformers, but at what current their cores will saturate? Don't despair! Fortunately, with a simple circuit it is trivial to characterize the magnetic core you're planning to use in your design. Another advantage of measurement is that it takes into account core gap, assembly specifics (amount of pressure holding parts of the core together) and even impact of glue type.

The schematic of simple jig I put together to characterize planar transformers for bi-directional DC/DC converters used in my BMS design is shown on fig. 5. Particular component types are not relevant, but I have used the same types I've used in my first iteration of real active balancer DC/DC converter circuit I built - same one recommended by LT in their demo circuit.

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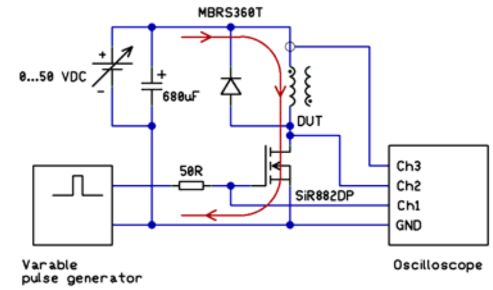
The objective was to measure the saturation current for the cores of different sizes and inductances. Reader can set up their own tests, so there is no need to overwhelm here with many data points I've collected for future reference. I'll present the test results just for the E22 planar core (3F3 material) I chose to use in my converter design. This core size should be able to handle about 3-4A of average continuous balancing current.



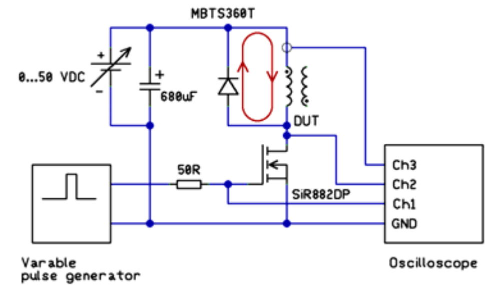


Fig.5.

The operation is trivial: a variable width pulses from pulse generator with sufficient drive amplitude turn on FET the same way it would in real circuit. When the FET is on, a variable output power supply gets connected to the primary winding of the transformer under test. With constant voltage on the coil the current starts ramping up in linear fashion. Increasing the voltage increases the slope of the ramp, so the saturation point will be reached sooner. Alternatively, one can change duration of the input pulse - the rate of current increase (the slope) remains the same but if you wait long enough, the current through the primary coil will reach the same saturation value. Once the FET is off, the current has to be allowed to decrease. On top schematic - ramp up current path is shown. On bottom schematic current that keeps flowing through the freewheeling diode diminishes back to zero before next ramp starts - this prevents magnetizing of the core. For this reason repetition rate was set very low (1kHz) which also helps to keep average power low and keep things cool. Because the voltage on the coil was not forced to zero during ramp down time and the current was allowed to flow through a freewheeling diode, inductor (in my case primary winding of the transformer) current will not ramp down in linear fashion, but is expected to be shaped as exponential decay.

Finally, before presenting the test data, some information regarding the transformers: five cores with different center leg gaps, evidently resulting in different inductance (with the same amount of turns) were tested. Inductance values were:

- 3.88 µH (0.24 mm gap)
- 5.11 µH (0.16 mm gap)
- 7.06 µH (0.10 mm gap)
- 11.68 µH (0.05mm gap)
- 44 µH (no gap)

The plot containing peak current vs pulse width data is presented on the plot on fig. 6. Note that the top plot line for the 3.88 µH primary inductance is a straight line - with primary peak current of 26A the core never went into saturation. I did not risk to stretch input pulse longer as the FET approached its rating for peak current. I know that such high currents will not be used in actual design since it is not realistic to find small enough sense resistor providing fixed 50 mV sense voltage required by the LTC3300 used in the design. Even at 20A peak current the sense resistor value would have to be just 0.05V / 20 A = 0.0025 Ohm. To stay within 10% accuracy the required tolerance is +/-0.00025 Ohm, so we can pretty much forget it.

This data were obtained at Vdd = 3.5V which is close to a lithium cell voltage. The current ramps are highly linear as expected. Note - the higher inductance, the lower current increase rate, but due to smaller gap and denser flux the core saturates at lower currents.

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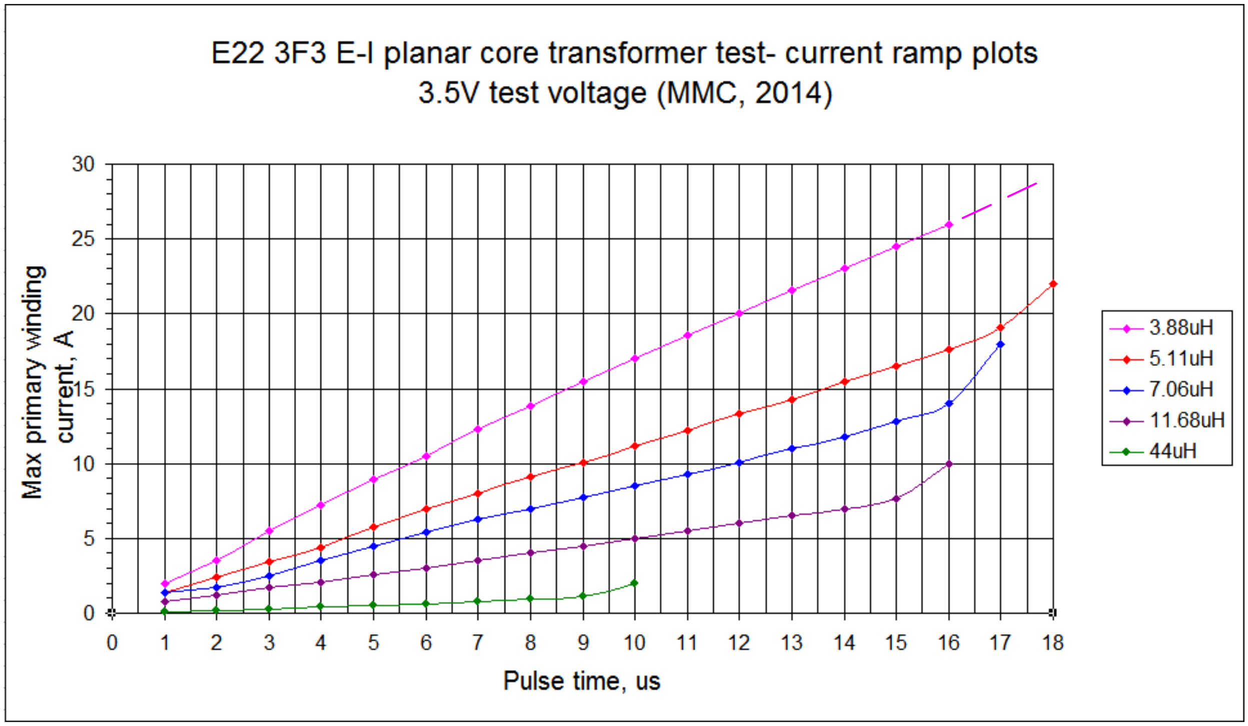
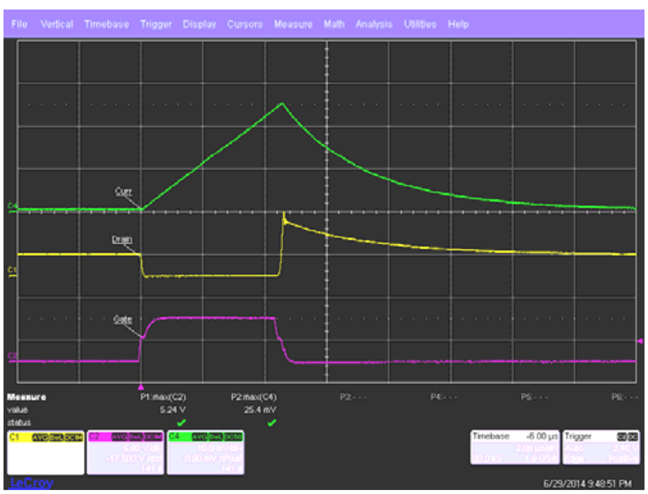


Fig. 6. Essentially this is saturation point vs. core gap plot.

First a standard Würth 750312504 wire wound transformer used in LT's demo circuit was tested on the jig built as shown on fig.5. The result is shown on fig. 7. Current scale (green trace) is 5A/div.



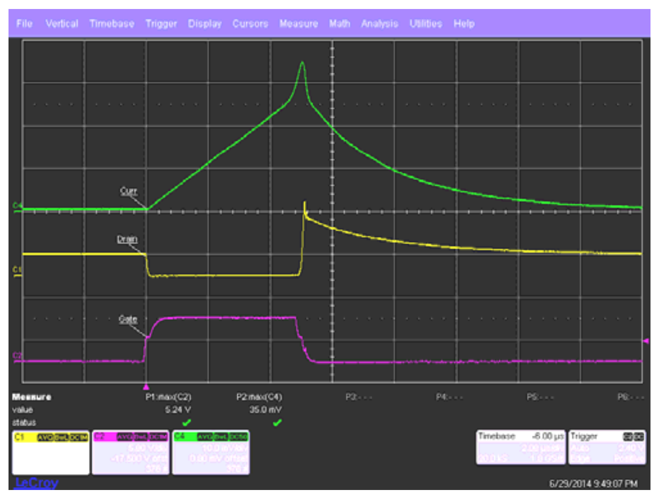


Fig 7. Standard transformer core saturation visualized.

As you can see the peak current it can handle is about 13A (left plot). You can also see nice exponential decay of the current, just as expected. Widening on-time pulse leads into the core saturation - on the right plot you can see primary current peaking at nearly 18A with non-linear spike caused by loosing inductance above saturation point. Since we know that in the LT demo current sense resistors are 0.008 Ohm, the max. peak current transformer will ever see in this circuit is only 0.05V / 0.08 Ohm = 6.25 A, so even such small(ish) transformer is well suitable for this demo.

Let see how larger E22 code based transformer stacks up against Würth 750312504. Current scale (green trace) is still 5A/div, the trace is just moved down to provide more head room since expected max current of beefier core is larger. Indeed, the test under the same conditions produced results shown on fig 8 plots.

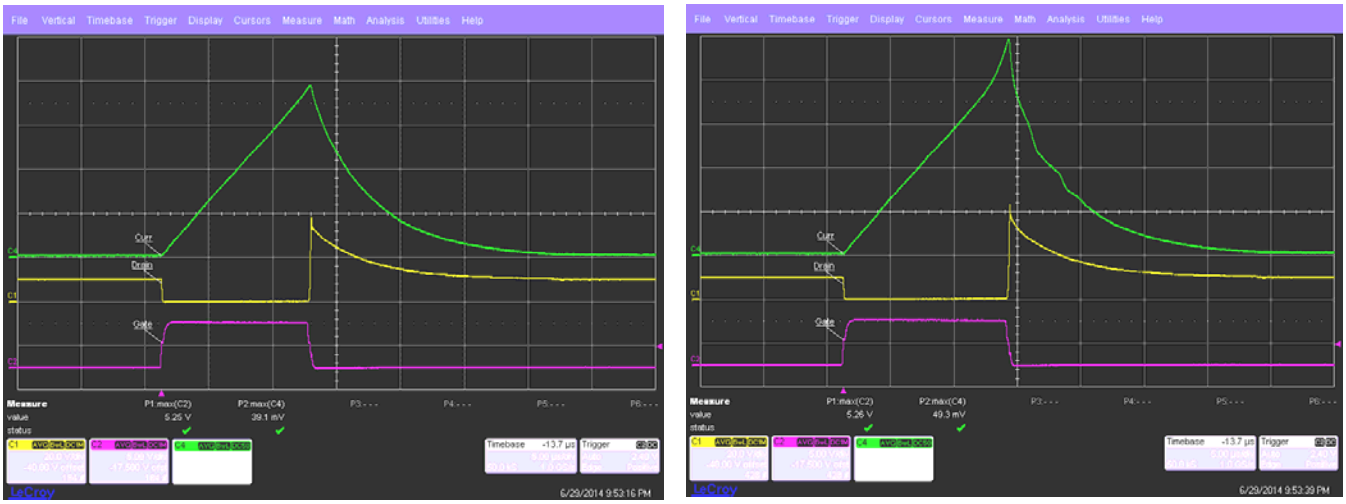


Fig.8. Planar magnetic core saturation current test

The peak current before the core goes into saturation is about 20A, which correlated with data on the plot in fig. 6. Beyond that you can see its core going in saturation - on the right plot it is peaking at 25A. So this planar core can handle 20 A / 13 A = 1.53 times more current without going into saturation than its wire wound counterpart.

One more observation: since inductance of the planar transformer's primary winding (5.11 µH) is higher than that of the wire wound one (3.16 µH), the current ramp slope is lower: it took proportionally longer (5us vs 3.6us) to reach 10A in case of planar transformer than using Würth 750312504.

Conclusions:

- Avoid getting close to core saturation in your power conversion circuit designs. This is runaway process - slightly saturated core will heat up which decreases material permeability, which in turn reduces winding inductance. That leads to steeper current ramps and in circuits with fixed timing - higher peak currents which saturate core even more and the very next thing you'll notice is loud pop of your power FET, or in best case - blown fuse.

- With given size core you can adjust saturation current by increasing magnetic resistance (decreasing total permeability) of the core, you can do that by increasing air gap normally introduced by grinding center leg of core's E half. That will require more current to reach the same flux density and drive the core into saturation. But increasing the gap will reduce core inductance, so now you will need more turn to restore designed value.

- Max. winding current before you drive magnetic core into saturation is very easy to check. Always test your transformer, whether planar or wire wound how much current and power it can handle and measure peak value produced in your circuit. I would be comfortable staying with peak currents in my circuits at 50% of the saturation current or lower - remember that unrelated core losses may increase its temperature, especially in non-ventilated enclosures, which lowers max current the core can handle. 50% mark will provide good safety margin.