

Measuring Inductance in Power Inductors

Determining saturation characteristics subject to pre-magnetisation

Initial inductance is often less important in power inductors with D.C. pre-magnetisation, than inductance during use in real circuits for the entire operating range. This inductance is not constant, rather dependent on the momentary current which is flowing. These ‘effects of saturation’ cannot be detected using normal small signal measuring bridges.

From Hubert Kreis

With the exception of air-core coils, all power inductors possess certain saturation characteristics. That means inductance decreases with increasing levels of current. This is due to the various core materials, which start to lose their permeability more or less strongly after a certain induction B has been reached and in extreme cases take on the characteristics of air. The saturation characteristics of an inductor can be influenced by:

- The type of core material,
- Core geometry,
- The number of turns,
- And the air gap.

However, deviations often exist between the calculated inductance at a certain current level (i.e. rated current) and the real inductance, because:

- the inductor geometry causes a non-homogenous field distribution
- the core’s spec sheet entries are inaccurate or incomplete
- production spread of the core
- manufacturing tolerances
- thermal influences.

For this reason it is important to measure saturation characteristics during the development phase and quality inspection of power inductors.

Power inductors in use

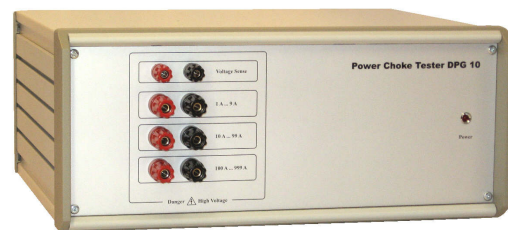
Power inductors are needed in many different applications, i.e.

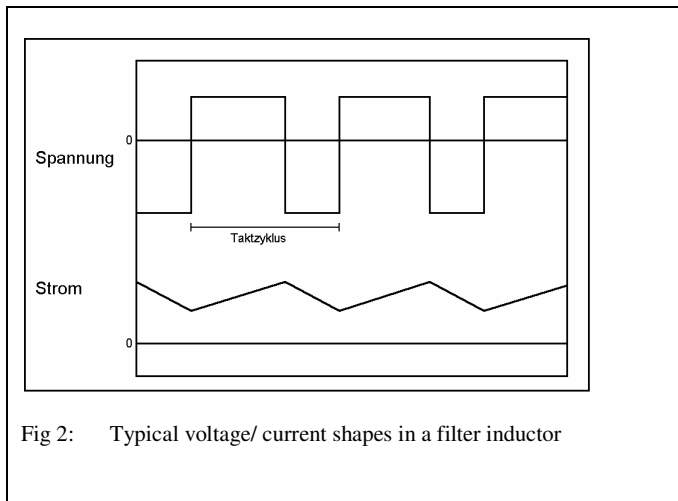
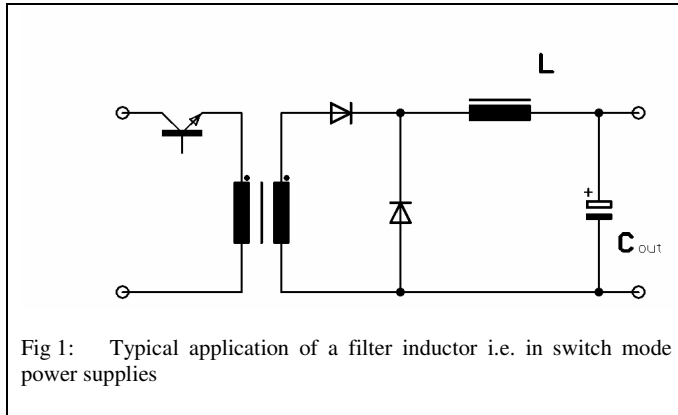
- Smoothing inductors for switch mode power supply (SMPS)
- Filter inductors for IGBT-Inverters (sinusoidal filter)
- Commutation inductor for line-commutated inverters
- Inductors for current source inverters
- And much, much more.

One of the main areas of use is smoothing inductors for SMPS. A typical application of this can be seen in Fig 1.

Voltage characteristics measured at the inductor are rectangular. A current flow is built up in the inductor, which acts as a constant DC component with a superimposed current ripple (see Fig 2). The frequency of the current ripple corresponds to the switching frequency of the application and can range from several 100 Hz to several MHz.

For circuit designers, initial inductance L_0 is mostly of little interest. The inductance present during the highest level of direct current is much more important, because it determines the current ripple (and therefore the output ripple voltage of the SMPS too) as well as the peak current which flows through the power semiconductors.





If the smoothing inductor should become saturated before the desired level of maximum output current $I_{out\ max}$ has been reached, then the power semiconductor can either become damaged or overheated, the capacitor C_{out} could be overloaded and the output ripple may strongly increase.

The same principles apply to most other forms of circuit topology and with many of areas of use for power inductors (i.e. sinusoidal filter for IGBT Inverters).

Only the initial inductance L_0 can be measured using a normal small-signal measuring bridge because the measuring currents are particularly low. In order to properly measure the saturation characteristics, an appropriately high amount of current needs to flow through the inductor.

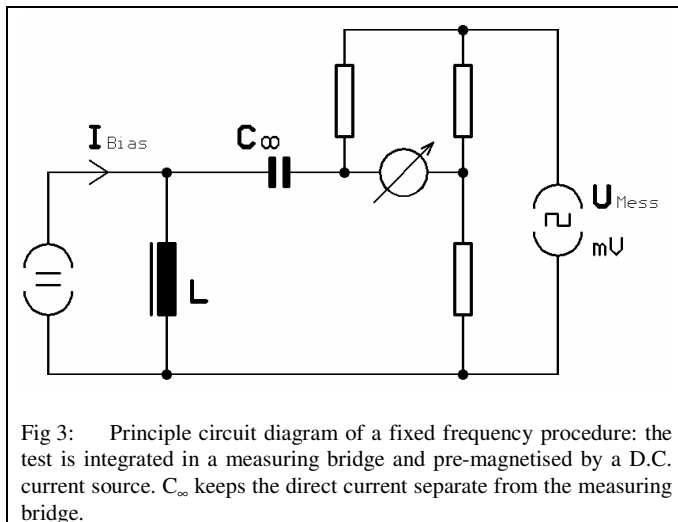
In the following it is important to realise that the inductance of every inductor depends on its frequency.

Different measuring methods

There are principally two different methods for measuring the inductance: the fixed frequency method and the di/dt method.

a) The fixed frequency method:

An appropriate amount of direct current from a DC source is applied to the tested component. A sinusoidal-shaped small-signal voltage of, let's say 10 kHz, is superimposed and the inductance is then calculated using the amplitude and the phase shift of the measured current (Fig 3).



The advantage of this procedure is that the measuring frequency can be accurately determined and reproduced.

The disadvantage is however that the measuring conditions have very little to do with the conditions of operation because during operation a sinusoidal-shaped low-signal measuring voltage is not applied to the inductor, but rather a rectangular-shaped voltage, which contains

harmonics of the switching frequency. Additionally, sometimes large measuring errors can occur due to the non-linear hysteresis characteristics of different core materials.

Furthermore, a corresponding DC source is also necessary, which can be very expensive when large amounts of current are needed (>20A). In order to produce a measurement curve for inductance $L(I)$ with direct current pre-magnetisation, many individual measurements of different currents need to be taken.

b) *The di/dt method:*

In this method, a rectangular voltage impulse is applied to the component being tested, as in a *real application*. A current ramp is then created in the test component, whose di/dt slew rate depends on the inductance and its saturation characteristics.

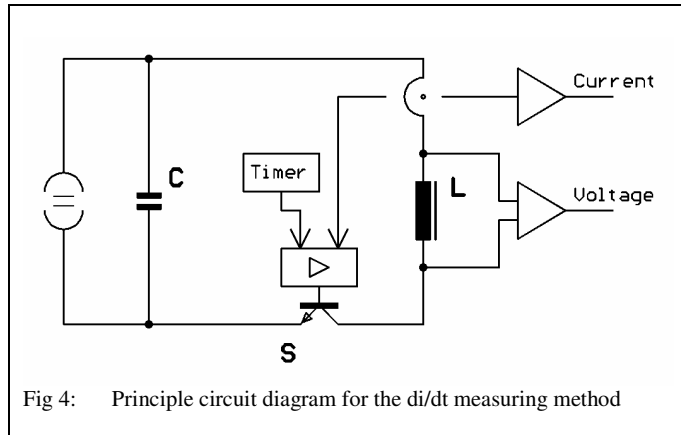


Fig 4: Principle circuit diagram for the di/dt measuring method

If the predetermined maximum current level is reached, the measurement impulse is cut off (Fig 4).

By making calculations based on the profile of the di/dt slew rate of the measurement current, a complete inductance curve (which displays the DC pre-magnetisation dependent inductance profile) for the test component can be produced by taking one single measurement. If the voltage of the measurement impulse corresponds to the voltage, which is applied to the test component during

normal operations, then the dependence on frequency of a result of a fixed frequency measurement is eliminated. Another advantage lies in impulse-shaped measuring because the energy source doesn't have to continually supply the measuring current and can therefore consist of an appropriate capacitor bank. *This saves considerably on costs and size.*

Practical realisation of the di/dt method

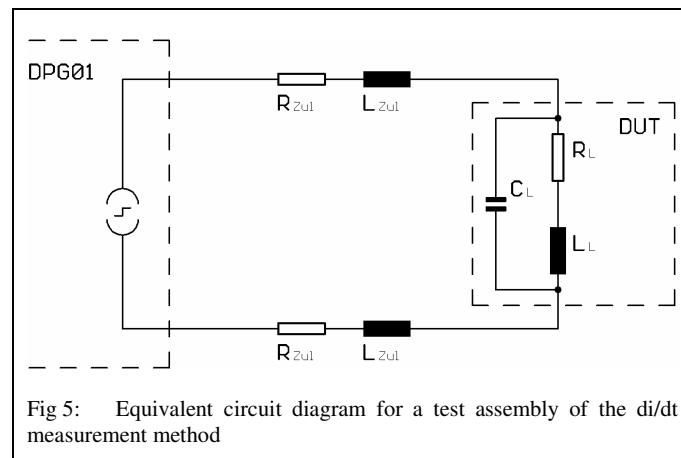


Fig 5: Equivalent circuit diagram for a test assembly of the di/dt measurement method

Several further points should be considered before putting the di/dt measuring method into practice. Fig 5 shows the equivalent circuit diagram for a test assembly. Due to parasitic voltage drops in the supply line, measurement impulse voltage never remains constant in the test component. This means that voltage V_{DUT} measurements need to be taken directly at the test component and included into calculations. Ohmic resistance R_L also needs to be considered. In practice, the influence exerted by C_L can be disregarded. The following formula can be used to

calculate inductance L_L :

$$L_L(i) = [V_{DUT}(i) - R_L * i] * dt/di.$$

(1)

Signal acquisition

Because the di/dt procedure works with individual measurement impulses, the current flow through the test component and the voltage must be recorded and stored in order to evaluate the curve characteristics. 12 bit resolution or better must be used to ensure a good degree of accuracy for inductance calculations.

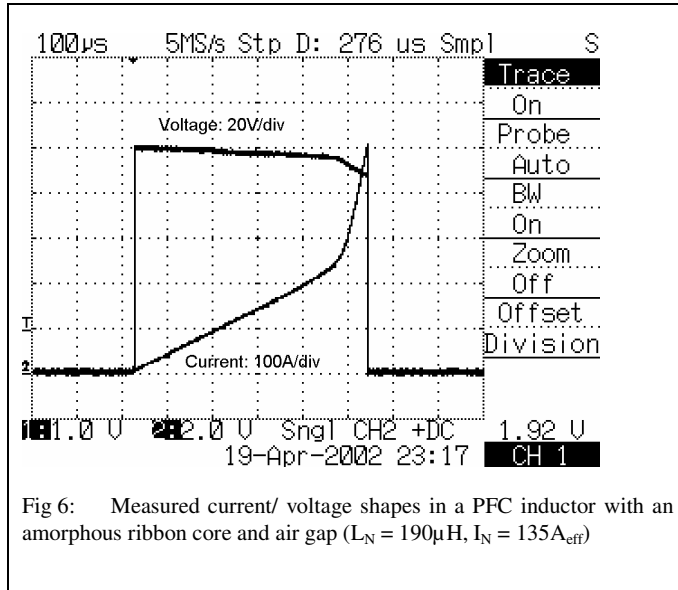


Fig 6 shows an oscillogram for measuring currents and voltages flowing through the test component. This example deals with a PCF inductor with an amorphous ribbon core for active power factor correction. The indicated rated inductance is $L_N = 190\mu\text{H}$ and rated current is $I_N = 135\text{A}_{\text{rms}}$. In this example, measuring impulse voltage lies at around 100V. The measuring impulse is cut off when measuring current level reaches 500A. By taking a quick look at the measuring current slew rate, it can be noted that this inductor will start to become saturated when current levels reach 200 to 250A. For an exact inductance curve $L(I)$, a numerical evaluation is essential.

Signal evaluation

Signal evaluation and calculating inductance curves is done according to formula (1). The incremental distance for Δi or Δt must be carefully selected. If the incremental distance is too short, then strongly fluctuating inductance curves are produced, even with minor analog/digital-conversion errors. Conversely, if the incremental distance is too large, then sudden occurrences of saturation will not be correctly reproduced. For this reason dynamic incremental distance controls, which automatically select incremental distance according to di/dt and d^2i/dt^2 are recommended.

The DPG10 Power Choke Tester

Due to the fact that inductance measuring instruments, which utilise the di/dt procedure had not been available up until now, the company ed-k from Krailling (near Munich) decided to develop the inductance measuring instrument *Power Choke Tester DPG10*. It functions using the di/dt procedure and utilises three current ranges (1 to 9A, 10 to 99A and 100 to 999A). This means that even the saturation characteristics of very large inductances can be measured.

Measurement impulse voltages can be adjusted from 10V to 400V. This means that all inductors can be measured with a measuring voltage, which corresponds to real operational situations (i.e. smoothing inductor for inverter output \Rightarrow 400V, smoothing inductor for the 5A output of an AC/DC converter \Rightarrow 20V).

Additionally, the length of the measuring impulse can be preset from 1 μs to 70 ms, which is useful for measuring voltage-time integrals for example.

The maximum possible impulse energy is limited by the internal capacitor bank to 800J at maximum measuring voltage levels. This is easily sufficient for even very large power inductors. Ohmic resistance is also automatically measured and displayed during each inductance measurement.

A PC is used to control the measuring instrument and to display the results. A simple and clearly laid out graphical user interface allows for intuitive use. The ability to save settings, helps greatly when making a series of measurements during quality control checks. The measuring protocol

incorporates current-dependent inductance profiles in diagrams and tables. Displays can be switched from one to the other, so that inductance subject to voltage-time integrals can also be displayed.

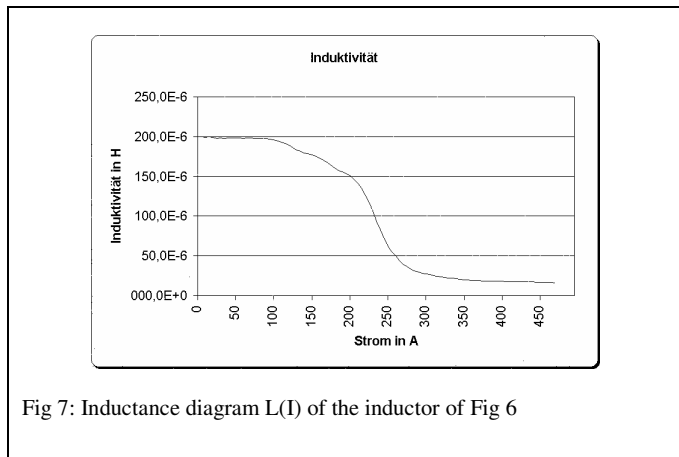


Fig 7: Inductance diagram L(I) of the inductor of Fig 6

Fig 7 shows the inductance diagram for the PFC inductor from Fig 6. This inductor has an inductance of $156\mu\text{H}$, when the peak value of rated current of $135\text{A} * 1,41 = 190\text{A}$ is reached. The real surge current in operation is once again increased by approx. 30A due to the superimposed peak current ripple of switching frequency. Inductance remains at $127\mu\text{H}$ at 220A and is therefore at 33% below the indicated

rated value. For circuit designers, this means that the surge current in the application is larger than was calculated and therefore no longer corresponds to the rating of the power semiconductors. It also leads to increased mains pollution and power losses. This means that an inductor with these saturation characteristics is not feasible in this application.