Design and Applications of Controllable Magnetic Devices in Power Electronic Circuits and Power Systems

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Abstract
Magnetic components are characterized by high robustness and reliability. Controllable magnetic components, which used to dominate, have been out of fashion for about 50 years. However, they have great advantages in terms of longevity, radiation resistance and overload capacity and become smaller and smaller with increasing operating frequency. This makes them interesting in modern power electronics applications with the increasing use of WGB semiconductors. The article shows how the performance of power electronic converters can be improved with modern power electronics and with field-controlled magnetic components using modern magnetic materials.

Keywords: Magnetic components; Passive components; Modelling; Magnetic amplifiers; Controllable filters;

Introduction
When there were no controllable semiconductors in power electronics, many control functions were performed by controllable magnetic components. These are characterized by extreme robustness against environmental influences. At low operating frequencies, however, large and heavy designs are obtained. The extremely flexible controllable and small semiconductor components took over the control functions almost completely in the 60s and 70s. Structure and application possibilities of controllable magnetic components are hardly known anymore. This contribution is intended to contribute to the further development of power electronics by using adjustable magnetic components in addition to modern semiconductor elements with new available materials for a wide frequency range.

Basics: Different Meanings of Permeability and Inductivity
Usually only the initial permeability \( \mu_i \) of materials is given as a characteristic value. This describes the \( B(H) \) characteristic curve at \( H=0 \) A/m. The value is easy to measure and is given by most manufacturers. As can be seen from Figure 1, it is generally not possible to draw any conclusions about the magnetization behaviour of a material. From the increase in the \( B(H) \) characteristic curve, which can be determined in various ways, the inductance value \( L^* \) can be determined if the number of turns \( N \), the magnetization cross section \( A_{Fe} \) and the mean magnetic length \( l_{Fe} \) are known.

Figure 1: Magnetisation characteristic \( B (H) \) for material M400-50A [3]
\[
L^* = \frac{\Psi}{I} = \frac{N \cdot A_{Fe} \cdot B}{H \cdot l_{Fe}} \approx \mu_0 \mu B \frac{N^2 \cdot A_{Fe}}{I_{Fe}}
\]
Permeability and induction result from a suitable definition of the increase $\mu^*$ of $B(H)$ characteristic if the maximum values of flux linkage $\Psi$ and current $I$ are divided by each other, the amplitude inductance or large-signal inductance $L_a$ is obtained (Figure 2).

In (Figure 3) one sees the definitions for a differential inductance $L_d$. It is measured as small-signal inductance at a set bias current. This value is the value displayed for inductance by most measuring instruments. This value is decisive for the magnitude of the ripple current in PWM-controlled power electronic converters, for example.

As is known, the energy content of an inductor is determined by the integral

$$W_{magn}(I) = \int_0^{\Psi_{max}(I)} I \cdot d\Psi$$

The following relationship is generally used for the relationship between energy and electricity:

$$W_{magn}(I) = 0.5 \cdot L_{eff} \cdot I^2$$

This connection is visualized in (Figure 4). From the equation of the two equations above one obtains a further definition. This quantity is, for example, together with a capacitance, responsible for the frequency that occurs in free oscillations.

As (Figure 5) shows, different inductance values are achieved at different operating points on the same component. The changes in inductance values due to shifting operating points can be used in different ways to control inductive components.

Figure 2: Definitions of the amplitude inductance $L_a$ of a soft magnetic component [3]

Figure 3: Definitions of the differential inductance $L_d$ of a soft magnetic component [3]

Passive Control (Control by Design) As a Basic Approach to Control Magnetic Components

In general, the inductance of components is adjusted by means of air gaps in the magnetization circuit. (Figure 6) shows an example of this. Due to the only partially inserted air gap, the magnetizing curve approaches the $\Phi(\Theta)$ curve of the ferrite even with small ampere-turns. With sufficiently high ampere-turns $\Theta$ the cross section without air gap saturates and the resulting $\Phi(\Theta)$ curve is dominated by the air gap.

Another method to influence the magnetization characteristic curve by design is to insert a permanent magnet into the magnetic circuit (Figure 7). The permanent magnetic section then acts as a magnetic flux source. As a result, the magnetization characteristic curve appears shifted on the $\Theta$ axis. In the case of unipolar magnetization, it is possible in this way to achieve double the change $\Delta \Phi$ with the same cross section $A_{soc}$ or the cross-section and thus...
Figure 6: Permanent changing of the magnetizing curve by a special shape of the air gap (example $l_{Fe} = 200\text{mm}$, $A_{Fe} = 4\text{cm}^2$, $\delta = 0.3\text{mm}$, material: B1).

Figure 7: The magnetization characteristic of a magnetic circuit is shifted by inserting permanent magnetic material with low AC losses; thus higher induction is possible with unipolar control [5].

the volume of the components in such applications can be halved. Due to available NdFeB materials, which are bound as powder in plastics, this application is also possible at higher frequencies. In the past, this was not possible in compact metallic areas due to the losses caused by eddy currents. Ferrite materials have the problem of relatively low coercivity field strength.

If one wants to superimpose a changeable additional (DC control) field on an AC main field, one has several possibilities. One possibility is a parallel superimposition of main field and control field (Figure 8). With the simple parallel superposition of the main field with an additional flux, the magnetization characteristic of the arrangement is shifted in one direction on the $\Theta$ axis. Symmetrical structure acting in both directions is shown in (Figure 8b). The main flux $\Phi$ is divided here into 2 branches. In each branch, the main flux is counteracted by the flow through the control winding. This results in symmetrical magnetization characteristics as shown in Figure 9. The average permeance at large-signal level is thus approximated.

Figure 8: Principle of parallel superposition of main magnetic field and control field: a - simple, unipolar superposition; b - bipolar superposition of main magnetic flux and control flux [1,3]
Another possibility is the orthogonal superposition of the main field and the control field (Figure 10). With a cylindrical cross-section, a radially symmetrical control field is created in addition to an almost homogeneous main field. For isotropic materials the components of the magnetic fields add up vectorially. Since the saturation induction of the material cannot be exceeded, a deformation of the magnetization curve $\Phi(\theta)$ or $\Phi(V)$ occurs. This then remains linear over a larger range - compared to the parallel superposition. Because of the necessary adjustments to the core, this variant can be implemented with considerably more effort. For the method to be highly effective, several holes with a small distance between them are required in the material.

Another possibility is the overlapping of both methods (Figure 11). Here too, holes are arranged in the core through which conductors for the control current are passed. The control current is surrounded by a magnetic field that is both perpendicular and parallel to the main field. The resulting characteristic curve of the magnetic branch is then composed of both components of the superposition. (Figure 11b) shows both variants using the example of E70 cores. The yellow wires serve as control windings. In the example on the left with the green test windings the yellow wires are led through the centre leg parallel to the main flux. In the right-hand example these wires are arranged across the main flow through the centre leg.

**Figure 9:** Example of a change in the magnetization characteristic of a symmetrical controllable permeance.

**Figure 10:** Orthogonal superposition of a main field $H_z$ with a control field $H_\phi$: a - Basic structure; b - Change of the magnetization characteristic curve by orthogonal magnetization [3]

**Figure 11:** Control field in mixed arrangement to the main field: a - principle arrangement of main winding and control winding [1]. b - design examples for orthogonal bias and mixed bias with E70 in comparison [3].
In order to achieve good controllability, the controlling conductors are arranged as evenly distributed as possible over the cross-section or width of the magnetic conductor. The smaller the distances between the conductors of the control winding, the greater the transpermeance. At the same time, however, the active cross-section of the magnetic conductor is lost. Depending on the dissipation of heat and the saturation induction, the result is an optimum conductor diameter and distances with maximum change in permeance (Figure 12).

This way one gets quadripole for AC applications with isolated input and output path (Figure 13). The control path is current controlled and inductive. The large signal performance is highly non-linear but can be simulated with concentrated devices or multi-physic FEM. Small-signal performance can be considered linear, similar to semiconductor devices:

\[
\begin{bmatrix}
  L_1 \\
  U_2
\end{bmatrix} =
\begin{bmatrix}
  P_{11} & P_{12} \\
  P_{21} & P_{22}
\end{bmatrix} \begin{bmatrix}
  L_2 \\
  U_1
\end{bmatrix}
\]

Figure 12: Conductors embedded in a ferrite core for orthogonal pre-magnetization of the ferrite material (main flux perpendicular to the image plane) (a); sensitivity of the permeance control by the pre-magnetization current \(I_{0,\text{max}}\) to the selected radius \(R_1\) at fixed maximum current density \((J_{\text{max}} = 2.5 \text{ A/mm}^2)\) (b)[3]

Figure 13: Quadripole for AC applications with isolated input and output path: a - schematic; b - equivalent control circuitry [7]

In this way, controllable permeances become controllable elements in electrical circuits similar to transistors (Figure 14). Electrically controllable capacitances (vary caps) are only used at very high frequencies due to their small/reduced control range. A special feature of controlled magnetic components is the inductive control path. This requires special drivers and limits the speed of the control.

Current controlling magnetic amplifier

The current controlling magnetic amplifier is one of the oldest designs of magnetic amplifiers. In the symmetrical design, two oppositely controlled inductive branches are connected in series (Figure 15). The advantage is the relatively low proportion of harmonics at grid and load side. The current amplification factor is significantly influenced by the number of turns of the control

Figure 14: Comparison of MOSFET, vary cap and magnetic amplifier as controllable devices in electrical circuits
winding. The control effect is based on a compensation of AC and DC ampere turns. If the AC active power is set in relation to the DC control line, high power amplifications can be achieved [10].

Voltage controlling magnetic amplifier

The voltage controlling magnetic amplifier (Figure 16) is also one of the oldest magnetic amplifier designs. Depending on the application, it can be constructed with or without diodes. In Figure 16 it controls the output voltage and thus achieves high values in current amplification and power amplification. The control effect corresponds to a phase-cut control. This results in relatively high harmonic components on the load side and mains side. It is interesting to note that both types of magnetic amplifiers (Figure 16a) can also be realized completely without semiconductor components.

An application of magnetic amplifiers in pwm converters is given in [13,14]. In any case a leading voltage or current source is necessary to run a system.

Control effect in resonant circuits

Control in applications by changing the inductance value is particularly effective in resonant applications. By shifting the resonance frequency in relation to the excitation frequency, even small changes can have a strong effect. (Figure 17a) is a good example of this. If the resonant frequency is increased by slightly reducing the inductance of a resonant circuit, the current consumption changes by more than 2 decades with a constant applied voltage. This approach can be used for adaptive control of filter circuits to eliminate harmonics in the network. In higher frequency applications, for example, it is conceivable to change the natural resonant frequency in order to shift the optimum operating ranges when the input voltage changes (Figure 17b).
Controlling Transformers

Control options of transformers

The controllability of the permeance can also be used to build controllable transformers. For explanation, the design according to (Figure 18) is used. (Figure 18a) shows a transformer with a strong yoke stray field with magnetic equivalent circuit diagram. (Figure 17b) shows the corresponding electrical equivalent circuit diagram. You can clearly see the basic components of a transformer (windings \(N_1, N_2\); magnetizing inductance \(L_{\mu}\) and leakage inductance \(L_{\sigma}\)).

By changing these components, the transformer properties can be influenced in different ways, as shown in (Figure 19). The numbers of windings not discussed here enable the output current and output voltage to be changed simultaneously via the transformation ratio \(N_2/N_1\). Because the magnetizing inductance is generally much greater than the leakage inductance, only a small control effect is obtained when using a controllable magnetizing inductance (Figure 19a). The output voltage of the transformer can be changed, especially in no-load operation, by changing the magnetizing inductance \(L_{\mu2}\). A strong change can be achieved by influencing the leakage inductance in (Figure 18b). The short-circuit current of the transformer is particularly affected by this [2,3,12].
Controlling the stray inductance

An example for the application of this principle is shown in (Figure 20) with a transformer with close winding coupling. For this purpose, a saturable material is placed between the primary and secondary windings and provided with control windings for premagnetization (Figure 20b). To increase the control effect, the magnetic circuit is closed (Figure 20c). The effect of this stray core can also be adjusted by an air gap or changed with a piezotranslator. This can be used to realize a transformer controlled by an electrostatic field.

![Figure 20: Current control of the leakage inductance of a transformer: a-winding structure; b-cross section, c-closed path for the stray field (example) [3]](image)

The construction of a transformer according to (Figure 20), results in the electrical equivalent circuit diagram (Figure 21a). It can be clearly seen that the secondary short-circuit current of the transformer is influenced and that the open-circuit voltage remains practically unaffected. The basic principles described can also be applied in the higher power and frequency range with completely different cores. The repercussions on the control circuit are relatively small in all the cases described, because they are either caused indirectly via parameter changes or compensate each other to a large extent in their effect.

![Figure 21: Controlling the stray inductance according Figure 20: a-electric equivalent circuit; b-change of the load characteristic curve with changed stray inductance (I_{sc} = short circuit current) [7]](image)

Control of the secondary voltage of a transformer by flux control

Finally, another control possibility for the output voltage of a transformer is presented in this article. It is temperature-compensated by the design and can easily be extended to a differential amplifier. The corresponding structure is shown in (Figure 22a). The work principle is inspired by [11]. An AC voltage $U_0$ magnetizes the middle leg. The resulting flux $\Phi_0$ is divided into the two fluxes $\Phi_1$ and $\Phi_2$. The two outer legs are crossed by conductors so that they can be orthogonally pre-magnetized. The effects on the linearity are therefore minimal. A current $I_0$ is used to set an operating point for the permeance of the outer legs. A useful operating point is the inflection point of the characteristic curve $L(I_0)$. A second conductor with the control current $I_{\text{contr}}$ runs through the outer legs so that the current in one leg has the same direction as under bias current and in the other leg the opposite direction. While the permeance of one leg decreases with increasing $I_{\text{contr}}$, it increases in the other leg. The control current thus leads to a change in the voltage difference $U_2-U_1$. If $N_1=N_2$ selected, $(U_2-U_1)=f(I_{\text{contr}}=0)=0$. The voltage difference then changes largely linearly with the control current $I_{\text{contr}}$. By using both legs, temperature influences, for example, are largely compensated. If an additional insulated conductor is inserted for another control current, the difference in output voltages is linearly dependent on the difference in input currents. The arrangement then works like an isolating differential amplifier.
Conclusions

Based on the mechanical design and knowledge of the material parameters, essential properties of controlled magnetic components can be mathematically modeled and simulated. Miniaturization and integration of several tasks into one device seem to be possible. Due to the high robustness of magnetic components and other failure mechanisms, electrically adjustable elements are an interesting addition to the semiconductor elements of power electronics. Both higher switching frequencies and new materials open new areas of application. With their special properties (e.g. isolation between control circuit and main circuit, possibility to transmit electrical energy, extreme robustness) controllable magnetic elements are an interesting addition to existing controllable semiconductor elements.

References


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