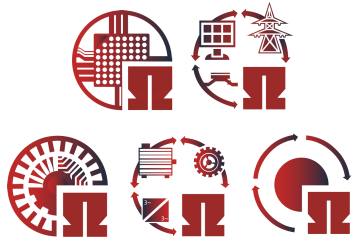


# ELSYS Note

## Energy Gap



This note presents the design of a gapped ferrite inductor for power electronic filters using an EF30 E-core example. The relation between inductance, magnetic reluctance, and stored energy is derived from magnetic circuit principles. It is shown that nearly all magnetic energy is stored inside the air gap. Analytical calculations are compared with finite element analysis, highlighting the influence of saturation and fringing effects on practical inductor designs.

### Power electronics

Power electronics is essential in modern electrical systems, particularly in variable-speed drives. Most converters consist of multiple stages, each requiring careful control of voltage and current ripple.

As an example, the buck (step-down) converter shown in Fig. 1 is considered. This DC-DC converter reduces a higher input voltage to a lower output voltage by high-frequency switching. The resulting pulsed output voltage must be filtered before it can be supplied to the load.

A simple LC low-pass filter is commonly used for this purpose. While the capacitor smooths the voltage ripple, the inductor determines the current ripple and stores the magnetic energy during the switching process. Consequently, the inductor is one of the key components in the converter design.

The performance and size of the converter are therefore strongly influenced by the inductor design. The dynamic behavior of the converter is therefore strongly influenced by the magnetic design of the inductor.

This note focuses on the design of the filter inductor using a gapped ferrite E-core.

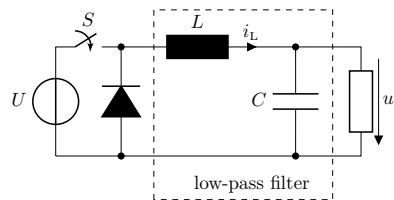


Fig. 1: Buck Converter

### Gapped E-core

To obtain a nearly constant inductance over the operating range, a gapped ferrite E-core is used. The air gap dominates the magnetic reluctance and therefore determines both the inductance and the stored magnetic energy.

The magnetic energy stored in the air gap can be expressed in several equivalent forms, as summarised in Fig. 2. These expressions connect the circuit, field, and magnetic-circuit viewpoints of the inductor.

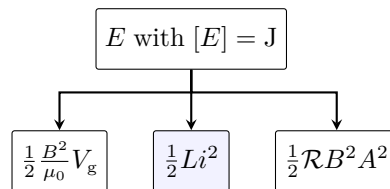


Fig. 2: Air Gap Energy

The magnetic energy density is given by

$$w = \frac{1}{2} \cdot \frac{B^2}{\mu} \quad \text{with} \quad [w] = \text{J/m}^3$$

Since ferrite materials have a very high permeability, the energy density inside the core remains small. In contrast, the permeability of air is much lower, resulting in a significantly higher energy density for the same flux density. Consequently, nearly all magnetic energy is stored inside the air gap.

The primary purpose of the ferrite core is therefore not energy storage, but efficient guidance of the magnetic flux between the air gap surfaces while maintaining a low magnetic reluctance along the remaining flux path. In the present example, the E-core shown in Fig. 4(a) is used. The resulting magnetic field distribution and the dominant energy storage inside the air gap are illustrated in Fig. 3.

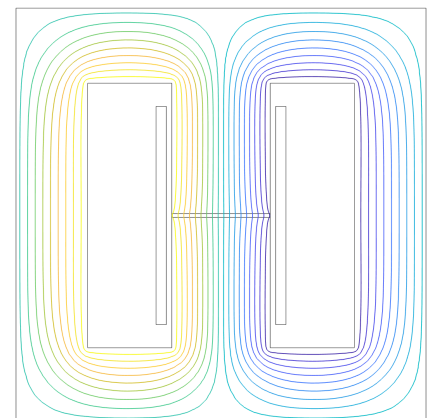
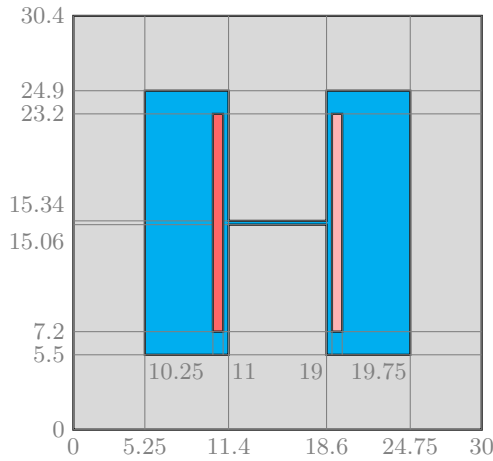
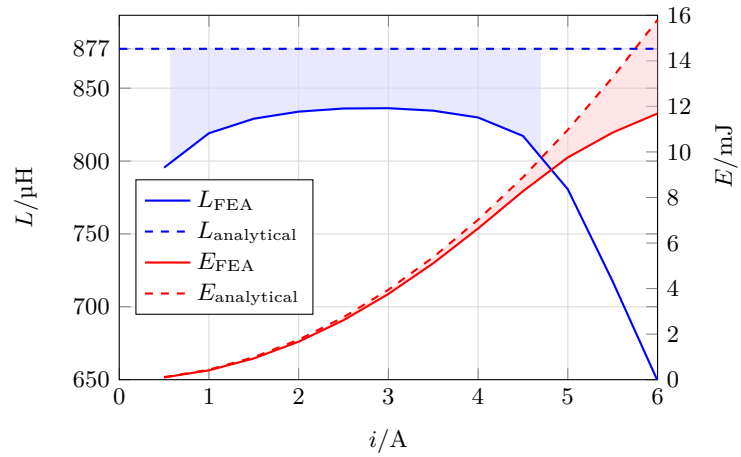


Fig. 3: Gapped E-core ( $N = 61$ )



(a) Geometry dimensions ( $A_{\text{core}} = 52.56 \text{ mm}^2$ )



(b) Inductance and Energy

Fig. 4: EF30 E-core for inductor design

## Inductance and Reluctance

Using the flux linkage together with Ampere's law, i.e.

$$\psi = N\Phi = Li \quad \text{and} \quad \Theta = Ni$$

the magnetic flux can be expressed using the magnetic reluctance

$$\Phi = \frac{\Theta}{\mathcal{R}}$$

Substituting the magnetic voltage  $\Theta = Ni$  into the flux linkage yields

$$\psi = N \cdot \frac{Ni}{\mathcal{R}} = Li$$

and therefore

$$L = \frac{N^2}{\mathcal{R}} = N^2 P \quad (1)$$

where  $P = 1/\mathcal{R}$  denotes the magnetic permeance.

The key observation is that the inductance is directly determined by the magnetic reluctance of the flux path. Since the air gap dominates the reluctance, it also becomes the dominant parameter of the inductor design.

## Energy and Reluctance

The flux density can be related directly to the current using

$$B = \frac{\Phi}{A} = \frac{Ni}{\mathcal{R}A_{\text{core}}}$$

which yields

$$i = \frac{BRA_{\text{core}}}{N}$$

Substituting this expression into the inductive energy (Fig. 2) together with (1) results in

$$E = \frac{1}{2} \mathcal{R} B^2 A_{\text{core}}^2$$

The stored magnetic energy is therefore directly related to the magnetic reluctance, the flux density, and the effective air gap geometry.

Since the permeability of ferrite is much higher than that of air, the air gap dominates the total reluctance and therefore stores nearly all magnetic energy. The ferrite core mainly serves to guide the magnetic flux.

For the present EF30 example, the analytical air gap permeance equals

$$P = 0.23 \mu\text{H}$$

which results in the following magnetic quantities at  $i = 1 \text{ A}$ :

$B$	$E$	$L$
0.27 T	0.44 mJ	877 $\mu\text{H}$

## FEA Verification

Finite element analysis (FEA) is used to verify the magnetic field distribution and the resulting inductance of the gapped E-core. The

simulated flux density in the air gap is shown in Fig. 5, while the inductance as a function of current is given in Fig. 4(b).

Within the operating range, the FEA inductance remains within an acceptable 10% tolerance band due to fringing and non-ideal material behaviour. A comparison of the magnetic energy shows significantly better agreement over a wide operating range.

The main challenge of analytical inductor design is estimating the onset of nonlinear effects such as saturation and fringing.

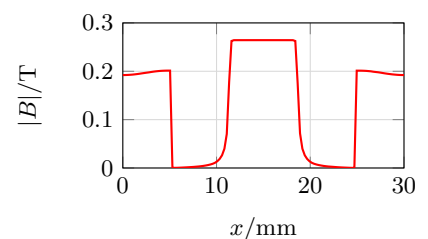


Fig. 5: Air gap flux density

## Summary

In gapped ferrite inductors, the air gap dominates both the magnetic reluctance and the stored energy. Analytical reluctance models provide good accuracy in the linear operating range, while FEA is required to evaluate saturation and fringing effects more accurately.