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# Using Powder Cores to Increase the Power Density of Flyback Storage Transformers

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## Abstract

Flyback converters are widely used in low to medium power converters. The flyback-storage-transformers – the heart of the converters - are traditionally based on gapped ferrite cores. In this paper we present powder cores as an alternative, which can be used to increase the power transferred through a flyback storage transformer of the same size, using their higher usable flux density. It is mentioned, how the soft saturation behaviour and core losses have to be respected during the design. On a 100kHz flyback we demonstrate a concrete example which underlines the theoretical findings.

## 1 Flyback Converters and Storage Transformers

Flyback converters are widely used in DC/DC power converters with a power of approximately 1 to 200 W. They have a couple of advantages compared to other switched mode power supplies, as they allow:

- the output voltage to be both, lower or higher than the input voltage of the transformer,
- to galvanically separate input and output circuit and
- multiple different output voltages within one converter.

The flyback transformer is not a classical transformer, which continuously transfers energy from primary to secondary side, but a storage-transformer, which is “charged” with energy from the primary side in the on-phase of the electronic switch and “discharged” via its secondary winding(s) in the off-phase. The energy is stored in the magnetic field of the cores air-gap (if it is based on a ferrite core) [1].

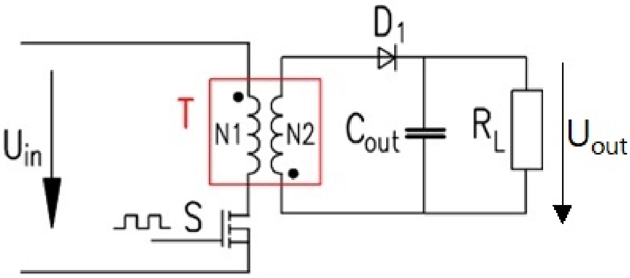


**Fig. 1:** Flyback-Converter Schematics

Beside gapped ferrites also soft magnetic powder cores are able to be used in such storage transformers, as they allow to store magnetic field energy in their magnetic circuit.

## 2 Saturation Flux Density and Energy Saving Capabilities

Powder cores (like MPP, Sendust or HighFlux cores) consist of ground and pressed soft magnetic metals (alloys), forming a core mostly in toroidal or E-shape. The metal particles are electrically insulated to each other by a binder material or oxidized surfaces, which act similar to an air-gap and pull down the overall permeability of the core.
Ferrite cores are sintered ceramics with a homogenous structure. They have a low electrical conductivity, which limits eddy current losses and makes

them applicable to work on higher frequencies. While both, powder cores and gapped ferrites, can store magnetic field energy, they have quite different characteristics. The comparison of two main magnetic properties – permeability $\mu_r$ and saturation flux density $B_{sat}$ – is shown Table 1.

**Tab. 1:** Permeability and Saturation of Powder Cores Versus Power-Ferrites [2] [3]

| | **Powder Cores** | **Power-Ferrites** |
|---|---|---|
| Chemical (alloy) composition | Pure iron or mixed with Al, Si, Ni, Mo in different quantities | MnZn |
| Range of relative Permeability $\mu_r$ | 10…550 | 300… 15000 (ungapped) |
| Saturation Flux Density | 0.8…1.6T | 0.2…0.5T |

As shown in Table 1, powder cores in general have a higher saturation flux density than ferrites. This enables them to save more magnetic field-energy, as both quantities are proportional to each other, considering the magnetic field H to be the same:

$$E_{mag} = \frac{1}{2} \cdot B \cdot H \qquad (1)$$

The magnetic field $H$ is the same, if the magnetic path length $l_m$ of the core is the same, as well as the number of turns $N$ and the exicitation current $I$.

$$H = \frac{\Theta}{l_m} = \frac{I \cdot N}{l_m} \qquad (2)$$

Considerind two cores with a equal permeability and so a equal B-H-relation

$$\mu = \mu_r \cdot \mu_0 = \frac{B}{H} \qquad (3)$$

and also the same dimensions (Volume V, cross section $A_{core}$ and magnetic path length $l_m$) the one with the higher saturation flux density $B_{sat}$ can store more energy. So powerder cores can in general store more engery as ferrites of the same size and gapped to the same permeability.

# 3 Losses

While the saturation is one effect limiting the transferable energy trough a flyback transformer, losses are a second. As Flyback storage transformers are working usually at high frequencies in the range of approximately 50 kHz to 300 kHz under normal conditions (no massive active cooling) the operational flux density has to be significantly lower than the saturation point as otherwise high core losses will occur, leading to the following effects:

- Increase of the primary current which will also push the core closer to the saturation point and so limit the transferable power.
- (Over)heat the device.
- The increasing temperature will lower the saturation flux density of the soft-magnetic material.

In practical designs working on very small flyback transformer (see example in Section 5) the maximal acceptable core losses were found to be in a range of 6 to 10 $W/cm^3$. Using this range the temperature increase was around 60 to 80 K compared to environment without additional cooling (no heat sink, no air flow). The concrete acceptable losses and temperature rise are also dependent on winding and core shape and size as well as mounting position and are therefore individual for each design.
Due to this maximum acceptable core losses, the usable flux density of powder cores is much lower than their material saturation flux density. Depending on alloy mix and working frequency it should be in the range of 0.3 to 0.8 T. This means it has to be checked in the design phase, whether (and which) powder cores are able to get the power density high. It can be also the case (especially at higher frequencies $>$ 200kHz) that powder cores are too lossy and a ferrite is the better solution, as they also reach usable flux densities of 0,3 to 0,4 T.

# 4 Design of Powder Core Flyback Transformer

When designing a flyback transformer with a powder core, its soft saturation behaviour has to be respected. Beside this, the design follows the same steps as using a gapped ferrite, when the inductivity is assumed to be fixed and the transformer is assumed to operate with a save distance to its saturation point.

At this point we give a rough procedure to find the right core and correct primary number of turns for a flyback-storage transformer using a powder core and respecting its soft saturation characteristic. It is based on the flyback-converter design procedure shown in [1], but respects the soft saturation of the powder core.

1. Calculate the energy $E_p$ which has to be transferred from primary to secondary in each period based on the desired power $P$, minimum working frequency $f$ and estimated efficiency $\eta$

$$E_p = \frac{P}{f \cdot \eta} \tag{4}$$

2. Choose a proper core to handle the energy calculated. Many manufacturer catalogs show "Core selector charts", e.g. [2]. If not, find the right size by try and error.

3. Set a proper L-value by calculating the right number of primary turns. The correct number of turns must allow the transformer

   – To get charged with enough power in the turn on time of the period.

   – Allow the core to store the desired energy. This has to be checked, as L will drop according the soft saturation characteristic of the powder core, which effects the stored energy, assording to the following formular.

$$E_{max} = \frac{1}{2} \cdot L \cdot \hat{I} \tag{5}$$

Assuming a constant primary inductance L is sufficient for gapped ferrite based storage transformers. For them the maximum primary current can be easily found by the following formula.

$$\hat{I} = \frac{U_{in} \cdot T_{on}}{L_p} \tag{6}$$

If powder cores are used, L is not constant, but dropping continuously with the magnetic field in the choke even if it does not saturate. This soft saturation behaviour has to be respected to calculate the maximum primary current, as the relation between maximum current $\hat{I}$ and $T_{on}$ will not be linear anymore. Equation 6 has to be rewritten to the following.

$$\hat{I} = \int_0^{T_{on}} \frac{U_{in}}{L_p(I(t))} \cdot dt \tag{7}$$

The formular shows that the primary inductance is depending on the actual current and is therefore changing over time. To get the formula $L(I)$ the material information given by the manufacturer has to be used. It is often given as the function of the drop of the relative permeability related to its initial value.

$$\frac{\mu}{\mu_i} = f(H) \tag{8}$$

This formular can be used as a base and formatted to the function of L in dependence of the current $I$ by using the information about the cores magnetic path length, initial $A_L$-value and number of turns applied.

$$L = f(I) \tag{9}$$

Equation 9, which can be formulated using datasheet and catalog information needs to be inserted in Equation 7. Then this equation needs to be integrated, to get the maximum primary current. It was found, that analytical integration of this equation is often not possible or too complex. Numerical integration using Matlab, Octave as shown in [4] or Excel is recommended.

After getting the maximum primary current and the corresponding inductance, it can be checked, whether the number of turns (or related inductance) is correct to allow the transformer core to absorb enough energy in the on-time and also not to drop too much to store this energy.

The calculation of the secondary(s) number of turns can be done according to [1] or other flyback design guidelines.

# 5 Practical Example

## 5.1 Flyback Circuit Setup

To validate the possibility of using powder cores and compare them to a gapped ferrite based solution, a flyback-like test circuit was realised, similar to the one shown in Figure 1, with the following parameters:

- $U_{in} = 27V$
- $f = 100KHz$
- $R_{load} = 160\Omega$
- $C_{out} = 30uF$
- $N_1 = 9$
- $N_2 = 12$

In addition to the circuit shown in Figure 1 a snubber circuit with a capacitance of 50nF parallel to a resistance of 3K$\Omega$ was used. It was connected in parallel to the primary winding N1 of the flyback transformer to protect the mosfet from voltage spikes. A BUZ73 n-channel mosfet was operated as a switch, controlled by a PWM-signal coming from a signal-generator.

## 5.2 Flyback Transformers Setup

To make the core materials comparable, soft magnetic cores with similar (magnetically important) dimensions were chosen for the flyback transformers. The exact data is shown in Table 2. A gapped N87-ferrite EE13/7/4 core as well as a MPP-toroid powder core with an outer diameter of 13mm are used. The resulting transformers are shown in Figure 2. It can be seen in both, Table 2 and Figure 2, that the powder core is even smaller (Volume, cross-section) than the ferrite core.

**Fig. 2:** Ferrite and Powder Core Flyback Storage Transformer of the Same Size

Both transformers have also the same number of turns and use the same litz wires for their primary and secondary winding. The transformer data, the resulting (measured) primary inductance and the overall permeability of both transformers are also shown in Table 2.

Both transformers were used in the same setup and switched with the same duty cycle of 10% to 40% (in steps of 10%), which equals an on-time $T_{on}$ of 1 to 4µs of a period of T=10µs.

The power transferred through the cores increases as expected with higher turn-on-times of the electronic switch. At low duty cycles (10% and 20%), both transformers show this similar behaviour. In this operation states the power transferred trough the ferrite core was a bit higher compared to the one transferred trough the powder core. This is most probably due to the lower losses of the core material. At duty cycles over 30% the power steadily stored in and pushed out from the MPP powder core becomes significant higher than the power transferred through the gapped ferrite. The MPP powder core based one can continuously transfer an energy of about 25W, reaching an output voltage of 64V at D=0.4. With the ferrite based version the output voltage can not be increased to more than 52V, which equals an output power of 17W. The reached continuous output voltages and output power are shown in the diagramms Figure 3 and Figure 4 respectively.

**Tab. 2:** Core size comparison EE13 and toroid OD=13mm

| | **Transformer 1** | **Transformer 2** |
|---|---|---|
| Core | EE13/7/4, ferrite material N87 | 58048A2 MPP Powder Toroid, OD = 12.7mm, |
| Core volume [mm³] | 369 | 340 |
| Magnetic path length [mm] | 29.7 | 31.2 |
| Core cross section [mm²] | 12.4 | 10.9 |
| N1 | 9 | 9 |
| N2 | 12 | 12 |
| $L_p$ [µH] (measured) | 6.3 | 6.2 |
| effective relative perm | 154 | 174 |

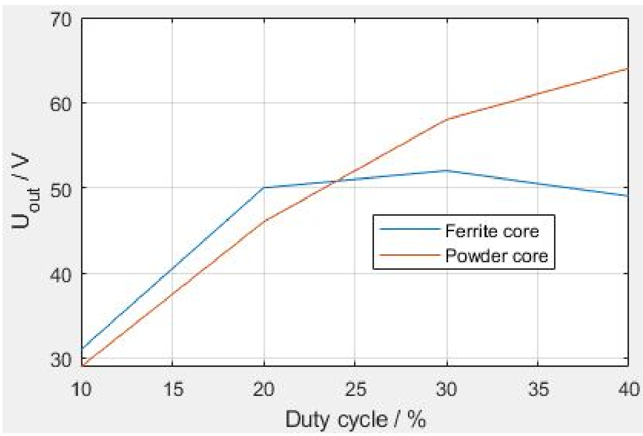


**Fig. 3:** Output Voltage of Both Transformers

The input (primary) peak-current $\hat{I}_p$ of both flyback transformers was monitored via a 0.1 shunt resistor and an oszilloscop at the different duty cycles. It

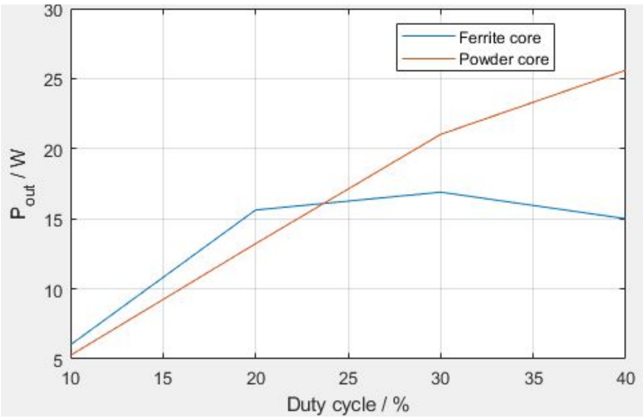


**Fig. 4:** Output Power of Both Transformers

is shown in Figure 5. It can be seen, that the primary current of the ferrite based flyback increases significantly at the duty cycle of 40%, what seems a contradiction to the constant remaining or even decreasing output power in this operation. This increase of the primary peak current shows again that the ferrite core is fully saturated - it is not able to store more energy, but primary current increases exponential as there is no limiting inductance anymore at higher turn-on-times. Also the current of the powder core transformer increases more than linear. This is due to its soft saturation character. In opposite to the ferrite one it does not fully saturate and keeps on transferring power to the load.

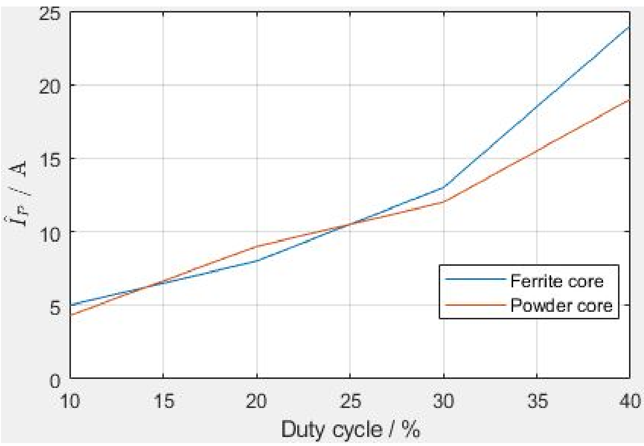


**Fig. 5:** Primary Peak-Current $\hat{I}_p$ comparison

The measured primary currents at the duty cycle of 40% were used to do a FEM-analysis of both designs. Its result is shown in Figure 6. The saturation flux density of both cores is marked with purple color in the legend. It is evident, that at the maximum current point, the ferrite E-core is already at or over saturation point (around 0,4T), while the MPP core is still in a save distance to its (around 0.8T).

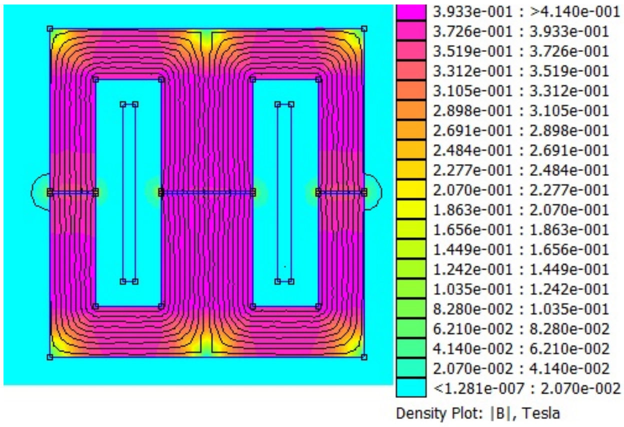


**Fig. 6:** Flux Density in the Ferrite E-core at $I_{max}$

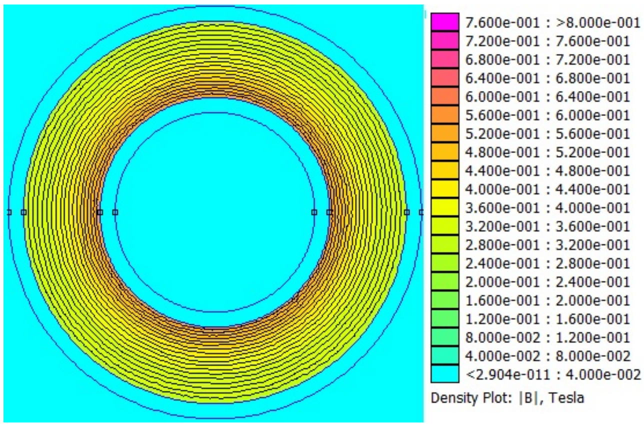


**Fig. 7:** Flux Density in the MPP Toroid at $I_{max}$

# 6 Conclusions

Powder cores offer both, a low permeability and a relatively high saturation flux density compared to ferrites. This makes them usable in the application of a flyback storage transformers. Although they cannot be used until their saturation flux density at high frequencies due to their losses, they are a good alternative to gapped ferrite cores to limit the size of the flyback transformer or transfer more power trough a transformer of the same size.

# References

[1] H.-W. R. Kories, *Taschenbuch der Elektrotechnik*, 4th ed. Harri Deutsch, 2000.

[2] Magnetics, “POWDER CORES Catalogue,” Pittsburgh: Magnetics International, 2017.

[3] Ferroxcube, “Soft Ferrites and Accessories Data Handbook,” 2013.

[4] P. Winkler and W. Günther, “Direct modeling of inductor saturation behavior in a spice-like transient analysis,” *International Journal of Modeling and Optimization*, 2019.