Effect of Frequency on Power Density of Magnetic Components

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Purpose of the presentation

- Size of Magnetics: Absolute v Relative Projection
- **Fundamental Question (absolute values):**
  - Given the power throughput and the input and output voltages of a transformer, what is the operating frequency that will minimize the transformer size/cost?
- The answer (absolute values): Iterative FEA (electrical, magnetic and thermal)
  - Laborious, dependent on modeling accuracy, inaccessible to the average practicing engineer.
- Relative projections:
  - If an optimized (hopefully!) design exists for given power
    - It contains all the correct electrical, magnetic and thermal parameters
  - Required operating frequency for higher power throughput or higher power density can be projected by “perturbing” the volume and or power.
    - Projection accuracy degrades as the amplitude of the perturbations increases.
- This presentation provides tools for relative projections

Relationship between power processed and the Area Product Ap

- **Area product Ap** of a magnetic component is the product of the window and core areas.
  - It can be demonstrated that:
- For transformers:

(1) $$A_{.p}(\text{Transformer}) = \frac{1}{2B\max \cdot \delta_{.B(f)} \cdot J_{.\max} \cdot \delta_{.J}(f)} \cdot \sum_i \left(Irms_{.i} \cdot VxSec_{.i} \right)$$

- For inductors:

$$Ap(\text{inductor}) = \frac{1}{B_{.\max} \cdot \delta_{.B}(f) \cdot J_{.\max} \cdot \delta_{.J}(f)} \cdot \left[\sum_i \left(Ipk_{.i} \cdot Irms_{.i} \cdot L_{.i} \right) \right]$$

Where:
J_{max}: Maximum allowable current density at low frequency
$\delta_J(f)$: Current density derating factor
B_{max}: Maximum allowable flux density at low frequency
$\delta_B(f)$: Flux density derating factor
Ipk: Peak current
Irms: Rms Current in the winding
VxSec: Half wave Volt Second product of voltage on winding

Derating considerations:

- As switching frequency increases:
  - Skin, proximity and gap fringing effects become more pronounced, so the allowable current density in the windings must be derated by a factor $\delta_J(f)$
  - Specific core loss increases, so the AC flux density must be derated by a factor $\delta_B(f)$
- To use equations (1) and (2) for finding the exact Area Product AP of the core necessary for a specific application we need to know the **current and flux density derating factors $\delta_J(f)$ and $\delta_B(f)$ appropriate for the specific situation.**
- Finding these values is an extremely complex problem.
  - Combined electrical, magnetic and thermal considerations

BxF Curves for Ferroxcube Ferrites

(no data available from other mfgs, but unlikely to be significantly different)

"Performance factor" for MnZn power ferrites

- Curves of $B \cdot f$ product for constant power loss density.
- 5 materials for 100 kHz to 2 MHz: 3C96, 3F3, 3F35, 3F45, 3F5.

Since the temperature is kept constant (100°C) $\delta_B(f)$ is accounted for!

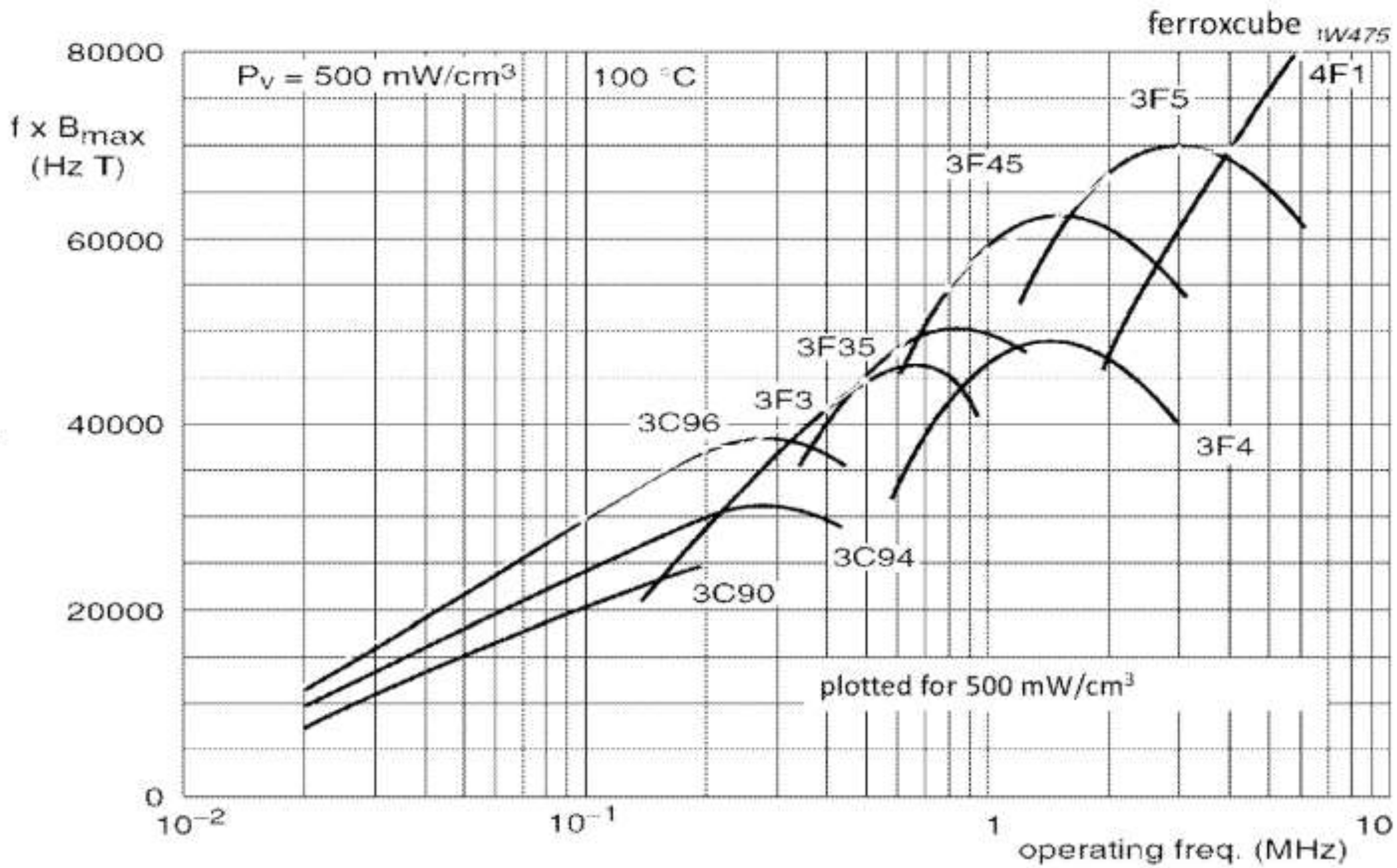


Figure 1

How Does the BxF Product affect Power Density?

- A transformer winding on a core area Ac and a N turns winding can support a square wave voltage V equal to:

(3)

$$V = 4 \cdot Ac \cdot BxF \cdot N$$

- Conclusion: The transformer windings can support a voltage proportional to the BxF product.
- Assuming the transformer can process constant current even as frequency increases, the power throughput of the transformer can be increased by increasing the voltage applied to the transformer
- **As the transformer volume is constant, the achievable power density in the transformer is (ideally!!!) proportional to the BxF product**

Comments

- Keep in mind:
  - Increase the transformer **linear dimension** **by a factor of two**.
  - The surface area of the transformer **increases** **by a factor of four**
  - The volume of transformer increases **by a factor of eight**
  - If the specific losses are kept constant, the **total losses are also higher by a factor of 8.** The transformer has to **dissipate 8x the power** from an **area that is only 4x larger!!!**
  - To limit the temperature rise the **specific loss must be reduced** by operating with lower flux/current densities, **so for equal frequency the power density of a high power transformer must be lower than that of a lower power transformer**
- What is High-frequency?:
  - "High frequency" is defined by the power processed:
    - At 1GW 60Hz is high frequency
    - At 1W 1 MHZ is low frequency!

I hope the above are not surprises!

BxF Maxima of Ferroxcube Ferrites

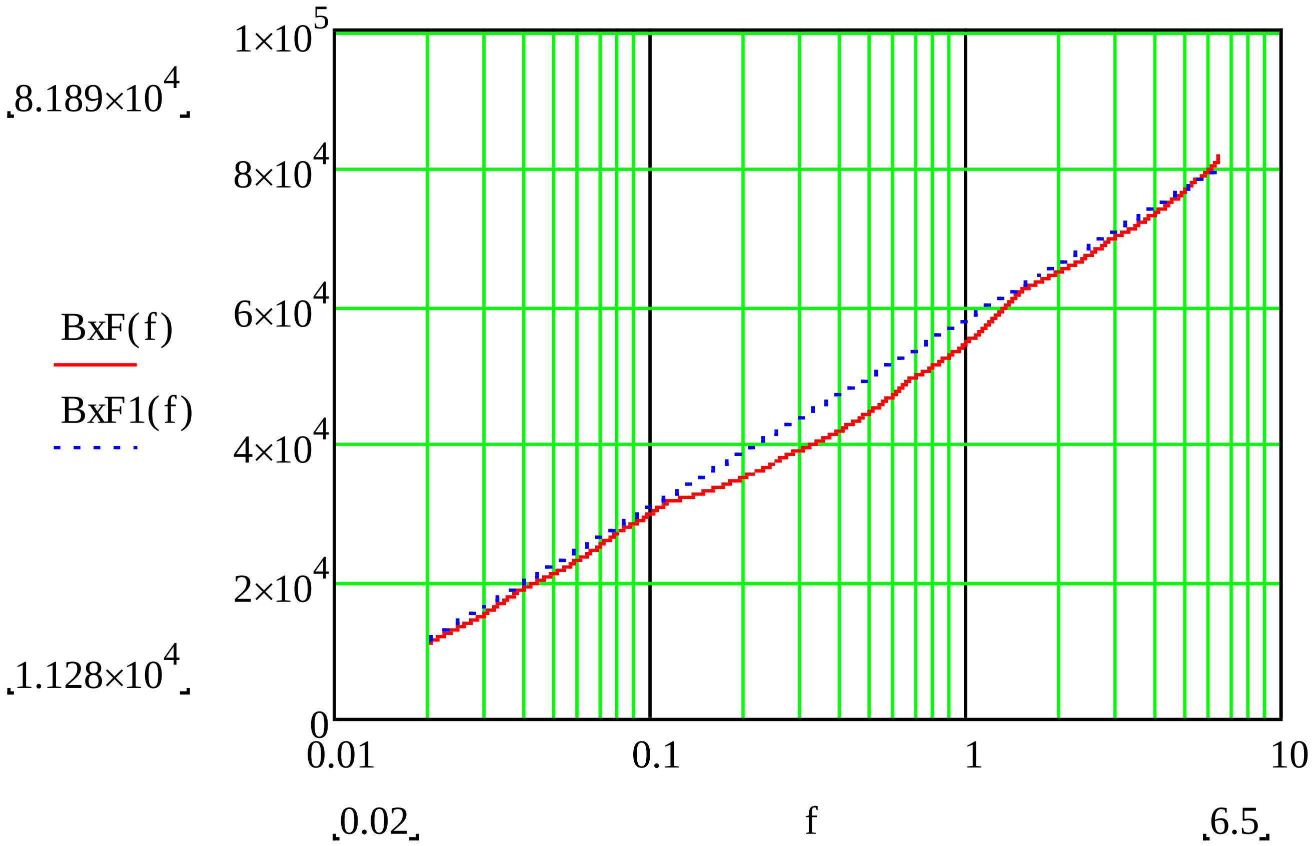


Figure 2

Red: Actual Maxima v F (MHz)
Dotted: Curve fitting approximation of Maxima v F (MHz)

Interpolating the BxF Data

- The maxima of all the BxF curves generates a new curve that represents the highest power density obtainable by selecting best ferrite as a function of switching frequency.
  - The curve is the red line in figure 2.
  - An function BxF1(f) (dotted line in figure 2) fitting the Maxima data is generated to facilitate further quantitative analysis.

(3) $$\mathrm{BxF1}(f) := 58017 + 54491\log\left(f^{.5}\right)$$

The increase in Power Density with Frequency is somewhat disappointing

- Pretty good initially:
  - Increasing frequency from **20kHZ to 100kHz (x5)** increases power density by a factor of **2.624**
- The rate of increase in power density decreases significantly at higher frequencies:
  - Increasing frequency from **100kHZ to 1MHz (x10)** increases power density only by a factor of **1.885**

BxF_N (=Power density) vs. F (20KHz to 10MHz) normalized to 20kHz

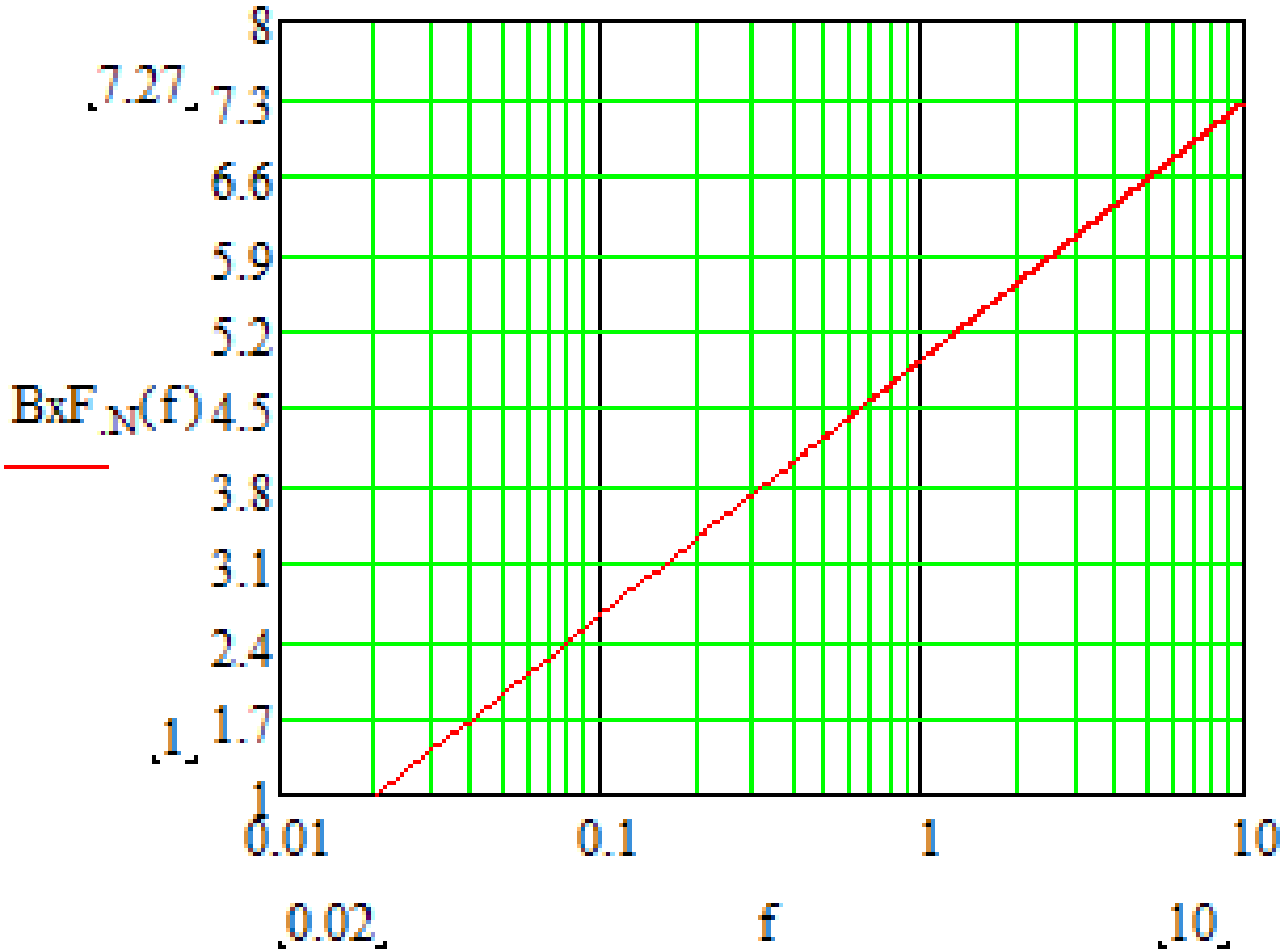


Figure 3

(4)

$$BxF_N(f) := \frac{\left(58017 + 54491\log\left(f^{.5}\right)\right)}{BxF(.02)}$$

Normalized Core Volume vs. F (20KHz to 10MHz)

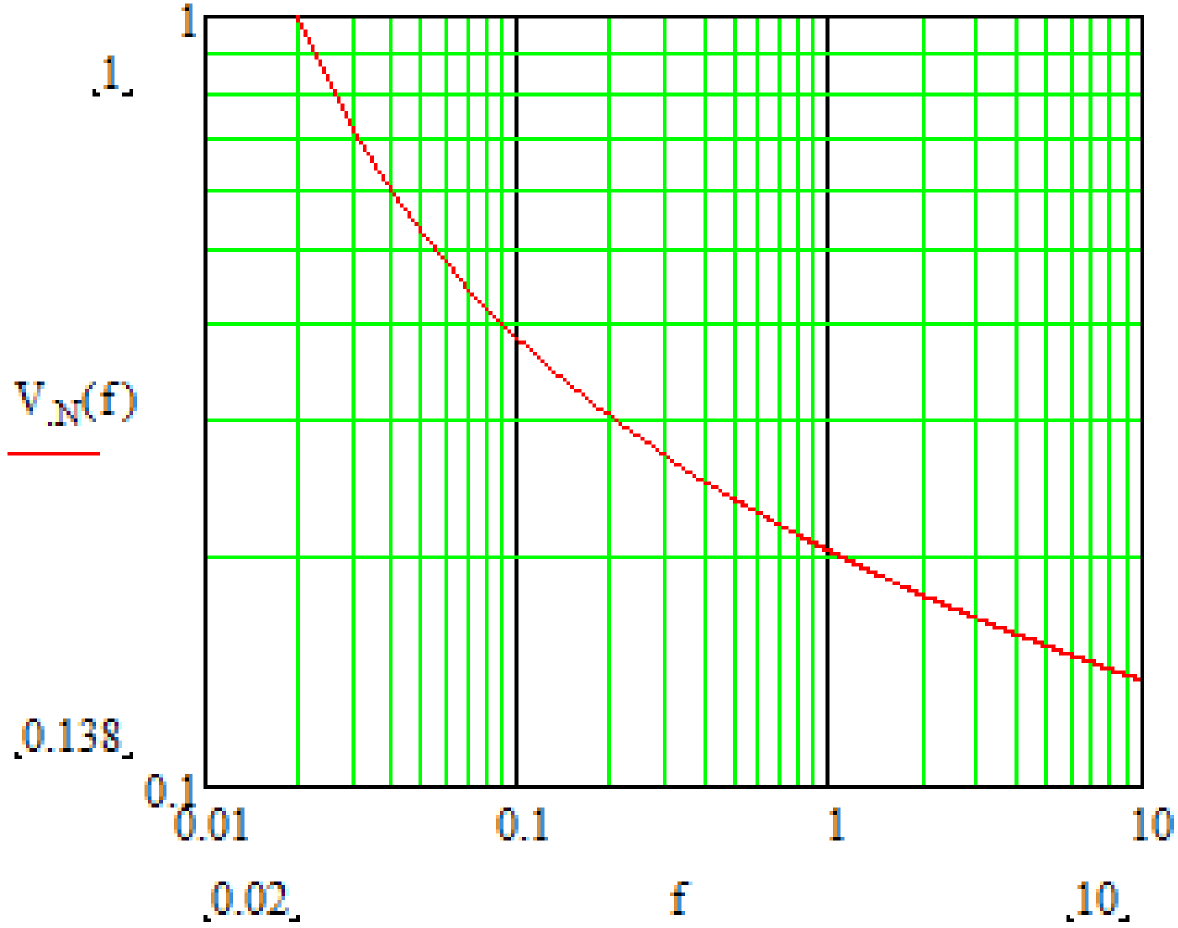


Figure 4

(4) $$V_N(f) := \frac{1}{BxF_N(f)}$$

Practical Use: Projecting Power Density

- Power density of a magnetic component can be increased by:
  - **Delivering more power from a given volume**
  - **Delivering a given power from a smaller volume.**

We will use the information contained in the BxF curves to investigate the effect of switching frequency on power density of transformers

- It can be shown that the effect is very similar on AC inductors (outside the scope of this presentation)

Increasing Power Density with Constant Transformer Volume **(more power out of the same volume)**

Assume we have a transformer operating at a frequency f_o, at what frequency f_1 we need to operate to increase its throughput power by a factor K?

- The power density is proportional to the BXF product (Eq. (2)), so to increase power we need to increase BxF by increasing frequency:

$$\frac{Pd(f_1)}{Pd(f_o)} = K = \frac{Bxf(f_1)}{BxF(f_o)} \qquad (5)$$

Substituting Eq (2) and solving for f_1 yields:

$$f_{.1}(K, f_{.o}) := e^{4.903 \cdot K - 4.903} \cdot \left(\sqrt{f_{.o}}\right)^{2.0 \cdot K} \qquad (6)$$

Eq (6) is optimistic, as it does not account for the increase in AC resistance of the windings (error increases as the frequency increases)

Examples:

fo=.035MHz, K=2: f1=165 KHz

fo=.035MHz, K=4: f1=3.67 MHz

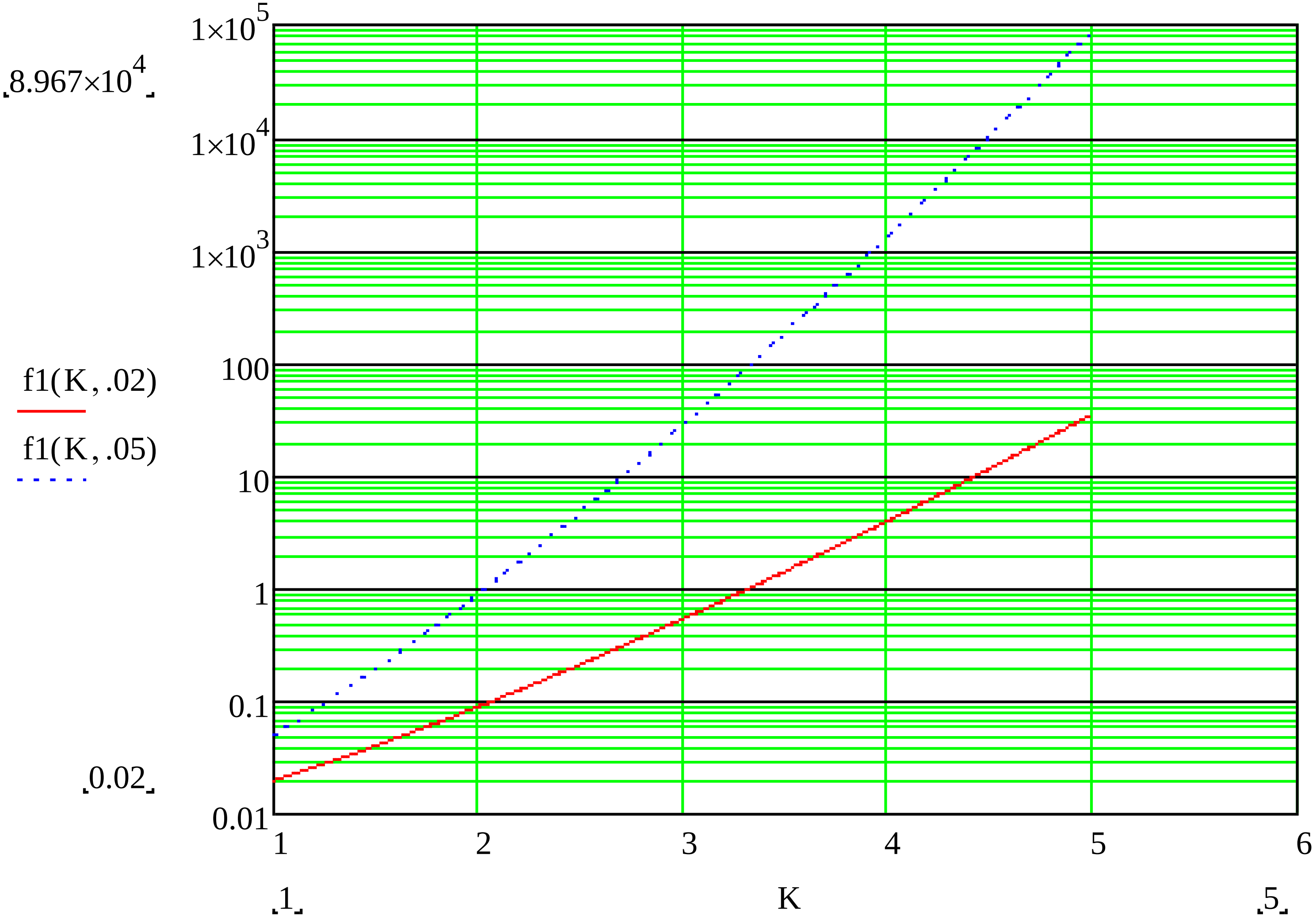
Increasing power density with reduced transformer volume **(<u>same power from smaller volume</u>)**

- Assume we have a transformer of volume Vo, delivering a power P and operating at a frequency f_o, what frequency f1 we need to operate at to reduce the transformer volume by a factor K?
- If volume decreases by a factor K
  - The core area decreases by a factor $K^{2/3}$
    - The supported voltage decreases by same factor $K^{2/3}$
  - The copper area decreases by the same factor $K^{2/3}$
    - The current decreases by the same factor $K^{2/3}$
- Consequently, the power throughput decreases by a factor of $K^{4/3}$
- To increase the power to the original value we need to increase the BxF by the $K^{2/3}$ factor by increasing the frequency from f_o to f_1:

$$f1(K, f_{.o}) := e^{4.903\times10^{0}\cdot K^{\frac{4}{3}} - 4.903\times10^{0}} \cdot \left(\sqrt{f_{.o}}\right)^{2\times10^{0}\cdot K^{\frac{4}{3}}} \qquad (7)$$

For K=2 and fo=50kHz the frequency f1 has to be 907 kHZ!!!

f1 v f_o and K



1×10^5
8.967×10^4
1×10^4
1×10^3
100
10
1
0.1
0.01
0.02
f1(K, .02)
f1(K, .05)
1
2
3
4
5
6
1
K
5

Increasing power density with reduced transformer volume (cont'd)

- The increase in frequency is massive
  - Note that the prediction assumes AC resistance independent of frequency
    - This assumption may be mitigated in reality, as the **total power dissipation decreases by a factor of K, while the surface area of the transformer creases only by a factor of $K^{2/3}$**, so a higher copper loss is allowable.
  - The large frequency increase also impacts switching and drive losses
  - **Note that if the baseline frequency is lower, the situation is not nearly as dire.**
    - **For K=2 and f_o=20kHz the frequency f1 is only 90kHz!**

Summary and conclusions

- A “quasi-quantitative” method is provided that predicts the potential power density improvement of magnetic components.
  - Useful to estimate relative improvement
  - A tool to sharpen intuition
- Projecting the frequency the converter has to operate at helps to decide whether soft switching is necessary and guides the design of other elements of the converter and the control circuit.
- **FEA Simulations for the achievable current density in the windings at the operating frequency can be used to improve the analysis accuracy.**