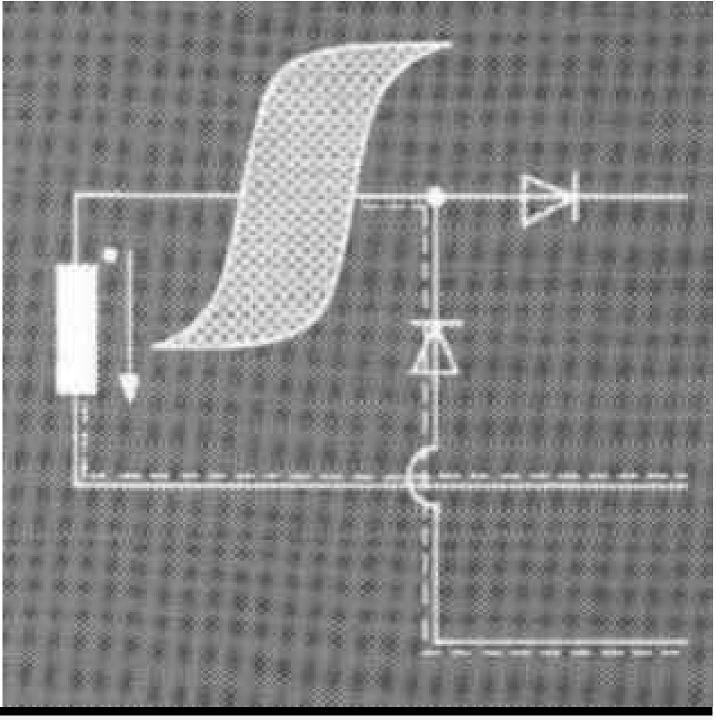
Tape-Wound Cores for Magnetic Amplifier Chokes

VITROVAC 6025 Z



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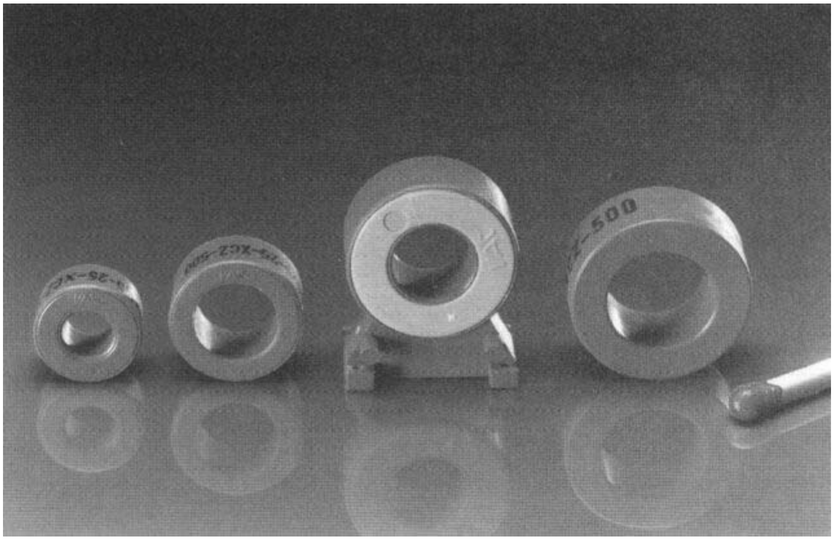


The world's first amorphous saturable reactor cores. Highly reliable and most efficient since 15 years.

Contents

Page

1. General Info on the Mag Amp Principle **1**

- 1.1 The Core Solution for Output Control 1
- 1.2 Cores from VAC 1
- 1.3 Basic Principle of Operation 1

2. Properties of VITROVAC 6025Z Cores **3**

- 2.1 Magnetic Properties 3
- 2.2 Magnet Quality 3
- 2.3 Application Temperature Limit and Temperature Characteristics 5
- 2.4 Core Design and Standard Sizes 6
- 2.5 Order Information 7

3. How to calculate a Mag Amp Choke **7**

- 3.1 Selection of Core Size and Number of Turns 7
- 3.2 Estimation of the Control Current 8
- 3.3 Example 8

4. Appendix **10**

- 4.1 Core and Copper Losses in Theory 10
- 4.2 Notes on more Theoretical Fine Tuning 10
- 4.3 Notes on Regulation Circuits 11

5. Definition of Terms **12**

6. Relevant Publications **13**

1. General Info on the Mag Amp Principle

1.1 The Core Solution for Output Control

The magnetic amplifier (Mag Amp) control technique has become the synonym for reliability in the old 50 Hz days and still is in modern switched-mode power supplies. Nowadays, Mag Amps are mainly used in switched-mode power supplies with multiple outputs to control the output voltages. Push - pull, forward and - more recently - fly-back converter principles with Mag Amp regulation have become established.

In most power supplies only one secondary output voltage is regulated closed-loop to the primary, other secondaries remain open-loop. The dynamic properties of these outputs are determined by the load and the primary switch. To control various different output voltages, independently from one another, different regulation principles are used. Conventional linear regulators reduce efficiency and are often limited to output currents of one or two amperes. Electronic regulators are more efficient but require more parts in the circuitry and are therefore more expensive and less reliable.

The Mag Amp regulation principle offers a low cost, efficient and, owing to the simple design, reliable solution to these problems. It meets the increasing demands on modern switched-mode power supplies excellently. An efficiency level of more than 90% can be realized even at higher switching frequencies. The low RF interference level is advantageous to the suppression filter.

The most popular and particularly economic magnetic amplifiers are those with a performance range from approx. 20 to above 150 W per output, for currents between approx. 1 and 30 A. With the new generation of ultracompact low voltage ICs (2.9 V, 3.3 V) suitable small Mag Amp cores are available at attractive prices.

1.2 Cores from VAC

With increasing frequencies core properties have become more and more important. It is now almost 15 years since one of VAC'S innovative customers ran tests using the Co-based amorphous VITROVAC 6025Z - at that time VAC'S most innovative core material.

The performance of VITROVAC 6025Z cores was convincing right from the start. Since then the cores have been continuously improved and, nowadays more than ever represent a state-of-the-art alloy for modern power supply output regulation.

This brochure describes VAC'S standard types of VITROVAC 6025 Z cores, their magnetic properties, testing methods and guaranteed values, gives some hints on how to select the core size and number of turns, as well as how to estimate core and copper losses, wire diameter, reset current and temperature rise.

VAC, a Siemens subsidiary, is the number 1 supplier in Europe for amorphous and nanocrystalline cores and inductive components using these cores. Fields of application for VAC cores and components are transformers and chokes for digital communication equipment, SMP's and converters up to several 10kW of power. VAC is certificated according to ISO 9000 since 1993.

1.3 Basic Principle of Operation

The heart of a Mag Amp-choke is a toroidal core made from a soft-magnetic alloy with rectangular hysteresis loop and, in most cases, just one winding for operation and control currents. The specification requirements with regard to choke material are very high. In addition to low magnetic reversal losses (effect on heat build-up, control current, efficiency), a markedly rectangular hysteresis loop featuring high remanence (effect on control range) and good saturation behaviour is required. For this reason, amorphous Co-based alloys such as VITROVAC 6025 Z have been accepted worldwide as ideal materials for this application.

The function of the Mag Amp can be described as a high speed on/off switch similar to a switching transistor. The rectangular B-H loop is causally related to two operating states. The switch is open as long as the choke is magnetized and the current flow to the output is blocked. As soon as the core material is saturated, the switch is on and current starts to flow to the output. This effect is based on a rapid change in impedance IZI (or inductivity L or permeability µ) of the choke across 3-4 orders of magnitude when going into saturated condition.

This switching function is used for pulse width control of the voltage pulse induced in the respective secondary winding (before this pulse is rectified and smoothed by the output filter). Figure 1 provides an illustration of the operating principle. Intervention takes place at the leading edge of the pulse by delaying the voltage rise for the time period Δt_{Reg} . This ,,off"-state is switched in the ,,on" position when the core reaches saturation. By modifying the duration of Δt_{Reg} it is possible to achieve an exact regulation of the output voltage. If for example the output voltage becomes too high, the delay time at the leading edge of the pulse increases and as a consequence the output voltage decreases until the desired value is reached. Following the law of induction, Δt_{Reg} can be adjusted by varying the operating point A on the hysteresis loop (see Figure 2), respectively its flux density swing ΔB_{Reg}:

$$\Delta t_{Reg} = \frac{N \times A_{Fe} \times \Delta B_{Reg}}{\hat{u}}$$

$$\Delta t_{Reg} = \frac{N \times \Phi_{Reg}}{\hat{u}}$$

N represents the number of turns, A_{Fe} the effective magnetic cross-section, and û is the voltage applied. $\phi_{Reg} = A_{Fe} \times \Delta B_{Reg}$ is designated as magnetic flux from operation point to saturation.

During the switch-off period of the primary switching transistor the reset of the Mag Amp from saturation to the operating point A is achieved by applying a current in the opposite direction. Some remarks on the regulation circuitry are given in Appendix 4.3. Figure 1 illustrates the waveforms of voltage and current for a single forward transformer with a duty cycle of 0.5 at different positions of the circuitry. u1 represents the transformer output voltage. Waveform u_{MagAmp} shows the voltage applied to the Mag Amp. Please note that the volt second products of reset (,,reset area") and the following delay period (,,delay area") are equal. The voltage at the output side of the Mag Amp is given in waveform u2 with $u2 = u1 - u_{MagAmp}$. The rectified voltage at the input of the smoothing filter is shown as u3.

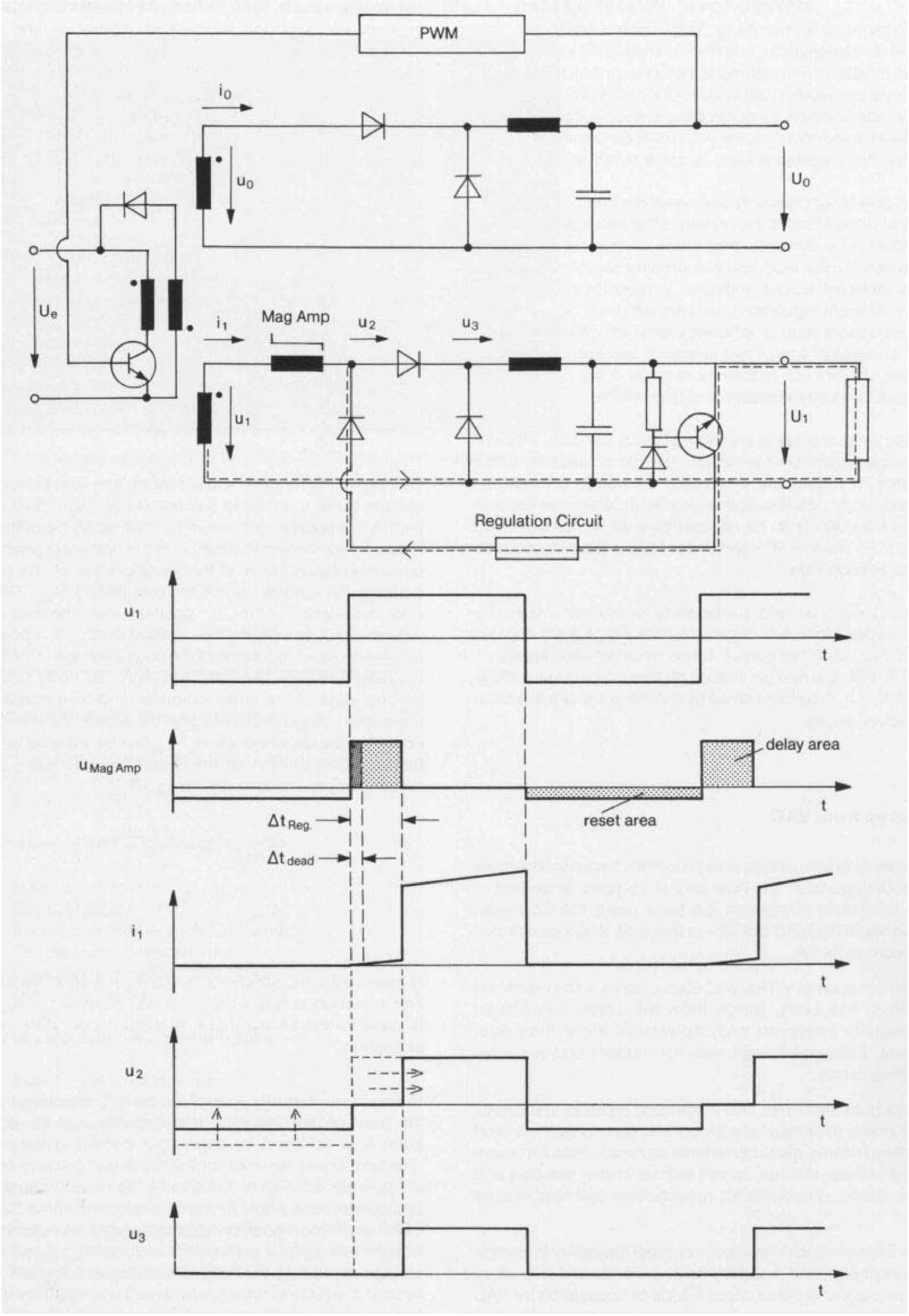


Figure 1: Basic Operating Principle of Magnetic Amplifier Regulation

The "dead time" defined as Δt_{dead} in Figure 1 occurs due to the non-ideal characteristics of real magnetic materials regarding the difference between remanence and saturation (even if, e.g., amorphous metals have already come very close to this ideal). The magnetic core will always be magnetized from remanence to saturation even if no control current is applied. During this period the voltage is blocked.

Dead time is dependent on remanence flux density swing ΔB_{rs} and, of course, on the magnetic cross-section and number of turns. Naturally, this additional voltage drop needs to be taken into account when defining the transmitter output voltage. The latter has a major influence on the design of the choke, i.e. cross-section and number of turns.

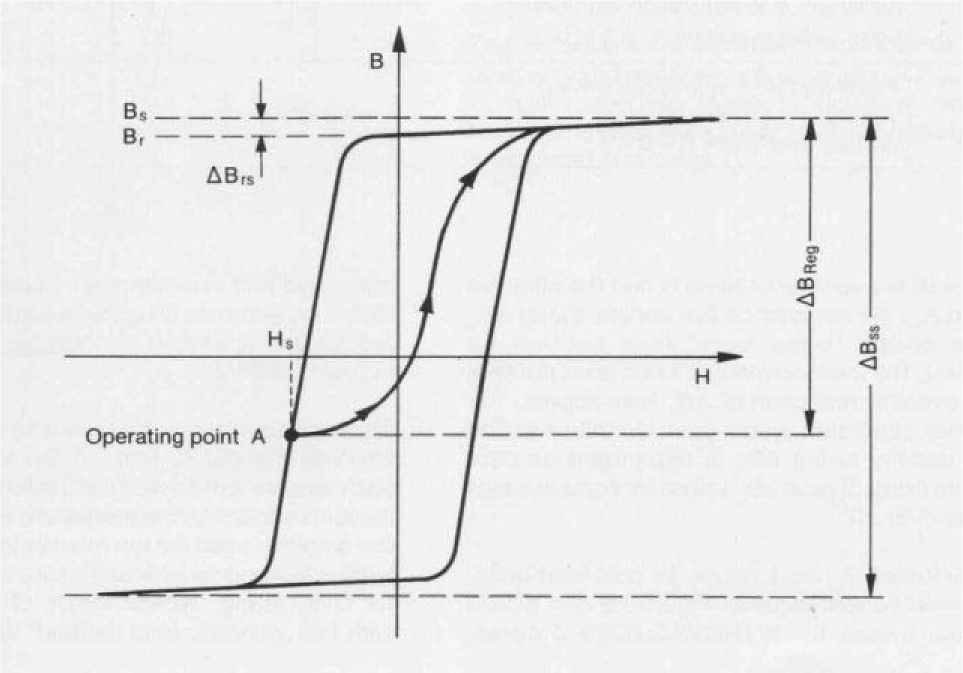


Figure 2: Operating on the B-H Loop of the Magnetic Core

2. Properties of VITROVAC 6025 Z Cores

2.1 Magnetic Properties

Table 1: Magnetic Properties of VITROVAC 6025 Z Cores (typical values)

Property	Term	Typical Value
Saturation flux density (25 °C)	B_s	0.58 T
Saturation magnetostriction (25 °C)	λ_s	$< 0.2x10^6$
Curie temperature	Tc	240 °C
Bipolar flux density swing (25 °C)	ΔB_{ss}	1.15T
Bipolar flux density swing (90 °C)	ΔB_{ss}	1.0T
Bipolar flux density swing (120 °C)	ΔB_{ss}	0.8 T (min.)

2.2 Magnet Quality

The magnet quality defines test conditions, test scope, and permitted limiting values to ensure proper operation of Mag Amp chokes with VITROVAC 6025 Z cores. The relevant core properties are:

- **total flux ϕ_{ss}** => to avoid voltage drop at low loads
- **squareness of the hysteresis loop B(H)** => to avoid voltage drop at full loads
- **cores losses** => to avoid excessive temperature rise

The total magnetic flux of each single core produced by VAC is measured on-line during core production. Testing conditions and limiting values for the squareness of the hysteresis loop and the core losses are defined in our magnetic quality XCZ-500 shown below. Additionally, a data sheet for each core size can be supplied.

Table 2: Magnetic quality XCZ-500:

Testing property	Testing method	Testing value			
		cased cores		coated cores	
		outer diameter > 12,5 mm:	outer diameter < 12,5 mm:	outer diameter > 12,5 mm:	outer diameter < 12,5mm:
squareness	measurement of the residual flux density swing ΔB_{rs} from remanence to saturation with unipolar voltage pulses, fp = 1 kHz	< 50mT	< 75mT	<80mT	<140mT
core losses P_{Fe}	measured with sinusoidal driving voltage (f = 50 kHz) and flux density amplitude B_{max} = 0.4 T	< 65 W/kg		< 75 W/kg	

When multiplied with the number of turns N and the effective iron cross-section A_{Fe}, the remanence flux density swing ΔB_{rs} determines the choke "dead time" (see section on dimensioning notes). The measurement at 1 kHz does not take into account the dynamic reduction of ΔB_{rs} from approx. 100 kHz, and therefore simulates worst case conditions. The remanence flux density swing ΔB_{rs} is dependent on core dimension and core fixing. Typical ΔB_{rs} values for cores in cases are between 15 and 40 mT

Magnetic reversal losses P_{Fe} are a gauge for core heat build-up as well as the reset current required. Figure 3 shows typical magnetic reversal losses for VITROVAC 6025 Z cores, measured with sine-shaped induction. In practice, somewhat higher losses are to be expected for unfavourable voltage form factors and operation of cores far into their saturation (high output currents).

An alternative testing method is to drive the cores with a field strength of about 80 A/m (= 1 Oe) and a frequency of 100 kHz and measure the relevant parameters directly from the dynamic hysteresis loop. As the results are influenced by the quality of the amplifier used for the measurement, we prefer to use this testing method for characterization of the cores only, and not for final testing. Typical values of VITROVAC 6025 Z cores with this “dynamic loop method" are indicated in Figure 4.

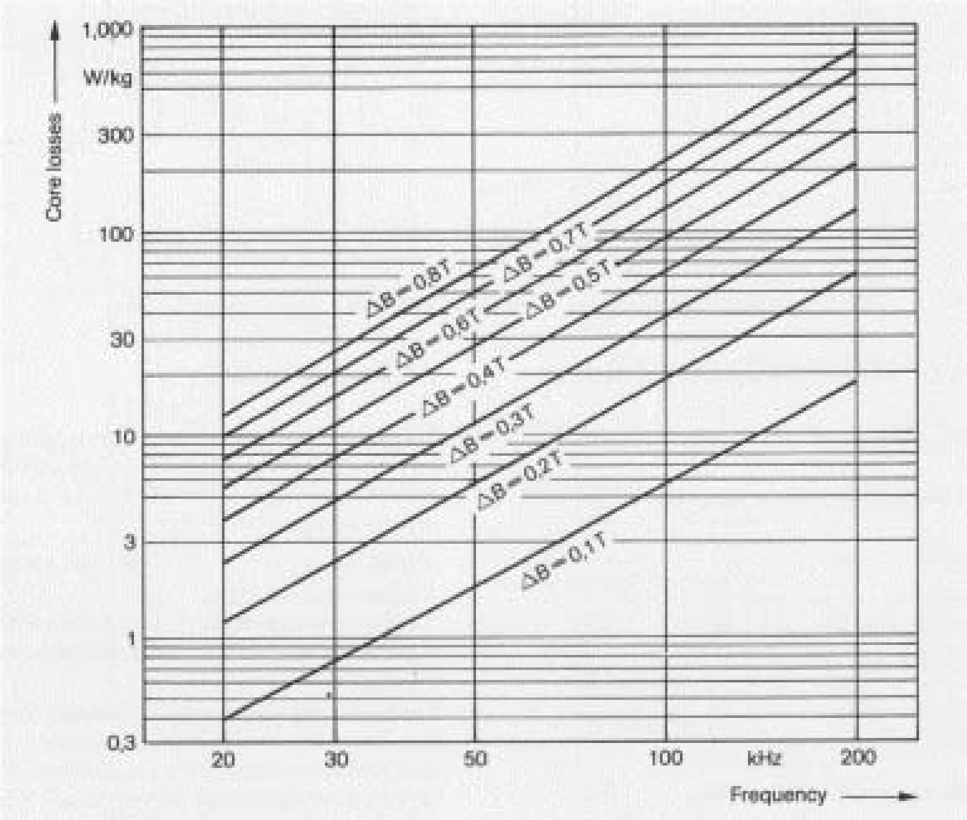


Figure 3: Typical Core Losses of VITROVAC 6025 Z Cores

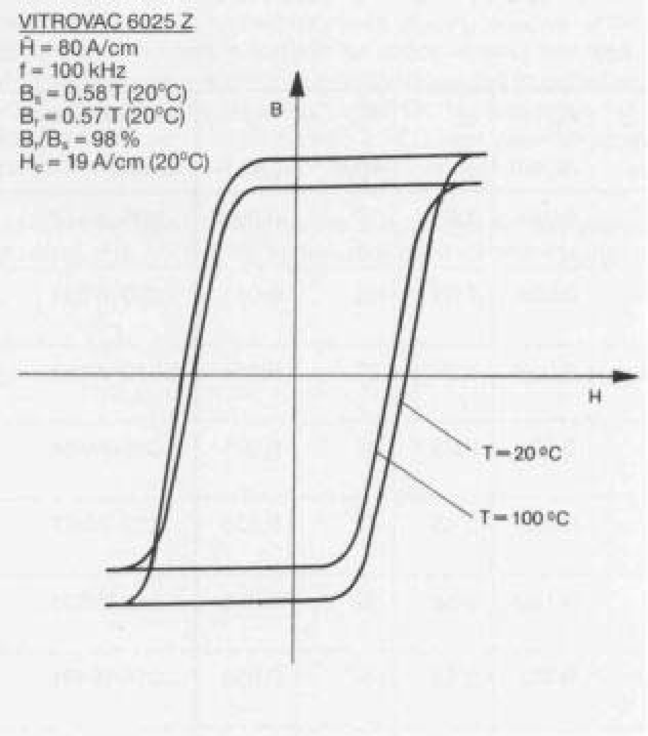


Figure 4: Dynamic Hysteresis Loop (Typical Values)

2.3 Application Temperature Limit and Temperature Characteristics

VITROVAC 6025 Z tape-wound cores have been designed for an upper continuous operating temperature of 90 °C. At higher temperatures, irreversible changes in dynamic coercive force might occur to a minor extent; however, up to approx. 120 °C these are usually within the typical variation range of magnetic characteristics.

The reversible temperature dependence of core losses, coercivity and remanence flux density swing ΔB_{rs} are negligible in most cases (see Figure 5). However, please note that at higher temperatures a lower total flux density swing has to be considered (see Table 1).

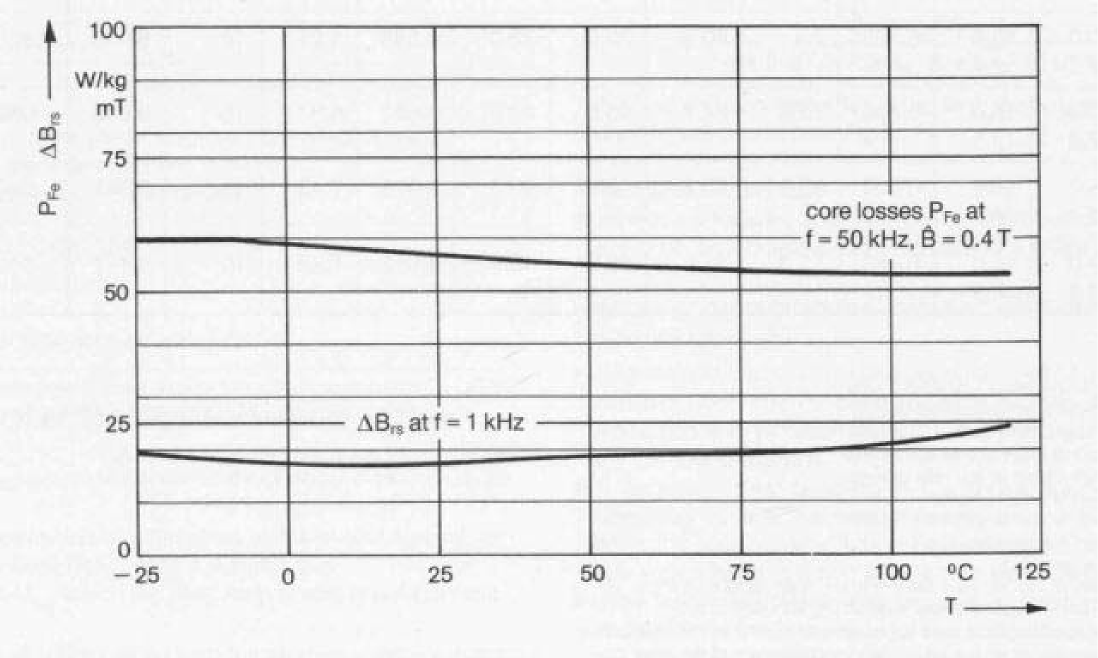


Figure 5: Reversible Temperature Dependence of Core Losses P_{Fe} and Remanence Flux Density Swing ΔB_{rs}

2.4 Core Design and Standard Sizes

Table 3: VITROVAC 6025 Z cores for Mag Amps, standard sizes, Fix 022

d_1 D_1 mm	d_2 D_2 mm	h_1 H_1 mm	A_{Fe} cm^2	l_{Fe} cm	m_{Fe} g	ϕ_{ss} (25°C) µWb	ϕ_{ss},min (90°C) µWb	A_{Cu} cm^2	l_{Cu} cm	R_{th} K/W	$W_a x A_{Fe}$ cm^4	part number T60006-E4
8.0 9.7	4.6 3.1	4.0 5.1	0.054	1.98	0.8	6.2	5.4	0.019	1.91	79	0.004	...008-W462
10.0 11.6	8.0 6.5	4.0 5.1	0.032	2.83	0.7	3.7	3.2	0.082	2.01	56	0.011	...010-W534
10.1 11.6	6.9 5.5	4.5 6.0	0.058	2.67	1.2	6.7	5.8	0.059	2.24	57	0.014	...010-W663
12.8 14.7	9.5 7.9	3.2 4.8	0.042	3.50	1.1	4.8	4.2	0.121	2.23	44	0.021	...012-W464
12.0 14.0	8.0 6.6	4.5 6.2	0.072	3.14	1.7	8.3	7.2	0.085	2.45	47	0.025	...012-W547
12.5 14.0	10.0 8.5	5.0 6.8	0.050	3.53	1.4	5.8	5.0	0.140	2.56	42	0.028	...012-W535
14.0 15.5	8.0 6.5	4.5 5.7	0.108	3.46	2.9	12.4	10.8	0.082	2.53	44	0.036	...014-W481
16.0 17.9	10.0 8.2	6.0 8.2	0.144	4.08	4.5	16.6	14.4	0.131	3.20	34	0.076	...016-W536
17.5 19.1	12.5 10.9	6.0 8.1	0.120	4.71	4.4	13.8	12.0	0.231	3.30	30	0.112	...017-W537
19.0 21.2	15.0 13.0	5.0 7.3	0.080	5.34	3.3	9.2	8.0	0.329	3.17	27	0.106	...019-W539
19.0 21.2	15.0 13.0	10.0 12.3	0.160	5.34	6.6	18.4	16.0	0.329	4.25	24	0.212	...019-W540
20.0 22.6	12.5 10.3	8.0 10.2	0.240	5.1	9.4	27.6	24.0	0.206	4.05	26	0.200	...020-W538
25.0 27.9	16.0 13.6	10.0 12.5	0.360	6.44	17.9	41.4	36.0	0.360	4.96	19	0.523	...025-W541
25.0 27.7	20.0 17.1	10.0 12.9	0.200	7.1	10.9	23.0	20.0	0.568	4.91	18	0.459	...025-W542
30.0 32.8	20.0 17.6	10.0 12.5	0.400	7.85	24.2	46.0	40.0	0.602	5.37	16	0.973	...030-W543
40.0 43.1	25.0 22.4	15.0 18.5	0.900	10.2	70.8	103.5	90.0	0.975	7.43	11	3.547	...040-W544
40.0 43.3	32.0 28.8	15.0 18.3	0.480	11.3	41.8	55.2	48.0	1.612	7.30	10	3.127	...040-W545

d_1 = nominal external diameter of core
d_2 = nominal internal diameter of core
h_1 = nominal height of core
D_1 = maximal external diameter of case
D_2 = minimal internal diameter of case
H_1 = maximal height of case
A_{Fe} = effective iron cross-section in cm^2
l_{FE} = mean iron path length in cm
m_{Fe} = core mass in g
A_{Cu} = effective copper cross-section in cm^2 (calculated by using a copper fill factor 0.33 and a remaining hole ratio of 0.5. The remaining hole ratio is the internal diameter of the wound core (remaining hole) divided by the interior diameter of the case)
l_{Cu} = mean length of a copper turn in cm
R_{th} = heat transfer resistance of an open wound choke with free convection in K/W

$W_a x A_{Fe}$ = core area product in cm^4, used in some other methods of Mag Amp choke design. W_a is the available winding area of the case in cm^2
ϕ_{ss} = total flux in µWb with $\phi_{ss} = 2 \times B_s \times A_{Fe}$.
$\phi_{ss,\ min}$ = total flux in µWb (minimum value at 90°C)

Updated core range and most popular standard sizes can be seen under http://www.vacuumschmelze.com

The standard core sizes for Magnetic Amplifiers are preferably supplied in plastic protective cases, adding silicone rubber (Fix 022). This finish is suitable for direct winding and offers optimum mechanical protection for the core, and thus the best magnetic properties. The resins used for the core cases fulfil for the most part UL94V-0 (with 130°C heat resistance), in particular cases UL94HB (with 120°C heat resistance).

As a further type of finish we are able to offer an epoxy resin coating (Fix 350). Due to the reduction of the magnetic properties this type of fixing is only to be recommended if special core sizes are required.

2.5 Order Information

For your orders please use our part numbers as given in Table 3.
In addition to the delivery of cores, we also offer the possibility of purchasing already wound cores (components). You will find information on these in our product sheet PB-410-2.

3. How to calculate a Mag Amp Choke

Although the Mag Amp choke is a very simple inductive component consisting of a core and some copper turns only, careful consideration of all influencing parameters is necessary to achieve a cost optimized design without too high temperature rise of the choke.

variables:

effective cross-section A_{Fe} (core size)
number of turns N wire diameter d_{Cu}
winding area A_{Cu}

influencing factors:

circuit design
output voltage U_1
voltage drops in magnetic amplifier controlled circuit
voltage drops in main circuit
possibly: short-circuit-proof design

to be taken into account:

magnetic core losses
copper losses
dead time" of magnetic amplifier choke

3.1 Selection of Core Size and Number of Turns

Starting parameters are

- the wire size (which is determined by the output current, for example current density S = 4 A/mm^2) and

- the voltage U_{Reg} which the Mag Amp choke should control.

U_{Reg} can be calculated for a given transformer output voltage $\hat{u}_{min}$ where there are no short-circuit requirements by:

$$U_{Reg} = \alpha \times \tau_{max} \times \hat{u}_{min} - U_1$$

and for a short-circuit-proof design by:

$$U_{Reg} = \alpha \times \tau_{max} \times \hat{u}_{min}$$

τ_{MAX} is then the maximum duty cycle ratio of the primary switching transistor, α = 1 for forward converter principle, α = 2 for push-pull.

If the transformer voltage is not fixed, Appendix 4.2 gives some hints on how to find a suitable value.

- The required number of turns can be calculated by:

$$N \geq \frac{10 \times U_{Reg}\,(V)}{\alpha \times 0.8(T) \times K \times A_{Fe}\,(cm^2) \times f\,(kHz)}$$

K is a correction factor for ΔB to limit the temperature rise due to core losses (see Figure 6).

- start with a small core
- increase core size, until the required number of turns can easily be distributed around the core in a single layer.

Now “empirical optimization" can start. Here, the following notes may be helpful:

- If the magnetic amplifier choke becomes too hot during open circuit or short-circuit operation, iron losses are the reason. A solution is to increase either the iron cross-section A_{Fe} or the number of turns N.
- If excessive heat build-up in the choke during full load operation occurs, the copper losses are too high. In this case, the wire diameter has to be increased. The next core size with a larger winding area is then perhaps necessary.
- “Too high" secondary voltages of the transformer cause excessive full load operation losses. If this occurs the choke will still need to correct this "excess" voltage, even under full load operating conditions, thus causing additional losses. A correction of the turn ratio (if possible) can solve this problem. Please see also Appendix 4.2.

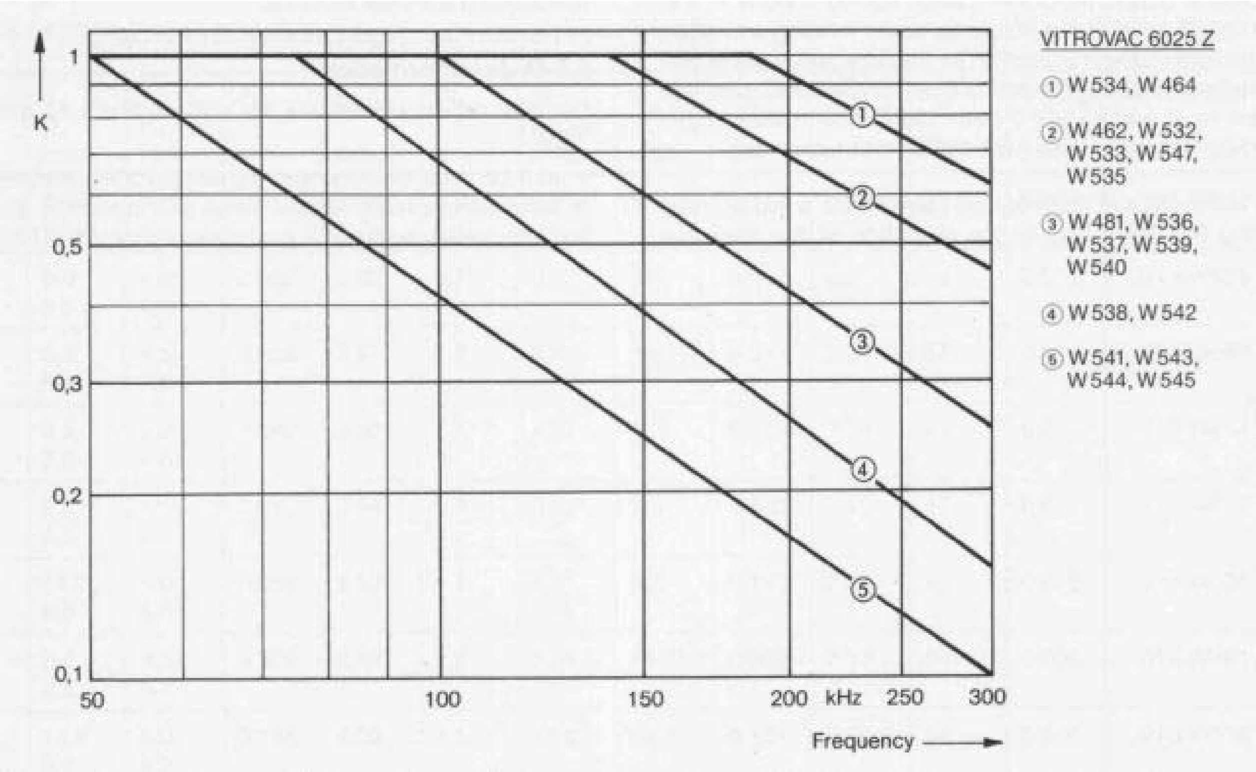


Figure 6: Empirical Correcting Factor K for a Temperature Rise of about 30 K

3.2 Estimation of the Control Current

The control current I_s is given by:

$$I_s = \frac{H_s\ (\mathrm{mA/cm}) \times l_{Fe}\ (\mathrm{cm})}{N}$$

The reset field strengh H can be estimated by:

$$\Delta B_{Reg}\ (\mathrm{T}) = \frac{10 \times U_{Reg}\ (\mathrm{V})}{\alpha \times N \times A_{Fe}\ (\mathrm{cm}^2) \times f\ (\mathrm{kHz})}$$

with:

$$H_s\ (\mathrm{mA/cm}) \approx 0.47 \times f\ (\mathrm{kHz})^{1.25} \times \frac{\Delta B_{Reg}\ (\mathrm{T})}{0.8}$$

3.3 Example:

Single forward converter principle; transformer output voltage (amplitude) $\hat{u}_{min}$ = 12 V; switching frequency f = 150 kHz; duty cycle τ_{max} = 0.5; output current I_1 = 10 A (RMS); U_1 = 3.3 V.

Not short-circuit proof:

- Required cross section per wire with current density S = 4 A/mm^2: 2.5 mm^2
- Voltage which the Mag Amp choke should control:

$U_{Reg} = \alpha \times \tau_{max} \times \hat{u}_{min} - U_1$

U_{Reg} = 1 x 0.5 x 12 V – 3.3 V = 2.7 V

First approach with core T60006-E4008-W462:

8 x 4.6 x 4 mm
A_{Fe} = 0,054 cm^2
l_{Fe} = 1.98 cm
K = 1 (value taken from fig. 6)

Short-circuit proof:

- Required cross section per wire with current density S = 4 A/mm^2: 2.5 mm^2
- Voltage which the Mag Amp choke should control:

$U_{Reg} = \alpha \times \tau_{max} \times \hat{u}_{min}$

U_{Reg} = 1 x 0.5 x 12 V = 6 V

First approach with core T60006-E4012-W535:

12.5 x 10 x 5 mm
A_{Fe} = 0,05 cm^2
l_{Fe} = 3.53 cm
K = 1 (value taken from fig. 6)

- Minimum number of turns:

$$N \geq \frac{10 \times U_{Reg}\,(V)}{\alpha \times 0.8\,(T) \times K \times A_{Fe}\,(cm^2) \times f\,(kHz)}$$

$$N \geq \frac{10 \times 2.7\,V}{1 \times 0.8\,T \times 1 \times 0.054\,cm^2 \times 150\,kHz} = 4.2$$

The available copper winding area A_{Cu} according to Table 3 is about 2 mm^2. Thus there is no possibility to wind 5 turns of copper wire with cross section 2.5 mm^2.

Next approach with core T60006-E4012-W535:

12.5 x 10 x 5 mm

A_{Fe} = 0.05 cm^2
l_{Fe} = 3.53 cm
K = 1 (value taken from fig. 6)

- Minimum number of turns:

$$N \geq \frac{10 \times 2.7\,V}{1 \times 0.8\,T \times 1 \times 0.05\,cm^2 \times 150\,kHz} = 4.5$$

The available copper winding area A_{Cu} according to Table 3 is about 14 mm^2. Empirical testing now can start with this core.

- Calculation of required control current

$$\Delta B_{Reg}\,(T) = \frac{10 \times U_{Reg}\,(V)}{a \times N \times A_{Fe}\,(cm^2) \times f\,(kHz)}$$

$$\Delta B_{Reg}\,(T) = \frac{10 \times 2.7\,V}{1 \times 5 \times 0.05\,cm2 \times 150\,kHz} = 0.72\,T$$

$$H_s\,(mA/cm) \approx 0.47 \times f\,(kHz)^{1.25} \times \frac{\Delta B_{Reg}\,(T)}{0.8}$$

$$H_s\,(mA/cm) \approx 0.47 \times 150^{1.25}\,kHz \times \frac{0.72\,T}{0.8}$$

$$H_s\,(mA/cm) \approx 222\,\frac{mA}{cm}$$

$$I_s = \frac{H_s\,(mA/cm) \times l_{Fe}\,(cm)}{N}$$

$$I_s = \frac{(222\,mA/cm \times 3.53\,cm)}{5} = 157\,mA$$

Allow for some margin.

- Minimum number of turns:

$$N \geq \frac{10 \times 6\,V}{1 \times 0.8\,T \times 1 \times 0.05\,cm^2 \times 150\,kHz} = 10$$

The available copper winding area A_{Cu} according to Table 3 is about 14 mm^2. Thus there is no possibility to wind 10 turns of copper wire with cross section 2.5 mm^2.

Next approach with core T60006-E4017-W537:

17.5 x 12.5 x 6 mm

A_{Fe} = 0.12 cm^2
l_{Fe} = 4.71 cm
K = 0.6 (value taken from fig. 6)

- Minimum number of turns:

$$N \geq \frac{10 \times 6\,V}{1 \times 0.8\,T \times 0.6 \times 0.12\,cm^2 \times 150\,kHz} = 7$$

The available copper winding area A_{Cu} according to Table 3 is about 23.1 mm^2. Empirical testing now can start with this core.

- Calculation of required control current

$$\Delta B_{Reg}\,(T) = \frac{10 \times 6\,V}{1 \times 7 \times 0.12\,cm2 \times 150\,kHz} = 0.48\,T$$

$$H_s\,(mA/cm) \approx 0.47 \times 150^{1.25}\,kHz \times \frac{0.48\,T}{0.8}$$

$$H_s\,(mA/cm) \approx 148\,\frac{mA}{cm}$$

$$I_s = \frac{(148\,mA/cm \times 4.71\,cm)}{7} = 100\,mA$$

Allow for some margin.

4. Appendix

4.1 Core and Copper Losses in Theory

Before or in addition to experimental testing, the following approximation formula can be used to check the temperature rise due to core and copper losses:

Core losses P_{Fe} (approximation):

$$P_{Fe}\ (W / kg) = 0.021 \times f^{2} \times \Delta B_{Reg}^{2} + 0.109 \times f^{1.5} \times \Delta B_{Reg}^{1.5}$$

with f in kHz and ΔB_{Reg} in T.

Temperature rise ΔT_{Fe}:

$$\Delta T_{Fe}\ (K) = R_{th}\ (K / W) \times P_{Fe}\ (W / kg) \times m_{Fe}\ (kg)$$

Copper losses P_{Cu} (approximation not considering skin and proximity effects):

$$P_{Cu}\ (W) \approx \frac{I_{out}\ (A)^2 \times N^2 \times l_{Cu}\ (cm) \times \rho_{Cu}\ (\Omega m)}{20 \times A_{Cu}\ (cm^2)}$$

Temperature rise ΔT_{Cu}:

$$\Delta T_{Cu}\ (K) = R_{th}\ (K / W) \times P_{Cu}\ (W)$$

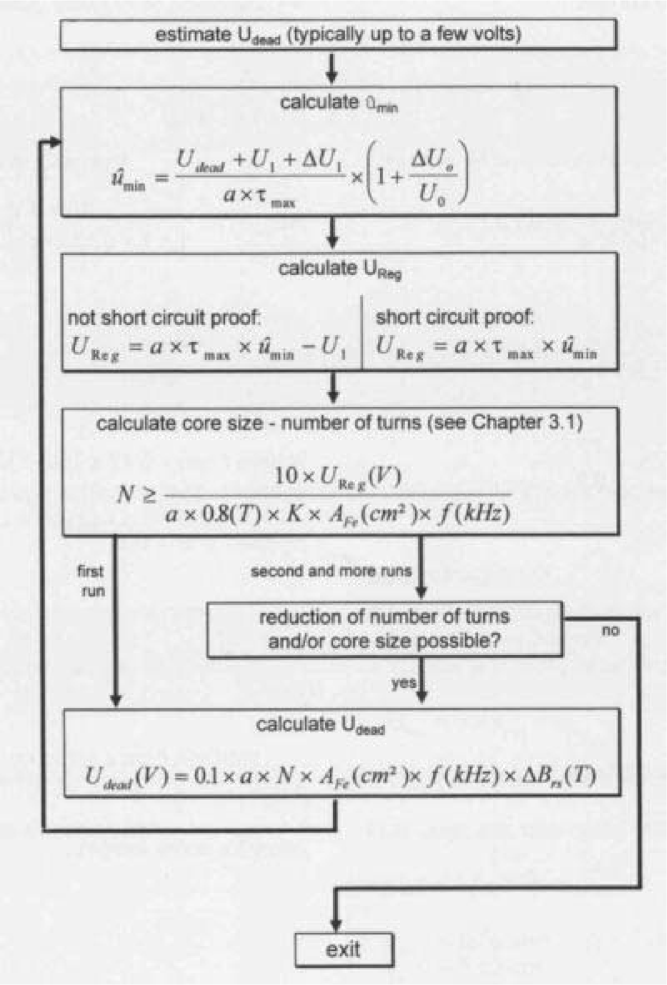
I_{out} is the maximum output current (direct current). Approximate values of the heat-transfer resistance of an open wound choke R_{th} with regard to free convection are listed in Table 3, as well as A_{Fe}, A_{Cu}, l_{Fe}, and l_{Cu}. The specific electrical resistance of copper ρ_{Cu} is given for T= 80-100 °C as $\rho = 2.3\ \mu\Omega m$.

The total losses will be smaller than the sum of magnetic reversal losses and copper losses as in full load operation (maximum copper losses) the control current and thus ΔB_{Reg} and P_{Fe} will be particularly low. Theoretical definition of the worst case, i.e. the operating condition with maximum total losses, is difficult; for this reason, we recommend proceeding empirically.

4.2 Notes on more Theoretical Fine Tuning

Some more theoretical ,,fine tuning" is possible, if the transformer output voltage can be adjusted. Then, the following iteration process may be used.

Please see Figure 7 for explanation of the voltages and voltage drops in a typical SMP's configuration.



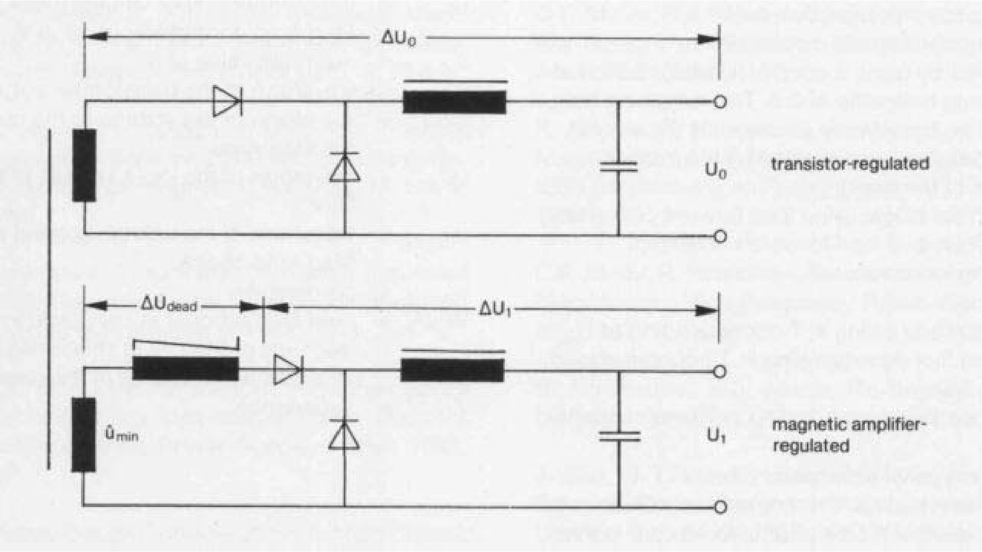


Figure 7: Principle Circuit with Voltages and Voltage Drops

4.3 Notes on Regulation Circuits

Several different principles of regulation circuits are well-established. To describe them all would be beyond the scope of this brochure. The interested readers are referred to the relevant literature. In the following, some general remarks are given and two well known principles are summarized.

The volt seconds applied to the Mag Amp during the switch-off period of the transformer secondary circuit adjust the operating point of the Mag Amp due to the desired delay of the following pulse. This is done by either ”voltage-" or “current-reset". The preferred type of reset depends mainly on the design of the reset circuit and its output impedance, respectively.

For example with a shunt controller 1C 431 very precise regulation circuitries are possible which are easy to implement and attractive in price. Very compact Mag Amp regulated switch mode power supplies in a modular design can easily be realized by using an integrated controller. The UC1838 for example has been designed specifically as a controller for Mag Amp switching regulators and provides a low-cost, easy to use, single chip solution.

5. Definition of Terms

A_{Fe} = effective iron cross-section in cm^2
A_{Cu} = effective copper cross-section in cm^2 (calculated by using a copper filling factor 0.33 and a remaining hole ratio of 0.5. The remaining hole ratio will be the internal diameter of the wound core (remaining hole) divided by the interior diameter of the case)
a = factor = 1 for single cycle feed forward converters, = 2 for push-pull feed forward converters
B_s = saturation induction
B_r = remanence
ΔB_{Reg} = the flux density swing in T corresponding to U_{Reg}
ΔB_{ss} = maximum flux density swing in T (recommended: $\Delta B_{ss} \leq 0.8$ T)
ΔB_{rs} = remanence flux density swing in T (see magnetic quality)
$\hat{B}$ = flux density amplitude (peak value) in T
d_1 = nominal external diameter of unfixed core in mm
d_2 = nominal internal diameter of unfixed core in mm
D_1 = nominal external diameter of fixed core in mm
D_2 = nominal internal diameter of fixed core in mm
f = frequency in kHz
f_p = pulse repetition frequency in kHz
H_1 = nominal height of fixed core in mm
h_1 = nominal height of unfixed core in mm
H_s = reset field strength in mA/cm
I_{out} = maximum output current (direct current) in A
I_s = control current in mA
i1 = waveform of the current of the Mag Amp regulated circuit
K = correcting factor for taking into account magnetic reversal and copper losses (see Figure 6)
l_{Cu} = mean length of a copper winding in cm
l_{Fe} = mean iron path length in cm
λ_s = saturation magnetostriction
m_{Fe} = core mass in g
N = number of turns
P_{Fe} = magnetic reversal losses of the core in W/kg
P_{Cu} = copper losses of the winding in W
Φ_{ss} = total flux in µWb with $\Phi_{ss} = 2 \times B_s \times A_{Fe}$
$\Phi_{ss,min}$ = total flux in µWb (minimum value at 120°C)
Φ_{Reg} = magnetic flux corresponding to ΔB_{Reg}
ρ_{Cu} = specific electrical resistance of copper ($\rho_{Cu} \approx 2.27 \cdot 10^{-5}\,\Omega$m at T = 80-100 °C)
R_{th} = heat-transfer resistance of an open wound choke with free convection in K/W
S = max. permissible current density of wire
T_C = Curie temperature
ΔT_{Fe} = maximum excess temperature of the core in K
ΔT_{Cu} = maximum excess temperature of the winding in K
Δt_{Reg} = delay time of the Mag Amp choke corresponding to ΔB_{Reg}
Δt_{dead} = dead time of the core corresponding to ΔB_{rs}
τ_{max} = maximum pulse duty ratio of the primary switching transistor
U_{Reg} = maximum voltage in V to be controlled by the magnetic amplifier choke
U_0 = nominal output voltage in V (Figure 1 and 7) of main output (transistor regulated)
U_1 = nominal output voltage in V (Figure 1 and 7) of magnetic amplifier regulated output
ΔU_0 = voltage drops in V (Figure 1 and 7) in main circuit
ΔU_1 = voltage drops in V (Figure 1 and 7) in magnetic amplifier-regulated circuit (without voltage drop across the magnetic amplifier choke)
ΔU_{dead} = minimum voltage drop in V across magnetic amplifier choke („dead time“)
$\hat{u}$ = transformer output voltage (peak value) for the Mag Amp controlled output in V
$\hat{u}_{min}$ = minimum value of $\hat{u}$
u1 = waveform of the transformer output voltage
u2 = waveform of the voltage at the output side of the Mag Amp
u3 = waveform of the input voltage of the smoothing filter
u_{MagAmp} = waveform of the voltage applied to the Mag Amp choke
µ = permeability
$W_a{*}A_{Fe}$ = core area product in cm^4, used in some other methods of Mag Amp choke design. W_a is the available winding area of the case in cm^2
Z = impedance

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J. S. Elias, Amorphous Magnetic Materials - Part III: High-Frequency Mag-Amp Output Regulator - Reset and Control Circuit Designs , PCIM issue October 1993