Optimal Design of a DC Reset Circuit for Pulse Transformers

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***Abstract* - Pulsed power systems often use a pulse transformer to generate high voltage pulses. In order to improve the utilization of the transformer core material usually a dc reset circuit is applied which results in a smaller transformer volume. However, by the use of a reset circuit additional losses are generated. Usually, in the dimensioning of the reset circuit only the copper losses are considered but these are only a small part of the whole losses. In this paper analytical equations for calculating the losses in the pulsed power system and a method for optimizing a dc reset circuit are presented. With the optimization method a reset circuit for an existing system is designed and the results are validated by simulation and by measurements.**

I. INTRODUCTION

Pulsed power systems are used in a wide variety of applications, for example in particle accelerators, radar, medical radiation (cancer therapy), sterilization systems (drinking water) or ion implantation systems (semiconductor manufacturing). In these applications pulses of several *kV* and *MW* are generated and the duration of the single pulse varies from a few *ns* to some *ms*. The requirements on the generated pulses regarding for example rise/fall time, overshoot, pulse flatness and pulse energy are high and can vary over a wide range. Therefore pulsed power systems are built in many different topologies [1]-[3].

A lot of pulsed power systems use a pulse transformer to step up the voltage as shown in **Fig. 1**. The design of a pulse transformer is comparable to high frequency transformers which are widely used in power electronics. But in contrast to many converter topologies using HF-transformers pulse power systems only generate repeated unipolar voltage pulses. In this case the core material of the pulse transformer is not optimally utilized.

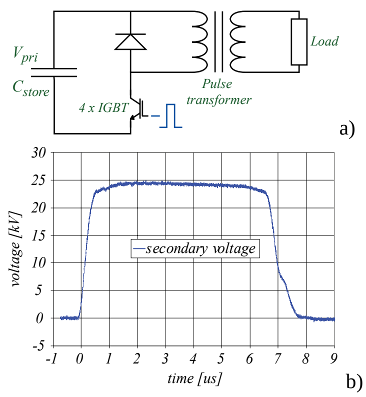

Figure 1: a) Possible schematic of a pulse modulator and b) corresponding 25kV pulse.

The unipolar voltage pulse leads to a unipolar flux swing in the core. This results in a core volume approximately twice as big as with a bipolar excitation. A bipolar operation of the transformer could be achieved with a reset circuit which premagnetizes the core to a negative flux density before the pulse.

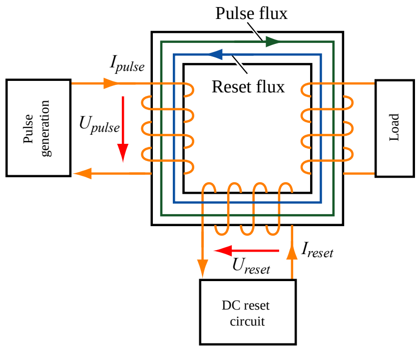

Figure 2: Block diagram of a pulsed power system with reset circuit and total flux in the transformer core.

In the literature different active [4] and dc reset circuit concepts are discussed. The active reset circuits are more complex than the dc ones, because additional components are required. However, energy recovery from snubber circuits can be realized with active reset circuits.

The most common method to reset transformer cores is the dc reset circuit, where a dc current is used. This current can be supplied to the primary, secondary or to a tertiary winding. In order to keep the considerations more general, a tertiary winding, also called reset winding, is used in this paper. The current of the dc reset is flowing in a direction that generates a magnetic flux which is in the opposite direction than the flux induced by the voltage pulse (cf. **Fig. 2**).

With the reset circuit a flux swing from a negative to a positive operation point instead form zero to a positive operation point (cf. A_1, A_2 and B_1 in **Fig. 5**) is possible. Therefore, the total flux peak-to-peak amplitude can be increased up to twice the value B_{sat} without a reset circuit. This enables a significant reduction of the core cross section because this mainly determined by the maximum flux density.

The dc current for the reset circuit is generated by an external power supply as shown in the equivalent circuit in **Fig. 3**. As later will be explained in detail, a large inductor is placed between the reset winding of the transformer and the power supply to protect the supply from high voltage pulses. The inductor, which reaches values of several mH, is one of the largest components of the dc reset circuit.

In the literature [5]-[11] many pulsed power systems are presented which use a dc reset circuit to improve transformer utilization. But there is no information about the design or in particular the optimisation of the reset circuit given. A more detailed description of the dc reset circuit for a magnetic pulse compression is discussed in [12] where also no information about the optimal dimensioning is presented.

Since the reset circuit has a significant influence on the volume and the efficiency of the pulse modulator, analytic design equations for the reset circuit are presented in the following. With these equations the volume and/or the efficiency of a pulse modulator is optimised in this paper which results in a smaller pulse transformer volume and optimal design of the reset circuit.

First, the dc reset is described in detail in **Section II**. For optimising the volume/efficiency of the reset circuit analytic equations for the losses are required. These are presented in **Section III** followed by the optimal dimensioning in **Section IV**. The results extracted form Section IV are verified in **Section V** where the analytic results are compared with simulations and measurements. **Section VI** describes how the optimal choke can be realized. In **Section VII** the systems with and without reset circuit are compared. Finally, a conclusion and topics of future research are presented in **Section VIII**.

II. The DC Reset Circuit

The operation of the dc reset circuit is analyzed for the pulsed power system shown in Fig. 3. The most important part is the non-ideal pulse transformer which matches the pulse generator on the primary side to the load on the secondary side. The numbers of turns are N_{pri} for the primary and N_{sec} for the secondary. The pulse generator itself is simply modelled by an ideal pulse source U_{pulse} with inner resistance R_{int} and the freewheeling Diode D_f with forward voltage U_f, because these do not significantly influence the design of the reset circuit.

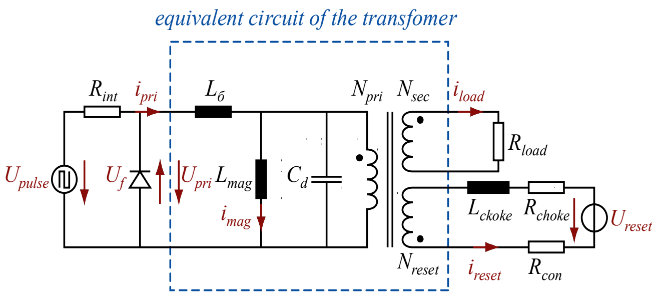

Figure 3: Detailed circuit of a pulsed power system.

The third winding is connected to the reset circuit which is represented by a series connection of the voltage source U_{reset} and the inductor L_{choke} with resistance R_{choke}. The pulse transformer is modelled with the parasitic elements like leakage inductance L_σ, stray capacitance C_d (calculation cf. [13]) and the magnetizing inductance L_{mag}.

In **Fig. 4** the input voltage U_{pulse} during an operation cycle is shown. Neglecting the source resistance R_{int} this voltage is equal to the primary voltage U_{pri}. One cycle of the voltage could be split into the three time sections S_1 - S_3 shown in Fig. 4.

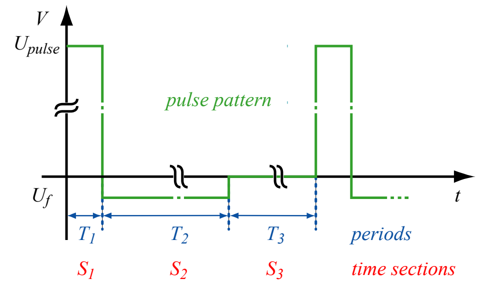

Figure 4: Common pulse pattern for pulsed power systems.

The period T_1 in time section S_1 is equal to the pulse width. T_2 is the time after the pulse in which the freewheeling diode is conducting and T_3 is the period between the end of freewheeling and the next pulse.

At the start up when the system is turned on, the currents in the windings are zero and – based on amperes law (1) - the magnetic field H in the core is also zero.

$$H = \frac{N \cdot I}{l_e} \tag{1}$$

Depending on the core material the flux density in the core is B_{rem} and the starting point of the system in the B-H curve is A_1 as shown in Fig. 5.

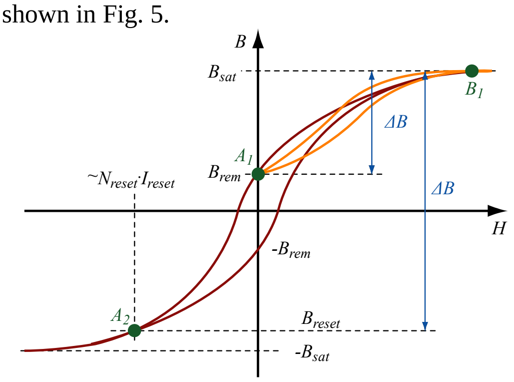

Figure 5: B-H curve with and without premagnetization.

Assuming U_{pulse} = 0, the current through the inductor and the magnetizing inductance is rising to I_{reset} as soon as the reset circuit is turned on. With equation (1) the dc current I_{reset} leads to a constant H-field and therefore to a constant flux density B_{reset} in the core (cf. Fig. 5). During start up the operating point moves from A_1 to A_2 where H_{reset} and B_{reset} can be expressed as

$$H_{reset} = \frac{N_{reset} I_{reset}}{l_e} \quad \text{and} \quad B_{reset} = \mu_0 \mu_r H_{reset} \tag{2}$$

Assuming H_{reset} is fixed due to the hysteresis curve of the core material increasing the number of turns N_{reset} results in a smaller reset current I_{reset} and vice versa according to (2). As soon as the system reaches operating point A_2 an output pulse could be generated (section S_1). With the assumption of a rectangular voltage pulse Faraday's law can be simplified to

$$U_{pulse} = N_{pri} A_{core} \frac{\Delta B}{\Delta t} \quad \text{with} \quad \Delta t = T_1 . \tag{3}$$

The voltage pulse results in a change of flux density ΔB which can be maximal $2 \cdot B_{sat}$ (with B_{sat}=B_{reset}) for a system with dc reset circuit.

A system without dc reset circuit is limited to B_{sat}–B_{rem} i.e. from A_1 to B_1 and back (there the hysteresis curve must be scaled to the core size for a system without reset circuit). By this reduction of the flux swing a core cross section twice as big as with reset must be used.

In the following, the design of the dc reset is carried out with respect to a symmetric H-field / magnetizing current swing from $-I_{reset}$ to I_{reset} because this results in an optimal usage of the core material. Therefore the dc reset current I_{reset} is equal to half of the total change of I_{mag}.

In section S_1 the voltage pulse is also transformed to the tertiary winding. Depending on the turn ratio N_{reset}/N_{pri} the voltage transformed to the reset circuit can be large. To protect the external low voltage supply a large inductance L_{reset} is placed between transformer and supply. Even though the inductance of the choke is large some energy is stored in the choke during S_1 which results in an increase of the reset current of ΔI_{reset} (cf. **Fig. 6**).

After the pulse, in section S_2, the energy which is stored in the leakage inductance, magnetizing inductance and the additional energy in the reset choke has to be dissipated through the freewheeling diode and the load R_{load}. The demagnetization of the magnetizing inductance and the reset choke is due to the approximately constant voltage U_f almost linear. Only the leakage inductance is demagnetized much faster, because the major part of the energy is dissipated in the load resistor R_{load}.

As soon as the magnetizing current I_{mag} reaches zero the reset current starts to commutate from the diode D_f to the magnetizing inductance and premagnetizes the core again. The detailed current waveforms for I_{mag}, I_{reset}, I_{load} and I_f are plotted in Fig. 6.

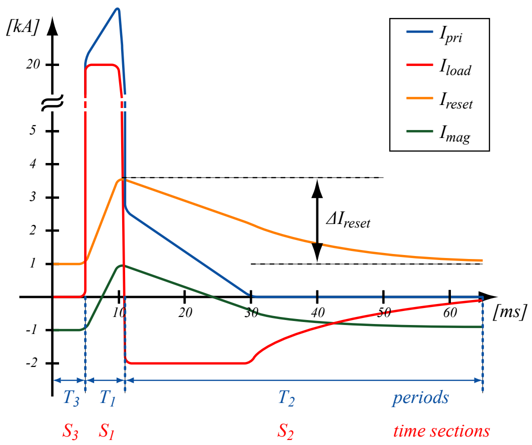

Figure 6: Current waveforms during pulse and freewheeling period.

III. Loss Calculation Methods

As explained in Section II most of the energy stored in the magnetic components is dissipated in the freewheeling path during section S_2. A significant part of these losses, which depends mainly on the inductance L_{choke} and the number of turns N_{reset}, is caused by the reset circuit. Therefore, a loss analysis is carried out in the following in order to optimize the reset circuit (cf. **Fig. 7**) - especially the design of the choke.

To achieve a large inductance value for the reset choke a magnetic core is needed. Therefore, the flux density in the core must be analyzed to determine the optimal number of turns.

In steady state, which corresponds to section S_3, a DC current is flowing through the choke. The constant current generates a constant H-field / flux density $B_{chokeDC}$ in the core as shown in **Fig. 8**.

In section S_1 the pulse which is also transformed to the tertiary winding causes a large voltage drop across the reset choke which results in an increasing flux density $B_{chokeAC}$ and an increasing current I_{reset}+ΔI_{reset}.

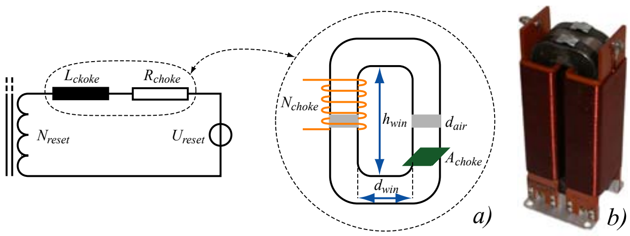

Figure 7: a) Reset circuit and b) a realization of a choke.

The maximum allowed flux is defined by

$$\Phi_{\max} = A_{choke} B_{\max} \tag{4}$$

and in order to avoid saturation the following equation must be fulfilled

$$\Phi_{\max} \geq \Phi_{chokeDC} + \Delta\Phi_{chokeAC} \,. \tag{5}$$

Using (3), (4) and (5) results in

$$A_{choke} B_{\max} \geq \mu_{eff} A_{choke} \frac{N_{choke} I_{reset}}{l_{choke}} + \frac{N_{reset} U_{pri} T_{pulse}}{N_{choke} N_{pri}} \,. \tag{6}$$

There, the effective permeability μ_{eff} is defined by the air gap length d_{air}.

For a given pulsed power system the free parameters are the numbers of turns N_{reset} and N_{choke} and the core dimensions A_{choke} and l_{choke}. The dc current I_{reset} is determined by the magnetizing current I_{mag} and the number of turns N_{reset} of the reset winding on the pulse transformer.

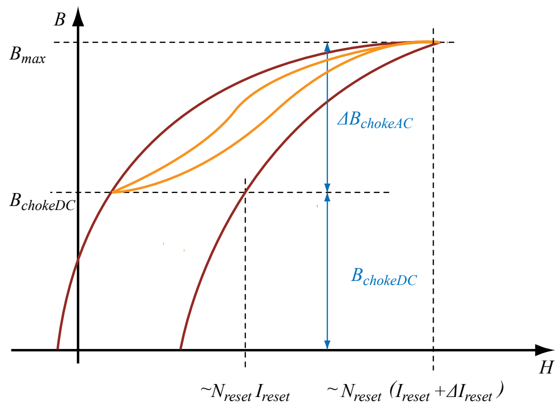

Figure 8: Hysteresis of the inductor core L_{choke}.

In the next step the losses of the system are calculated. This could be done by two different approaches. With the first one the overall losses are calculated by summing up the losses in the magnetic components, the copper losses and the losses in the supplies.

The second possibility is to calculate the difference between the input and the output power for one cycle. In the following the equations for the first approach are presented. The equations for the second approach are presented in the appendix. In both approaches it is assumed that the input voltage pulse and also the diode are ideal.

A. *Overall Losses (stored energies)*

The total losses result of dc copper losses, losses in the power supplies and losses due to stored magnetic energy in the parasitic elements. The losses have to be dissipated through the freewheeling path. Ac copper losses, the losses due to the parasitic capacitance C_D and the core losses are neglected in the following, because the energy in C_D is wasted in the load resistor and the other losses do not influence the design of the reset circuit.

The losses of the magnetic components are calculated by comparing the energy stored in the system at two different point of time. One point in time is just before the pulse generation and the second just after the pulse. The difference of the energy is equal to the energy dissipated by the magnetic components because no energy is recovered.

In **Fig. 9** the energies stored in the inductances during one cycle are displayed. Before the voltage pulse is generated a dc current is flowing through the choke and the magnetizing inductance. Therefore, the energy at this time is

$$E_{before\_pulse} = \frac{1}{2} L_{choke} I_{reset}^{\ 2} + \frac{1}{2} L_{mag} \left(\frac{N_{reset}}{N_{pri}} I_{reset} \right)^2 . \qquad (7)$$

Now the pulse is generated and energy is transferred to the leakage inductance and the choke. If the flux swing of the transformer is symmetric ($I_{mag} = -I_{reset}$ at the end of the pulse) the magnetizing inductance is demagnetized in the first half of the pulse and remagnetized to the same absolute value at the second half of the pulse (cf. Fig 9).

Hence, after the pulse the energy stored in the leakage inductance, magnetizing inductance and dc choke is

$$E_{after\_pulse} = \frac{1}{2} L_{choke} \left(I_{reset} + \Delta I_{reset} \right)^2 + \frac{1}{2} L_{mag} \left(\frac{N_{reset}}{N_{pri}} I_{reset} \right)^2 + \frac{1}{2} L_{\sigma} I_{pri}^{\ 2} \qquad (8)$$

$$\text{with } i_{pri}(t) = i_{load}(t) + i_{mag}(t) + \frac{N_{reset}}{N_{pri}} \Delta i_{reset}(t) . \qquad (9)$$

The difference of the two energies is dissipated through the freewheeling path and the load before the next pulse is triggered. Therefore, the losses in the magnetic components are

$$P_{mag} = \left(E_{after\_pulse} - E_{before\_pulse} \right) f_{rep} \qquad (10)$$

The copper losses have to be calculated for each time section independently. These losses consist of the copper losses in the choke, in the tertiary winding and in the connectors/cables of the reset circuit. Losses in the secondary winding are independent of the design of the reset circuit and are not considered during the optimisation.

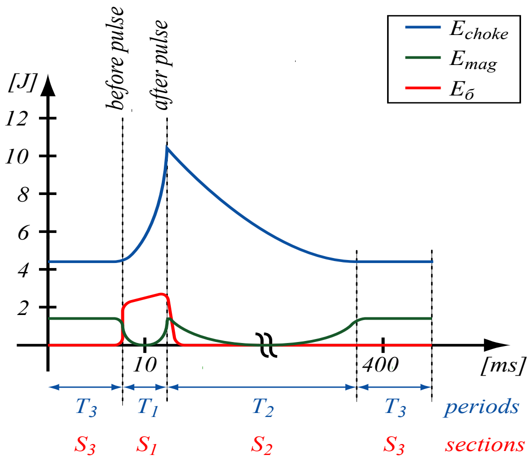

Figure 9: Energy stored in the magnetic components.

Generally, the dc copper losses can be calculated as

$$R_{cu} = \rho_{cu} \frac{l_{cu}}{A_{cu}} , \qquad (11)$$

where l_{cu} is equal to the mean turn length of the core times N_{reset} / N_{choke} for the tertiary winding / choke.

In section S_3 the current through the winding is a dc current (cf. Fig. 6) and the copper losses can be calculated by

$$P_{cu\_S3} = R_{choke} I_{reset}^{\ 2} \frac{T_3}{T_{rep}} . \qquad (12)$$

Because of the rectangular voltage pulse in sections S_1 and S_2 a triangular ac current is added to the dc reset current.

This results in the following copper losses for sections S_1 and S_2

$$P_{cu\_Sx} = \frac{1}{T_{rep}} R_{choke} \int_0^{T_x} \left(I_{reset} + \frac{\Delta I_{reset}}{T_x} t \right)^2 dt \qquad (13)$$

with x = 1 or 2. Period T_1 is equal to the pulse width and T_2 can be calculated by the equivalence of the voltage time product.

$$T_2 = \frac{U_{pri} T_1}{U_f} \qquad (14)$$

The resistance due to the cables/connectors is independent of the number of turns and is assumed to be a constant value R_{con}.

In addition to the magnetic and copper losses the power supplies also have an influence on the optimal design. If the design of the supply is already known, an internal voltage source U_{int} and an internal resistance R_{int} can be substituted for the power supply. Otherwise, the losses of the supply can be modelled with an output efficiency η between 0.9 and 0.95. The general losses of the former approach results in

$$P_{ps\_int} = U_{int} I_{out} + R_{int} I_{out}^{\ 2} \qquad (15)$$

and the general losses of the second approach leads to

$$P_{ps\_int} = U_{out} I_{out} (1 - \eta) . \qquad (16)$$

IV. Optimal DC Reset Circuit Design

With the derived equations the losses now can be expressed as a function of the number of turns N_{reset}, N_{choke} the cross section A_{choke} and the window dimensions h_{win} and d_{win} of the choke.

For the choke in **Fig. 10** for example the maximal wire diameter would be

$$d_{wire} = \frac{2h_{win}}{N_{choke}} . \qquad (17)$$

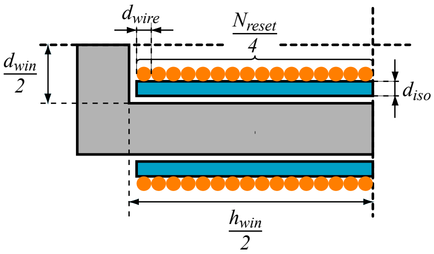

Figure 10: Quarter of the cross section of the choke.

During the optimisation additional constraints like maximal current density in the wire or minimal isolation thickness d_{iso} between core and coil must be considered. In order to limit the optimization problem to two dimensions - N_{reset} and N_{choke} – the core of the reset choke is fixed (here: *AMCC1000* from *METGLAS*). In **Fig. 11** the resulting losses depending on N_{reset} and N_{choke} are plotted for a pulsed power system with the specification given in **Table 1**.

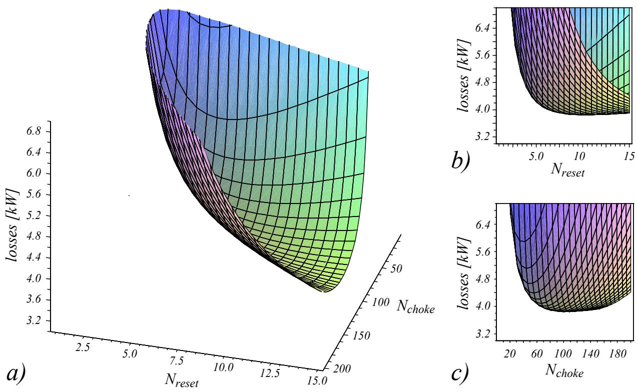

Figure 11: a) 3D Plot of total losses depending on N_{choke} and N_{reset}. Losses depending on (b) N_{reset} and on (c) N_{choke}.

There, minimal losses of 4100W are achieved with N_{reset} = 50 and N_{choke} = 100. The reset current I_{reset} is therefore 50A. The inductor has an air gap d_{air} = 4mm per leg and a wire diameter d_{wire} = 2.1mm. This results in an inductance L_{choke} of 3.5mH.

In **Table 2** it can be seen that the major part of the losses is generated in the magnetic components, especially in the choke. Usually, only the copper losses in the choke are considered but these are only a small part of the overall losses. Therefore, it is important to take the overall system into account.

Table 1: Specification of Power Modulator.

Pulse voltage U_{pulse}	*1kV*
Pulse duration T_{pulse}	*5us*
Primary current I_{pri}	*20kA*
Repetition rate f_{rep}	*500Hz*
Number of turns on the primary N_{pri}	*1*
Magnetizing inductance L_{mag}	*2.5uH*
Magnetizing current I_{mag}	*2kA*
Resistance of connectors / cables R_{int_rs}	*0.1Ω*
Choke core	*AMCC1000*

Table 2: Individual and total losses.

Total copper losses	*450W*
Losses in power supplies, cables and connectors	*450W*
Losses due to magnetic components	*3200W*
Total losses	*4100 W*

V. Validation by Simulation and Measurement

In order to validate the analytical equations different calculated results are compared with simulation and measurement results acquired with the system shown in **Fig. 12.**

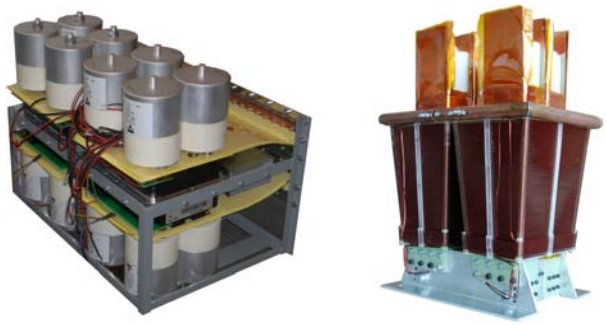

Figure 12: Pulse generator (45cm *x* 30cm *x* 20cm, pulse power density: 500kW/ltr.) and pulse transformer.

Fig. 13 shows the losses generated by the reset circuit for different choke inductances L_{choke} and constant copper resistance R_{reset} of the reset circuit obtained by measurement, simulation and calculation.

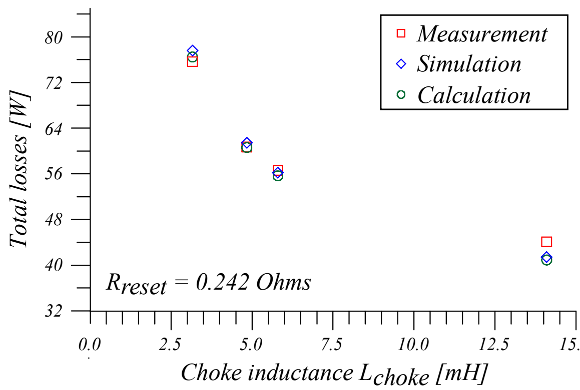

Figure 13: Losses in the diode and the copper resistance.

For all measurements the same choke, designed for 50 A DC and 70 A peak current, was used. To realize different inductance values only the air gap length δ respectively the magnetic resistance R_m was changed.

$$L_{choke} = \frac{N_{choke}^{\ 2}}{R_m} \text{ where } R_m \approx \frac{\delta}{\mu_o A_{core}} \qquad (18)$$

The results in Fig. 13 might lead to the conclusion that for higher inductance values fewer losses are generated. But, the increase of the choke inductance by reducing the air gap length results in a faster saturation of the core. Contrariwise the decrease of the choke inductance results in a worse utilization of the choke core.

To get the best core utilization for all choke inductances equation (8) has to be fulfilled. With this condition for each choke design the magnetic resistance R_m is fixed and/or at least limited to a realizable value. Therefore, to get higher choke inductances considering equation (18) the number of turns N_{choke} has to be increased which results in a higher copper resistance R_{reset} of the reset circuit. To achieve smaller choke inductances and still fulfilling condition (8) the number of turns has to be decreased which leads to a smaller copper resistance R_{reset}.

Reasonably, considering equation (8) increasing inductance values L_{choke} respectively increasing number of turns N_{choke} result in increasing copper losses and decreasing losses due to the energy stored in the choke. Therefore, the total losses always results in an optimal number of turns N_{choke}. In **Fig. 14** the loss curve considering equation (8) is shown for calculation and simulation.

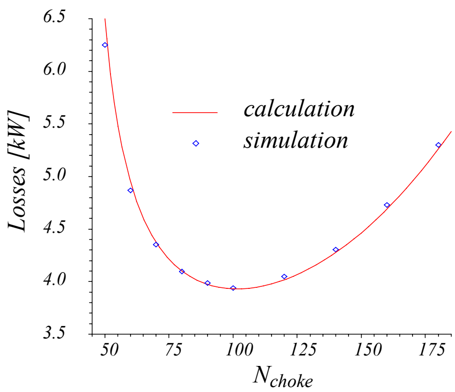

Figure 14: Losses in the freewheeling diode and the copper resistance considering equation (8).

As could be seen in Fig. 13 and 14 the analytical equations correlate really well with the measurements and simulation.

VI. Realization of the Choke

The described dimensioning of the choke results in an optimal number of turns N_{choke} of the choke, an optimal number of turns N_{reset} of the reset winding and the magnetic resistance R_m of the choke. The magnetic resistance is adjusted by the air gap length δ. To calculate the associated air gap length, for small magnetic resistances the correlation given in (18) can be used. A better analytic relation between magnetic resistance and air gap length is given in [14]. Due to the fringing field around the air gap for bigger gap lengths the relation between R_m and δ is not longer linear and therefore the air gap length δ has to be simulated by FEM.

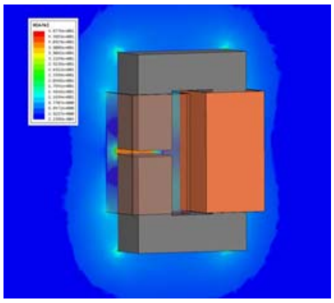

Figure 15: FEM based calculation of the inductance value.

To reduce the ohmic losses further, the choke can also be designed with several layers in parallel or wire with a rectangular cross section could be used. To avoid overheating space between the layers should be provided. Attention has also to be paid to the winding arrangement because of the high voltages (cf. Fig. 7).

VII. System without Reset Circuit

The pulsed power system could also be designed without the presented reset circuit. The major advantage is that the system without reset circuit needs less components (no choke, no additional power source, no reset winding). Because of the absence of the reset choke the stress in the diode will be smaller.

Table 3: Pulsed power system with and without dc reset circuit.

	A Pulse power system without reset circuit compared to a system with reset circuit needs/has …
+	less components: choke, power supply, third winding
+	less power to waste in the diodes
-	minimum twice the core cross section of the transformer
-	min. $\sqrt{2}$ longer windings
-	min. $\sqrt{2}$ bigger copper resistance in the windings
-	min. $\sqrt{2}$ times bigger distributed capacitance C_d
-	min. $\sqrt{2}$ times bigger leakage inductance L_σ
-	min. $\sqrt{2}$ longer pulse rise time

On the other hand the core cross section of the transformer will be at minimum twice as big as with reset circuit due to the unipolar flux swing and the possible remanence of the core material. As a result of the doubled cross section the winding length on the transformer will be $\sqrt{2}$ times longer than with reset circuit for a quadratic core cross section. This causes $\sqrt{2}$ times more copper losses in the winding. Also the leakage inductance L_σ and the distributed capacitance C_d [13] have to be multiplied by $\sqrt{2}$. Considering the relation between rise time and the parasitic elements L_σ and C_d given in [1] and [15]

$$t_{rise} \approx k\sqrt{C_d L_\sigma} \;, \qquad (19)$$

also the rise time is increasing by the factor of $\sqrt{2}$. **Table 3** summarizes the advantages and disadvantages of a system with and without dc reset circuit.

VIII. CONCLUSION

In this paper a method for optimizing a dc reset circuit for a pulse modulator was presented. The analytic equations are validated by simulation and also by measurement results for different system specifications. Based on the equations it is shown that the major part of the losses due to the reset circuit is caused by the stored energy in the magnetic components and therefore the optimization of the dc reset circuit requires the consideration of the overall system for a complete cycle. It is also shown that the system with reset circuit compared to a system without reset circuit offers some important advantages.

In further work also active reset circuits will be analyzed and compared to dc reset circuits regarding volume and efficiency.

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APPENDIX

B. Overall Losses (input/output power)

The input power is provided by the pulse source and the reset power supply. The output power is equal to the transferred power with positive current direction into the load. All current flowing in negative direction through the load is also considered to be losses. Based on this, the input power during one cycle delivered by the two sources can be written as

$$P_{input} = P_{ps\_pulse} + P_{ps\_reset} \qquad (20)$$

with

$$P_{ps\_pulse} = U_{pulse} \int_0^{T_1+T_2+T_3} i_{pri}(t)dt = U_{pulse} \int_0^{T_1} i_{pri}(t)dt \qquad (21)$$

and

$$P_{ps\_reset} = U_{reset} \int_0^{T_1+T_2+T_3} i_{reset}(t)dt = U_{reset} \int_0^{T_1+T_2+T_3} (I_{reset} + \Delta i_{reset}(t))dt \qquad (22)$$

whereas the pulse voltage U_{pulse} of the source is assumed to be rectangular as shown in Fig. 4 and the reset voltage U_{reset} is constant.

The primary current i_{pri} is the sum of $i_{load}(t)$, $i_{mag}(t)$ and $\Delta i_{reset}(t)$ as defined in (9). The load current can be derived from the load resistance and the load voltage which is equal to the transformed pulse voltage neglecting the source resistance R_{int}. The magnetizing current $i_{mag}(t)$ and the AC part of the reset current $\Delta i_{reset}(t)$ are due to the constant voltages U_{pulse} and U_f linear which results in a linear increasing during the pulse and a almost linear decreasing during the free-wheeling time section S_2.

$$I_{load} = \frac{U_{pulse}}{R_{load}} \left(\frac{N_{sec}}{N_{pri}} \right)^2 \qquad (23)$$

$$i_{mag}(t) = \frac{U_x}{L_{mag}} \frac{t}{T_x} \qquad (24)$$

$$\Delta i_{reset}(t) = \frac{U_x}{L_{choke}} \left(\frac{N_{reset}}{N_{pri}} \right)^2 \frac{t}{T_x} \qquad (25)$$

whereas U_x and T_x stand for U_{pulse} during T_1 and for U_f during T_2.

The total power losses can be calculated by simply subtracting the effective output power from the input power. The output power is given by

$$P_{output} = U_{pulse} \int_0^{T_1+T_2+T_3} i_{load}(t)dt = U_{pulse} I_{load} T_1 \qquad (26)$$

and therefore the losses are

$$P_{losses} = P_{input} - P_{output} \qquad (27)$$

So far in this approach both sources are ideal. The internal losses resulting from the power supply have to be explicitly added as with approach I. Hence, the total losses are

$$P_{losses} = P_{input} - P_{output} + P_{ps\_int} \qquad (28)$$

With this, now the optimal choke can be calculated.