Design and Control of an Active Reset Circuit for Pulse Transformers

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***Abstract*— In pulse modulators applying pulse transformers reset circuits are used to achieve optimal utilization of the core material, which results in lower costs, downsized pulse transformer/system volume and therefore in an improved pulse behavior due to the smaller parasitics. Because of its simplicity the most common method to reset the core is a dc reset circuit, where a dc current is used to premagnetize the core. However, the dc reset circuit - even with an optimal design - leads to significant losses in the freewheeling path. By applying an active reset method the losses due to the passive reset circuit can be significantly. So far, only the theoretical behavior of the active reset circuit has been examined. Therefore, the detailed design and measurement results are presented in this paper. Furthermore, a new control method for achieving symmetrical flux swings in the core are presented.**

I. Introduction

In pulsed power systems utilizing pulse transformers for voltage conversion, as shown in Fig. 1, the repetitive unipolar voltage pulses lead to a unipolar flux swing in the core material.

In this cases the core material of the pulse transformer is not optimally utilized and according to (1) the core volume will be approximately twice as big as with a bipolar excitation for the same output pulse.

$$V_{DC} = N_1 \frac{d\Phi}{dt} = N_1 A_{Fe} \frac{dB}{dt} \quad \Rightarrow \quad A_{Fe} = \frac{V_{DC}}{N \frac{dB}{dt}} \qquad (1)$$

A bipolar operation of the transformer could be achieved with a reset circuit - dc reset or active reset - which premagnetizes the core to a negative flux density before the pulse is generated. The dc reset circuit, which is widely used because of its simplicity, leads to significant losses in the freewheeling path even if the design of the dc reset circuit is optimized for minimal losses [3]. In order to reduce the losses and consequently the stress in the freewheeling diode an active reset circuit has been proposed [4], [5]. There, the stored energy in the magnetizing and leakage inductance can almost completely be recovered and reused for premagnetizing the transformer for the next pulse. This leads to a significant reduction of the losses due to the premagnetisation and an improved efficiency of the pulse modulator. There, it is important to note that active reset circuits can only be applied in power modulators, which are driving a load with a diode characteristic like a klystron, due the inverted voltage at the output during premagnetization.

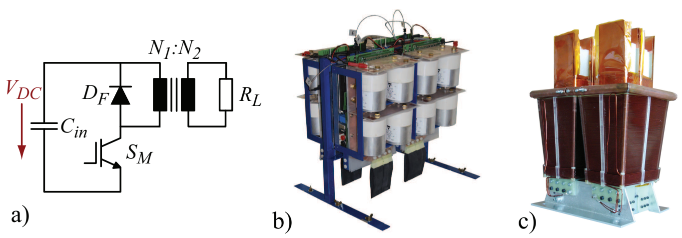

Fig. 1: **a)** Schematic a solid state power modulator, **b)** Pulse generator unit with four parallel connected IGBT modules and **c)** step up pulse transformer.

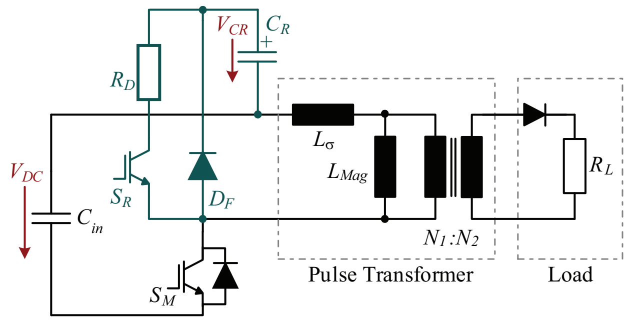

Fig. 2: Schematic of the pulse modulator with the active reset circuit.

In **Section II** the operation of the active reset circuit is be explained in detail and advantages of the active reset method compared to the dc reset circuit are highlighted. Thereafter, in **Section III** the design equations for the system are derived and it is shown that the active reset circuit automatically balances the flux swing in the core in case the losses in the system are low.

If the losses are higher than the the active reset circuit is still self-regulated, but the flux swing tends to be more and more asymmetric. In order to achieve a symmetric flux swing the premagnetization current of the core has to be controlled. Therefore, in **Section III** the control loop of the active reset circuit is explained. Thereafter, the design and experimental results for the active reset circuit of the 20MW/5us pulse modulator with the specifications given in Table I are presented in **Section VI**.

II. Active Reset Circuit

In Fig. 2 the schematic of the power modulator with the active reset circuit for loads with diode characteristic, like klystrons, is shown [4], [6].

The active reset circuit consists of a freewheeling diode D_F, a series capacitor C_R for storing the recovered energy and

DC link Voltage V_{DC}	1000V
Output Voltage V_k	200kV
Pulse Duration T_pulse	5μs
Output Power P_{out}	20MW
Repetition Frequency f_{rep}	200Hz
Magnetizing Inductance L_{Mag}	2.5μH
Magnetizing Current I_{Mag}	1kA
Turns ratio	1:200

TABLE I: Specification of the solid state pulse modulator with active reset circuit.

improving the efficiency and a switch S_R for premagnetising the transformer core.

To premagnetize the transformer core the capacitor C_R has first to be charged up (e.g. by a boost converter, as will be later shown) to a specific voltage level - in the considered case $100V - 200V$ ($= 10\% - 20\%$ of V_{DC}). Then, during the premagnetization interval T_{Premag} the switch S_R is closed and the premagnetization current I_{mag} starts to flow in the primary winding of the transformer (cf. Fig. 3a) & Fig. 4). Current I_{mag} flowing in opposite direction as the load current generates a magnetic flux, which is in the opposite direction than the flux induced by the voltage pulse.

The energy stored in the capacitor C_R is now transferred to the magnetizing inductance L_{Mag}, which results in an linear current slope of I_{Mag}, if an approximately constant capacitor voltage V_{CR} is assumed. In this case, the current level reached at t_1 can be calculated by (2). With (2) it is also possible to calculated the length of the premagnetization interval T_{Premag} so that the magnetization current I_{mag} reaches the required level $L_{Mag,nom}$ if V_{CR} is known.

$$I_{Mag,1} = \frac{V_{CR} \cdot T_{Premag}}{L_{Mag}} \tag{2}$$

As soon as $I_{Mag,nom}$ is reached, switch S_R is turned off at t_1. Thereafter, a short interlocking delay T_I follows before S_M is turned on in order to avoid a short circuit. During T_I the magnetizing current I_{Mag} flows either via the DC link capacitor and the antiparallel diode of the main switch S_M or through the load in positive direction depending on the voltage across the klystron (cf. Fig. 3b)). The klystron voltage can be calculated with (3), where k_p is the perveance of the klystron [7], [8].

$$I_k = k_p \cdot V_k^{\frac{3}{2}} \quad \Rightarrow \quad V_k = \left(\frac{I_k}{k_p}\right)^{\frac{2}{3}} \tag{3}$$

Due to the transformation ratio of the transformer, the premagnetization current I_{Mag} is usually more than a factor of ten smaller than the load current transformed to the primary. Therefore, also the klystron voltage V_k during the premagnetization transformed to the primary is much smaller than the DC link voltage V_{DC}. Consequently, the premagnetization current I_{Mag} will freewheel through the klystron and not via the DC link capacitor during the interlocking delay T_I.

As the resulting voltage V_k, which is proportional to the voltage across the magnetizing inductance, is relatively small ($V_k << V_{DC}$, cf. Fig 4), the rate of change of the magnetizing current during the interlocking delay is small. Therefore, the length of the interlocking delay is not very critical for the operation.

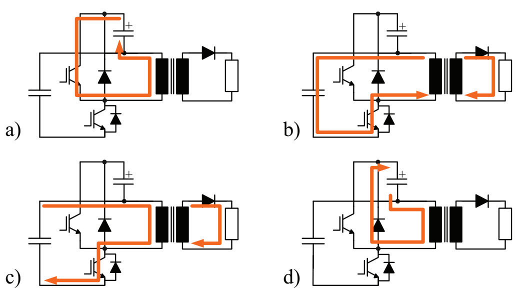

Fig. 3: Current paths during **a)** the premagnetization time T_{Premag}, **b)** the interlocking delay T_I, **c)** the pulse duration T_{Pulse} and **d)** the demagnetization time T_{Demag}.

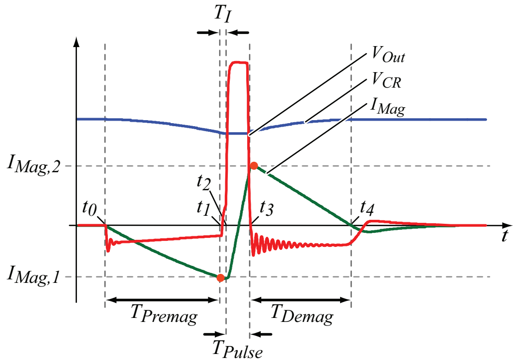

Fig. 4: Current and voltage waveforms for the active premagnetization for one pulse period.

The stored energy in the leakage inductance causes a current, which flows via the DC link capacitor C_{in} and the antiparallel diode of the main switch S_M. Due to the small leakage inductance and the relatively large DC link voltage V_{DC} compared to the klystron voltage V_k, the leakage current through the input stage decreases rapidly.

After the interlocking delay T_I at time instant t_2 the pulse is generate by turning on the main switch S_M. Then, the magnetizing current is linearly ramping up from $-I_{Mag,1}$ to $I_{Mag,2}$ as shown in Fig. 3c) and Fig. 4 due to the constant pulse voltage V_{DC} .

After the pulse during T_{Demag}, the energy stored in the magnetizing inductance L_{Mag} (and the part of the energy stored in L_σ, which is not dissipated in S_M while turning off) is fed back to the reset capacitor C_R via the freewheeling diode D_F (cf. Fig. 3d) and Fig. 4). Since the reset capacitor voltage V_{CR} is much larger than the forward voltage of the diode D_F the losses in the diode can be kept small and the time for demagnetization T_{Demag}, which is mainly defined by the capacitor voltage V_{CR}, is short. For an almost constant capacitor voltage V_{CR} the freewheeling interval can be approximated by (4).

$$T_{Demag} = L_{Mag} \cdot \frac{I_{Mag,2}}{V_{CR}} \tag{4}$$

III. Self-Stabilization of the Flux Swing

If the core is excited symmetrically from $-I_{Mag}$ to I_{Mag}, for an ideal system without losses the energy recovered after the pulse will be the same as the energy, which was used to premagnetize the core. Therefore, after the freewheeling interval T_{Demag} the reset capacitor C_R is recharged to the same voltage level as before the pulse was generated. In practice, however, the voltage across C_R will be below the voltage level as before the pulse due to the losses in the freewheeling diode D_F, the switch S_R, the bus bar, the winding and the core. The voltage drop, caused by the system losses E_{Losses}, can be calculated by means of the difference of the stored energy in the capacitor C_R at t_2 and t_3 with (5), which can be solved with $V_{CR,t3} = V_{CR,t2} - \Delta V_{CR}$.

$$E_{Losses} = \frac{1}{2} C_R V_{CR,t2}^2 - \frac{1}{2} C_R V_{CR,t3}^2$$
$$\Delta V_{CR} = V_{CR,t2} - \sqrt{V_{CR,t2}^2 - \frac{2E_{losses}}{C_R}} \tag{5}$$

In case the magnetizing current directly before $I_{Mag,1}$ and after the pulse $I_{Mag,2}$ are not equal, energy is stored/removed in/from the magnetizing inductance L_{Mag} during the pulse interval as shown in Fig. 5. The amount of energy ΔE_{Pulse} depends on the current level $I_{Mag,1}$ in comparison to $I_{Mag,2}$.

For example, the energy variation ΔE_{Pulse} for a symmetric flux swing in the magnetizing inductance would be zero if $|I_{Mag,1}| = |I_{Mag,2}|$ and consequently $\frac{1}{2}L_{Mag}I_{Mag,1}^2 = \frac{1}{2}L_{Mag}I_{Mag,2}^2$. In (6) the relation between $I_{Mag,1}$ and the additional pulse energy ΔE_{Pulse} stored in the magnetizing inductance L_{Mag} is shown.

$$\Delta E_{Pulse} = \frac{1}{2}L_{Mag}I_{Mag,2}^2 - \frac{1}{2}L_{Mag}I_{Mag,1}^2 = \frac{1}{2}L_{Mag}\left(\Delta I_{Mag}^2 - 2\Delta I_{Mag}I_{Mag,1}\right) \qquad (6)$$

If the premagnetization interval T_{Premag} is set to a fix value determined with (2), a variation in capacitor voltage V_{CR} will lead to a variation in the magnetizing current $I_{Mag,1}$. Therefore, if the capacitor voltage V_{CR} is below the nominal voltage $V_{CR,nom}$ the magnetizing current $I_{Mag,1}$ is smaller than the nominal magnetization current $I_{Mag,nom}$. Consequently, this results in an asymmetric flux swing, where E_{Pulse} is bigger than zero (cf. (6) respectively Fig. 5b)). The additional energy ΔE_{pulse} stored in the magnetizing inductance L_{Mag} will be fed back to the reset capacitor V_{CR} and depending on the system losses E_{losses} the capacitor voltage V_{CR} will increase if $\Delta E_{pulse} > E_{losses}$ or will drop if $\Delta E_{pulse} < E_{losses}$.

Assuming for example $\Delta E_{pulse} < E_{losses}$, the voltage V_{CR} will decrease and for the next pulse the current $I_{Mag,1}$ will be again smaller if a fixed premagnetization time T_{premag} is assumed. This results in an increasingly asymmetric flux swing until the condition $\Delta E_{Pulse} = E_{losses}$ is fulfilled, where the system stabilizes to the reset capacitor voltage $V_{CR,stable}$.

$$V_{CR,stable} = \frac{L_{mag}}{T_{Premag}} \cdot \left(\frac{\Delta I_{mag}}{2} - \frac{\Delta E_{Pulse}}{L_{mag}\Delta I_{mag}}\right) \qquad (7)$$

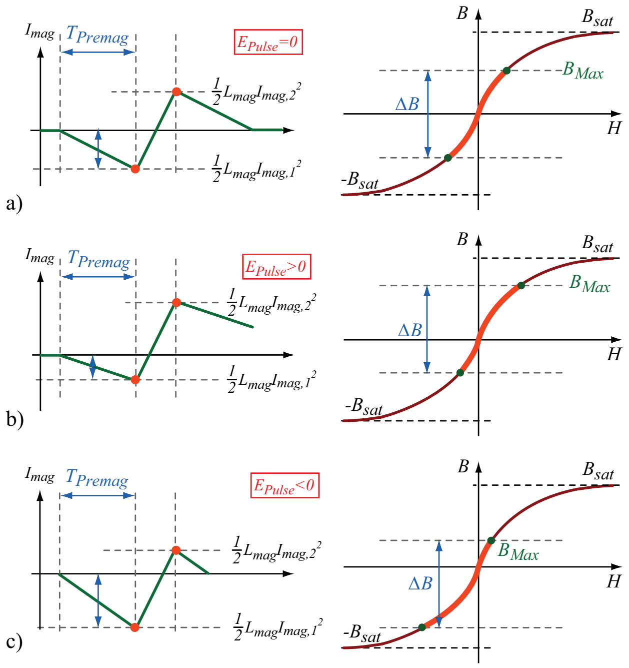

Fig. 5: **a)** $I_{Mag,1} = \frac{1}{2}\Delta I_{Mag}$: The energies after and before the pulse are the same, **b)** $I_{Mag,1} < \frac{1}{2}\Delta I_{Mag}$: The energy after the pulse is the higher than the energy before the pulse and **c)** $I_{Mag,1} > \frac{1}{2}\Delta I_{Mag}$: The energy after the pulse is the lower than the energy before the pulse .

Therefore, in order to achieve a desired capacitor voltage $V_{CR,stable}$ the duration of T_{Premag} has to be adjusted depending on the resulting system losses E_{losses}. Based on (7), longer T_{Premag} lead to lower capacitor voltages $V_{CR,stable}$ and vice versa.

Consequently, for relatively small system losses E_{losses}, the active reset circuit can be operated with a fixed premagnetization interval T_{Premag}, which results in a slightly asymmetric flux swing and therefore to a slightly larger core cross section A_{Fe}, where the system losses are compensated by the additional energy ΔE_{Pulse}. If the active reset circuit is self-regulated, the reset capacitor C_R has not to be precharged, because at start up due to the more asymmetric flux swing more energy will be recovered and therefore the reset capacitor will be charged to $V_{CR,stable}$ by the system itself.

IV. Flux Swing Control of the Active Reset Circuit

For larger losses E_{losses}, the active reset circuit can no longer be operated with self-regulation, because the more asymmetric flux swing can lead to saturation of the transformer core or a significantly larger core area is required. Therefore, the system losses E_{losses} have to be compensated by a DC/DC power supply, which regulates the capacitor voltage V_{CR} to a fix value $V_{CR,nom}$. Additionally, a control loop has to be implemented, which results in a symmetric flux swing in the transformer core.

In Fig. 6 the schematics of the power modulator system with the added DC/DC power supply is shown. There, a DC/DC boost converter, transferring energy from the input capacitor C_{in} to the reset capacitor C_R, is added to the system to recharge the reset capacitor C_R to the nominal capacitor voltage $V_{CR,nom}$. For changing the magnetization level $I_{mag,1}$ for a constant capacitor voltage $V_{CR,nom}$ the premagnetization time T_{Premag} has to be adjusted (cf.(2)).

In the same manner, the demagnetization time T_{Demag} is defined by the magnetization current $I_{Mag,2}$ at the end of the pulse and the resulting back EMF, which is approximately equal to the reset capacitor voltage V_{CR} and the forward voltage of the freewheeling diode V_{DF}.

$$T_{Demag} = \frac{L_{Mag} \cdot I_{Mag,2}}{V_{CR} + V_{DF}} \qquad (8)$$

If the core is excited symmetrically from $-I_{Mag}$ to I_{Mag}, what results in $|I_{Mag,1}| = |I_{Mag,2}|$, if the capacitor voltage V_{CR} is regulated and if forward voltage V_{DF} is neglected compared to V_{CR}, the duration of T_{Premag} and T_{Demag} are equal (cf. Fig. 7). Consequently, for asymmetric excitation the duration of T_{Demag} will be shorter if $|I_{Mag,1}| > |I_{Mag,2}|$

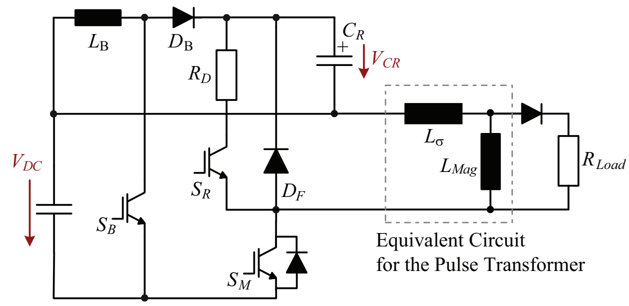

Fig. 6: Schematic of the measurement setup for the active premagnetization and the DC/DC supply.

and contrariwise, the duration T_{Demag} will be longer for $|I_{Mag,1}| < |I_{Mag,2}|$ as shown in Fig. 7 b) and c).

Therefore, to achieve a symmetric flux swing in the transformer core the premagnetization time T_{Premag} has to be controlled in such a way that $T_{Premag} = T_{Demag}$ is achieved (cf. Fig 7). There, the duration of T_{Demag} can be measured by detecting the edge times $t_{E,1}$ and $t_{E,2}$ of the negative primary voltage with an high speed comparator (cf. Fig. 7)

V. Design and Experimental Results

In Fig. 8 a picture of the prototype is shown.

The reset capacitor voltage V_{CR} was set to $150V$, which results in an secondary voltage of $-30kV$. Depending on the given klystron specifications this values must be adapted for other applications. In the test circuit a series connection of a resistor and a diode was used instead of a klystron. For a magnetizing current I_{Mag} of $100A$ the resulting equivalent 'klystron voltage' V_k is 17V, which leads to a slow decay of the premagnetizing current I_{Mag} during the interlocking delay. Therefore, the interlocking delay was selected to be $3\mu s$ to avoid an intersection of the turn off of S_R and the turn on of S_M.

In order to test the flux control of the active reset circuit the transformer with the magnetizing inductance was replaced by an inductor equivalent to the magnetizing inductance.

In Fig. 9 and 10 the measured magnetizing current I_{mag}, the IGBT current I_C and the IGBT voltage V_{CE} for a symmetric and an asymmetric flux swing are shown. For the symmetric flux/current swing it can be seen, that the durations of the two magnetization times T_{Premag} and T_{Demag} are almost equal. The relative error results due to the forward voltage drop and the reverse recovery time of the used freewheeling diode D_F. As expected, the demagnetization time T_{Demag} will become shorter if $I_{Mag,1}$ is getting larger (cf. Fig. 10). The waveform of V_{CE} shows a very short negative peak when S_M is turned off, which is caused by the current flowing through the leakage inductance L_σ and the input stage.

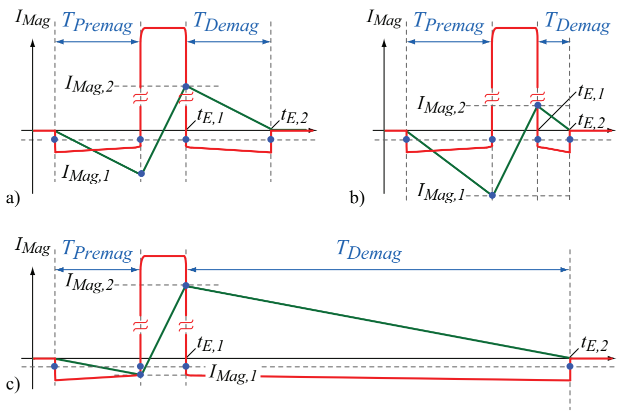

Fig. 7: **a)** Symmetric flux swing, where $T_{Premag} = T_{Demag}$, **b)** and **c)** asymmetric flux swing, where $T_{Premag} > T_{Demag}$ respectively $T_{Premag} < T_{Demag}$.

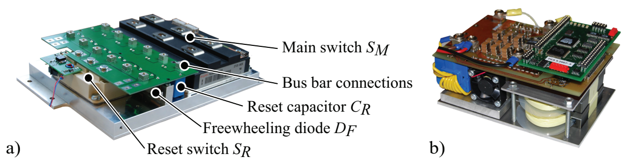

Fig. 8: **a)** Prototype of the active reset circuit and **b)** DC/DC boost converter ($V_{in} = 1000V, V_{out} = 0...200V, P_{out} = 1kW$).

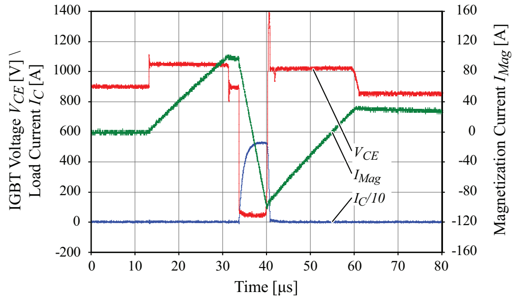

Fig. 9: Symmetric flux swing, where $T_{Premag} \approx T_{Demag}$

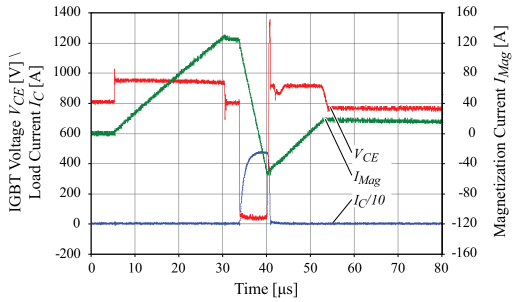

Fig. 10: Asymmetric flux swing, where $T_{Premag} > T_{Demag}$

VI. Conclusion

In this paper a detailed description of the active reset circuit operation principle and the control is given. It is shown that for systems, with low losses, the active reset circuit balances the flux swing in the transformer core automatically. In this case the premagnetization time T_{Premag} can be set to fix value.

In systems with higher losses an additional boost converter, which compensate the losses related to the premagentization and which stabilizes the reset capacitor voltage V_{CR}, is required in order to achieve a symmetric flux swing. Additionally, the premagnetization time T_{Premag} has to be control to achieve $T_{Premag} = T_{Demag}$, which can be simply measured with a high speed comparator.

These results are validated by measurements, which are in good correspondence with the theoretical predictions.

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