INDUCTIVE HIGH VOLTAGE PULSE GENERATOR BASED ON RESONANCE SYSTEM

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A high voltage pulse generator based on inductive intermediate energy storage has been constructed. The current switching technique used in the generator is based on a resonance system. Opening switches for high currents are generally difficult to construct and the switch used here has proven to turn off 1.8 kA DC-current at a rate of 300 A/µs. The generator is equipped with a step-up transmission line transformer as intermediate magnetic energy storage and the primary and secondary energy storages are capacitive. An LC-resonance circuit is combined with 3 vacuum interrupters in series as an opening switch on the primary side of the transformer. Discharging the capacitor bank into the primary winding of the transformer introduces a 200 Hz sinusoidal oscillation on the primary current. The movable contacts in the vacuum interrupters are operated mechanically and stable arcs are formed as the gaps are opened. As the 200 Hz sinusoidal current reaches its first maximum, the small LC-resonance circuit is triggered and the current achieves a new frequency of 25 kHz. The large amplitude and high frequency generated by the LC-resonance circuit results in a zero crossing of the primary current. As the current crosses zero the arc deionises and the current is switched off. Pulse shaping with a 2 × 50 m Blumlein configuration on the secondary side of the transformer has been investigated. A rise-time of 40 ns and pulse duration of 700 ns were measured for a resistive load. The aim with this pulse generator is to get familiar with the challenges involved in scaling the system to higher performance.

Keywords: high voltage, pulsed power, transformer, transmission line, vacuum interrupter, current switch

1 INTRODUCTION

Generation of high power microwaves puts specific demands on pulse generators, the rise time and pulse length have to be within certain limits. This generator was designed in order to learn how to handle and interrupt large currents. Switching techniques involving large currents are necessary to handle in order to sustain low costs for transformers. This becomes especially important for pulse generators based on intermediate magnetic energy storages. The pulse generator investigated in this article is equipped with primary and secondary capacitive energy storages as shown in Fig. 1. A step-up transformer with an air-core is used as an intermediate energy storage. The opening switch for the pulse generator is based on a triggered resonance circuit in combination with vacuum interrupters. Designing the generator with a resonance circuit in combination with vacuum interrupters allows a repetitive function. The easiest way to interrupt a large current is to use exploding wires, however, exploding wires have drawbacks such as a low repetition rate. The transformer used in this generator is similar to the one tested in [1] and [2]. Both transformers are made from coaxial high voltage transmission lines [3]. The transmission lines are made from cross-linked polyethylene and can withstand a DC-voltage stress of 100 kV/mm [4]. The transmission lines have been used successfully in high voltage rotating machines such as Powerformer™ [5] and transformers without oil immersion [6].

2 PULSE GENERATOR

2.1 Full scale 500 kV generator

The aim with the investigated scale model in this article is to get familiar with the challenges involved in a full-scale pulse generator. A full-scale generator designed for the performance 500 kV, 50 kA, 20 ns rise time and 1 µs pulse duration provides an engineering challenge. The semi-square pulse would contain 25 kJ and the resulting primary energy storage should contain at least 50 kJ considering 50% overall efficiency. Further, using a 1:4 step-up air-core transformer sets the primary current to 3.3 kA considering a 9 mH primary inductance and 1 mF primary capacitor bank. As the primary current is switched off, induction voltages of 125 kV and 500 kV appear on the primary secondary winding, whereas the secondary winding is connected to a 0.2 µF pulse forming Blumlein. Semiconductors at reasonable cost and size are not suited as commutators [7], [8], [9] for the vacuum interrupters because the energy transport and induction voltage is too high. A slightly different approach that uses a resonance circuit (instead of semiconductors) combined with vacuum interrupters is explained in section (2.2).

2.2 Scale model pulse generator

Figure 2 describes a simplified schematic of the pulse generator where the components \( C_p, R_p, L_p \) are the primary capacitance, resistance and inductance. \( C_s, R_s, L_s \)
Fig. 1. Pulse generator using a transformer as an intermediate energy storage. The high voltage energy storage is replaced (section III) with a Blumlein in order to sustain a square load voltage.

Fig. 2. a) Pulse generator circuit with a transmission line transformer and a secondary high voltage capacitor $C_s$, the resonance circuit consists of $L_d$, $C_d$ and is used for achieving zero current crossing. b) Table with component values used in the simulation of the simplified circuit.

Fig. 3. A simplified version of the circuit used in the simulation program [11].

The input impedance is calculated with the primary capacitor $C_p$ removed and all switches closed. The transformer is converted into an equivalent reciprocal two-port network [14]. This common procedure is applied because it makes the circuit calculations simple. Figure 3 shows a simplified version of the circuit used in the simulation program [11]. The transformer model used in the electric circuit simulations was previously presented in [1] and has a distributed inductance, capacitance and resistance. The lumped circuit element [9], [10] approach was used in the electric circuit model. The input impedance is calculated and the result becomes

$$Z_{in}(j\omega) = R_p + j\omega L_p + \frac{R_d + j\omega L_d}{1 - \omega^2 L_d C_d + j\omega R_d C_d} + \frac{j\omega k^2 L_p L_s C_s}{1 - \omega^2 L_s C_s + j\omega R_s C_s}.$$  

where $k$ is the coupling factor of the transformer and $\omega$ is the angular frequency. The real roots of the modulus of eq. (1) can be solved analytically with the resistance set to zero. The easiest way to get an overview of the circuit impedance is to run the circuit in the electric circuit simulation program. However, the analytical solution gives an overview of the components that significantly affect the impedance. Figure 4 shows the modulus of the input impedance with switch $S_3$ (Fig. 2) closed and opened.

3 GENERATOR DESIGN

3.1 Opening switch

The opening switch $S_2$ has three vacuum interrupters in series resulting in a higher electrical insulating capability [15]. The electric circuit model of the vacuum interrupter in switch $S_2$ is shown in Fig. 5 and contains a
Fig. 4. The impedance changes as switch $S_3$ is operated and resonance occurs at 25 kHz.

Fig. 5. Spice model for the opening switch, the switch $W_2$ is opened as switch $W_1$ senses zero current.

current switch $W_1$. The current switch $W_1$ outputs the voltage $V_1$ as the current $I_p$ passes zero, in turn this voltage control the switch $W_2$ and the opening procedure is established. The circuit shown in Fig. 5 is a rough simulation model of the vacuum interrupters that is used in the experimental setup. A stable arc occurs in each vacuum interrupter if the movable contact is operated during current flow. The conducting arcs are modelled as an inner resistance in switch $W_1$ and the extinguishing of the arcs are modelled by switch $W_2$ that has the logic function on or off.

Switch $S_3$ (shown in Fig. 2a) is closed as the 200 Hz primary current reaches its maximum and this results in zero crossing. Figure 6 a) shows a quarter wave period of the simulated primary current. Figure 6 b) illustrates a magnification of the current switch with different resonance capacitor polarity. Simulations show that a better efficiency is acquired with positive charge in the resonance capacitor $C_d$. However, it does have some drawbacks that will be discussed further in section VI. The polarity of the charge voltage in capacitor $C_d$ has a 10% influence on the efficiency of the circuit.

The switching frequency of the current is determined by all components included in the circuit. The coupling factor $k$ of the transformer influences the resonance frequency most. The frequency dependence of the resonance peak can be analyzed by sweeping of the coupling [11]. The parameter sweep shows that the resonance frequency changes much as the coupling factor is changed. The partly ideal circuit presented in Fig. 2 has lower resistance values than the non-ideal circuit tested in section IV.

3.2 Coaxial transformer

Coaxial transformers are designed using a high voltage coaxial cable where the inner conductor is used as the secondary and the screen is the primary winding [1]. The transformer used in this pulse generator was FEM (Finite Element Method) analyzed magnetically in [2]. The results showed that the FEM model was accurate at low frequencies. Deviations of the inductance occurred at higher frequencies and the behaviour is explained by the use of isotropic conductors in the model. However, a measurement of the primary and secondary impedance has been made using a function generator and a power amplifier. The transformer was analyzed for two different winding ratios $N = 1$ and $N = 4$ respectively. Figure 7 illustrates the measured primary and secondary impedances. Measurement of the primary and secondary currents was made using Pearson current probes. Measurement with the secondary winding short-circuited is shown in Figure and the phase angle between the voltage and current is also shown.

3.3 Pulse forming

In order to deliver a square load voltage pulse forming can be made by replacing the secondary capacitor $C_s$ with a Blumlein [12], [13]. Figure 9 shows the pulse generator system and it works in the same way as described in section II, however, $S_2$ is another type of opening switch that combines vacuum interrupters and semiconductors. The secondary capacitance $C_s$ has to be 0.25 $\mu$F for this specific circuit in order to make the LC-resonance circuit (section B) efficient. This relative large capacitance requires a large amount of cable and therefore the vacuum interrupter/semiconductor switch was used.

The capacitance of the Blumlein that was used had a value of 20 nF and the opening switch used could handle $\sim 200$ A and thus limiting the secondary charge voltage to 12 kV. Since the opening switch limited the maximum current to 200 A the transformer was set to a winding ratio of $N = 2$ in the pulse forming tests. The load is connected to the screen conductor of the line $T_2$ and the spark gap is connected to the inner conductor as shown in Fig. 9. As the secondary sinusoidal charge voltage reaches its first maximum, the spark gap closes. A square load voltage is formed in the load.
4 HIGH VOLTAGE RESULTS

4.1 Switching current

The high voltage measurements were made with a 0.25 µF high voltage capacitor $C_s$ mounted on the secondary winding of the transformer. The high voltage capacitor should be replaced with a Blumlein in order to produce square pulse shapes but the relatively high capacitance requires a large amount of cable. The voltages and currents were recorded with Tektronix 430 oscilloscopes (100 Ms/s). The primary current was measured with Pearson probes (model 101, rise time 100 ns) and the primary voltage was measured with a (Tektronix P6015 A, 20 kV DC). The measurement on the secondary side of the transformer was made with a high voltage probe (Ross Eng. Corp. Model VMP120, 120 kV DC). Figure 10 shows the results from a test with a primary
current peaking at 1.8 kA and the resonance capacitor $C_d$ was charged negative. The energy in the pre-charged resonance capacitor $C_d$ and inductor $L_d$ becomes equal as the current reach its maximum ($L_d \sim 80 \text{ J at 1.8 kA}$), usually the capacitor have to contain slightly more energy due to resistive losses ($C_d \sim 90 \text{ J at 6 kV}$). Simulations from a non-ideal circuit model are included next to the measured data.

A typical test as illustrated in Figs. 10 and 11 have a primary capacitor bank energy of 1440 J (at 1.2 kV) of which 1.2 kJ discharges into the transformer and 240 J is left after switching. The resonance capacitor contains a energy of 90 J at 6 kV. The secondary load capacitor is charged to 450 J at 60 kV as the current is switched off. Losses occur in the vacuum interrupters $\sim 75 \text{ J (assuming 50 V forward arc voltage at 1 kA for 1.5 ms)}$. The resonance inductor $L_d$ have an energy of 80 J at switching which will be lost and the rest is resistive losses $\sim 600 \text{ J}$. The efficiency of this test circuit is $\sim 40 \%$, however, the efficiency can be improved by using larger conductor cross-section areas.

4.2 Blumlein pulse forming

The Blumlein pulse forming was made using two 50 m coaxial transmission lines. The transmission lines $T_1$ and $T_2$ illustrated in Fig. 9 were both wound as solenoids. The total capacitance for the coaxial cable was 20 nF. The resonance circuit $L_d$ and $C_d$ in the opening switch $S_2$ loses some of its efficiency because of the small secondary capacitance. Many parallel coaxial cables are needed to achieve $0.25 \mu \text{F}$ corresponding to the high voltage capacitor. Therefore the Blumlein tests were made using the switch described in section 3.3. The load was a water/NaCl mixture in order to reduce inductance. The load current was measured with a Pearson current probe (model 2878, rise time 5 ns) and the voltage was measured with a (Tektronix P6015 A, 20 kV DC). The spark gap shown in Fig. 9 has two copper spheres with radius 5 mm and gap distance 4 mm. The Blumlein was tested using three different load setups. The coaxial cable used in the Blumlein has the calculated characteristic impedance of $30 \Omega$ and is calculated from measurements on the cable. The total capacitance of 20 nF stores 1.44 J at 12 kV. The energy discharged into the main pulse is 1.35 Joule, which makes an efficiency of 90 to 95 % considering capacitance calculation errors etc. Figure 12 shows the measured load power with three types of loads.

5 COMMENTS

Care should be taken to have a proper shield outside the vacuum interrupters because harmful X-rays may be generated [17]. X-ray radiation may be generated if electrical breakdown occurs in the vacuum interrupters due to mismatched mechanical timing of the movable contact [18]. The rise time for the load voltage on the Blumlein is strongly dependent of the closing time for the spark gap. The electric circuit model for the opening switch should be complemented with the deionization dependence of the
vacuum interrupters. The spark gap shown in Fig. 9 may be moved to the secondary side of the transformer and connected directly to ground. The load voltage is reversed as the spark gap is located in this new position. Alternating load voltage may be achieved if spark gaps are used at both places. The load power is calculated using [16] and the power is peaking at the load resistance 110 Ω. Calculations according to [12] predicts a power peak at 60 Ω. A pulse length of 500 ns is achieved assuming a relative dielectric constant of cross-linked polyethylene of 2.3, however, we measure 700 ns.

Triggered vacuum interrupters should be used in order to remove the mechanics. Triggered vacuum interrupter contacts are always open and therefore the switch $S_1$ can be removed and switch $S_2$ works as a closing and opening switch. This enables a higher repetition rate but another trigger circuit for the vacuum interrupters are necessary.

### 6 CONCLUSIONS

The hybrid switch used in this pulse generator combines the durability of the vacuum interrupters and the strong resonance of the LC-circuit. Combination of the two devices has proven to switch 1.8 kA. The switching of the current using positive compared to negative potential in the resonance capacitor $C_d$ has proven to increase the overall efficiency of the generator. Positive charge in the resonance capacitor $C_d$ gives a superimposed current as shown in Fig. 6 resulting in an inverted initial potential on the secondary side of the transformer. Measurement of the transformers impedance show that the coupling is very high for this type of transformer, as shown in Fig. 8 where the primary impedance is below 1 Ω up to 25 kHz with the secondary winding short-circuited. The pulse forming Blumlein consists of $2 \times 50$ m coaxial cable with solenoid windings. This type of winding is preferred when compactness is desired. By placing two spark-gaps, i.e. one additional directly on the secondary side of the transformer opens the possibility to alternate the load voltage using constant polarity of the charge voltage. Considering the full-scale generator the hybrid switch should manage to switch off 3.3 kA, the coaxial transformer for 125 kV primary voltage is a challenge to design, the secondary 500 kV will constitute a challenge at the cable joints between the transformer and the Blumlein.
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References


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