Pulsed operation of a SDBD plasma reactor

Beckers, Frank

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Pulsed operation of a SDBD plasma reactor

door: F.J.C.M. Beckers
EPS.08.A.195
Abstract

The Surface Dielectric Barrier Discharge (SDBD) plasma reactor could possibly make comprehensive surface treatment industrial applicable. Non-thermal, highly chemical active plasma can be generated on a large reactor surface. It can for example be applied to improve dye ability, printability, adhesion properties and dirt repellency of paper, plastic foils and textiles. Pulsed and AC operation of the reactor is possible. Bursts of weak micro discharges are created during AC operation. Single discharges are created during ns pulse operation. Homogeneous plasma can be created relative simple by applying several kV to the reactor, but scale-up of these SDBD reactors proves to be difficult. Large reactors have massive capacitances. AC power modulators have to be able to deliver large amounts of reactive power. Efficient ns pulsed operation proves to be very difficult; the source has to be able to deliver high currents to charge the reactor capacitance in several ns, only a limited amount of the capacitive stored energy can be dissipated in the plasma, the rest should subsequently be partially transferred back to the source or else dumped. The capacitance problem can be overcome by constructing a large reactor in a modular way by using multiple smaller reactors. Each section will be fed by a separate low cost power supply.

The research focused on determining the most efficient manner to create chemical active and homogeneous plasma on these reactors (pulsed or AC excitation), and subsequently the development of a small low cost power supply. The plasma's ability to produce ozone was used as a measure to compare the chemical activity of the pulse and AC excited plasma (chemical activity vs. power consumption). The yield could only be compared for low power levels, because of the relative small energy per pulse which is dissipated in the reactor during pulse operation and the limited pulse repetition rate of the pulse source which was used during experiments. The pulsed excited plasma appeared to obtain higher O$_3$ yields. Comparison at higher power levels should give a conclusive answer.

High speed imaging was used to compare the plasma surface coverage and homogeneousness for the AC and ns pulse operation. The high speed images showed single shot homogeneous pulsed excited plasma. The plasma intensity along the reactors high voltage electrodes is similar for AC and pulse excitation, which indicates similar plasma surface coverage and development of streamers.

Pulse operation would be preferred, because of the single shot homogeneous plasma and presumably better chemical efficiency. Also, a major advantage of pulsed operation is that average plasma power can easily be varied by means of the pulse repetition rate. However, a solution must be found to recycle the energy in the reactor capacitance, which is not fully used by the discharge. The capacitance problem can probably be reduced by modifying the reactor, which could make pulse operation more efficient.

An attempt was made to develop a high repetition rate (15 kHz) DSRD (Drift Step Recovery Diode) based ns pulse source. Losses in the circuit and parasitic effects prevented the source to reach the required reactor voltage.

A second developed pulse source based on a low stray inductance pulse transformer is able to produce 2μs wide quasi resonant pulses with a repetition rate up to 15kHz. The source generates multiple discharges on the reactor during each pulse. The circuit is able to recover a large part of the capacitive stored reactor energy after each pulse. Ozone yield measurements showed an unfortunately low yield in comparison to AC and pulse excitation.

An AC DBD (Dielectric Barrier Discharge) electric equivalent model was adapted for SDBD, which enables estimation of the plasma's power dissipation for any applied AC voltage. Important parameters could be determined by experimental verification of the model; such as the values of the various capacitances that are involved in the SDBD reactor.
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1 Introduction

Today's plasma technology has a wide range of applications. Atmospheric plasma's can for example be applied to improve dye ability, printability, adhesion properties and dirt repellency of paper, plastic foils and textiles. There's a need for cost reduction of industrial production processes and more environment friendly technology. Requirements for a large scale atmospheric plasma system are: homogeneous plasma across a large surface, stable plasma which is independent of process gasses, short treatment times and low power consumption. The Surface Dielectric Barrier Discharge (SDBD) reactor (figure 1.1) fulfills this description, and could possibly make comprehensive surface treatment industrial applicable. Non-thermal, highly chemical active plasma is generated on the surface of the reactor at room temperature under atmospheric pressure. SDBD has a streamer like nature on macroscopic scale. These streamers move rapidly and they overlap so that the treatment is microscopic uniform, resulting in homogeneous treatment. Streamers are parallel to the treated material resulting in good contact (between the discharges and material) and longer exposure time, which leads to relative short treatment times. The plasma is only created in a thin layer on the surface of the reactor which results in more efficient operation and lower power consumption. SDBD reactors are constructed of a dielectric material with parallel strips (high voltage electrode) at one side of the reactor (small horizontal lines figure 1.1). A ground plane is located at the backside. Discharges are initiated from the electrode to the dielectric surface of the reactor when a high voltage waveform (several kV) is applied to the electrode.

Figure 1.1: Example of a small SDBD reactor

Pulsed and AC operation is possible because any applied voltage variation dU/dt will result in a displacement current in the dielectric barrier which enables discharge current to flow. Therefore DC operation is precluded because the dielectric barrier is an insulation material which cannot pass a DC current. Although homogeneous plasma can be created relative simple, scale-up of these SDBD reactors proves to be difficult. Large reactors have massive electrode and dielectric surface capacitances. AC power modulators have to be able to deliver large amounts of reactive power. Efficient pulsed operation proves to be very difficult; the source has to be able to deliver high currents to charge the reactor capacitance as fast as possible, unused capacitive stored energy should subsequently be partially transferred back to the source or else dumped. The idea is to construct a large reactor in a modular way by using multiple smaller reactors to overcome the capacitance problem. Each section will be fed by a separate low cost power supply.

1.1 Objectives

The research focuses on determining the most efficient manner to create chemical active and homogeneous plasma on these reactors. Pulsed operation creates presumably more chemical activity compared to AC operation with equal power dissipation. The plasmas ability to produce ozone will be used as a measure to compare the chemical activity of the pulse and AC excited plasma. High speed
imaging will be used to compare the plasma surface coverage and homogeneousness for the AC and pulsed operation.
Second part focuses on the development of a low cost power modulator. Choice of the modulator type and specifications (for instance output voltage and current) will be based on the research which is discussed in the first part of the report.

1.2 Outline

This report describes the research which was performed on the SDBD reactor, and the development of a power modulator for these plasma reactors. The project was carried out by the author of this report as his Master of Science graduation project.
Chapter 2 describes the basic operation of the SDBD reactor. A reactor equivalent model and a technique to estimate several parameters will be introduced. The AC and pulse modulator used during experiments will also be discussed.
The measuring equipment and setup will be described in chapter 3. Several techniques are described in chapter 4 to calculate the power dissipation and ozone production of the SDBD plasma. All electrical and chemical measurement results are also admitted in this chapter. Finally the high speed imaging results will be described.
Two developed power modulators will be introduced in chapter 5. Several electrical and chemical measurements to investigate the performance are admitted in this chapter.
The conclusions and recommendations can be found in chapter 6.
2 Model for a (S)DBD reactor

This chapter provides background information about the discharge behavior of the SDBD reactor for AC and pulsed excitation. Since a SDBD reactor has some similarities with a dielectric barrier discharge (DBD) we start this chapter with a brief review of a DBD model for AC plasma excitation. An electric DBD model for AC operation and a technique to estimate several parameters of the model will be discussed. The introduced DBD model has been modified in section 2.2 for SDBD and will later be discussed in detail. The model can be used to estimate the power dissipation of the plasma and will give insight in the discharge behavior of the reactor. An analytic model is proposed in section 2.3 to calculate actual gap voltage and discharge current out of measurements.

2.1 Model for a DBD reactor (AC operation)

The traditional DBD consists of a high voltage electrode, a dielectric barrier, a gas gap and a ground plane (figure 2.1a) [Bec04], [Kog03]. The $\varepsilon_r$ (relative dielectric constant) of the barrier is normally chosen much higher than the $\varepsilon_r$ of the gas in the gap resulting in a concentration of the E field in the gas gap when a voltage is applied over the electrodes. If an AC voltage is applied over the electrode ($U_e$), the voltage in the gap will rise until the discharge inception voltage of the gas is reached. A small short live (ns) discharge will occur which accumulates charge on the dielectric barrier. The charge causes a voltage drop in the gap which results in extinguishment of the discharge after the electric field in the gap drops below the critical value to maintain the discharge. The gap voltage increases again when the electrode voltage increases, resulting in a next discharge. This process will repeat itself, resulting in a burst of micro discharges and a nearly constant voltage over the gap. So the electric charge accumulated on the surface of the barrier during these discharges combined with the applied voltage to the electrodes will determine when the voltage in the gap is high enough to initiate the discharges. The exact characteristics of the micro discharges are determined by gas pressure, type of gas and the frequency of the applied electrode voltage $U_e$. At very high frequencies of the applied voltage $U_e$ there may be not enough time for charge carriers to recombine or to be swept out of the gas gap. In this case some electrical conductivity can remain throughout the voltage period.

![Figure 2.1: Schematic DBD and model](image)

An electric model for the DBD is shown in figure 2.1b [Bec04]. The DBD can be seen as two capacitors in series if no discharges occur. $C_d$ is the capacitance of the dielectric barrier and $C_g$ the capacitance of the gas gap. During discharges the discharge inception voltage $U_{dis}$ over the gap remains more or less constant as explained before. The model uses two zener diodes to clamp the gap voltage $U_g$ to the discharge inception voltage $U_{dis}$. Note that a single discharge in the model occurs instead of several micro discharges. The energy dissipation of the plasma takes place in the zener diodes.

The parameters of the model can be determined by measuring the external reactor current $I$ and applied electrode voltage $U_e$. A charge ($Q$) - applied electrode voltage ($U_e$) lissajous figure can subsequently be plotted as shown in figure 2.3, where $Q$ is the total instantaneous reactor charge which can be calculated by integrating the external measured reactor current $I$. The fact that $q(0)$ (initial reactor charge) will in practice be unknown isn't a problem for estimating the model parameters because this value introduces only an offset in the charge, raising the lissajous plot up or down.

$$q(t) = \int_0^t i(\tau) d\tau + q(0)$$

(2.1)
To create a lissajous diagram the charge (Q) is plotted in the y direction and the applied electrode voltage (U_e) in the x direction. As example, figure 2.2 schematically shows a typical gap voltage U_g and applied electrode voltage U_e. During time interval 1→2 the gap voltage U_g is below the inception discharge voltage U_{dis}; no discharges occur. The slope of the Q - U_e diagram during time interval 1→2 corresponds to the total capacitance of the reactor \( C = \frac{dQ}{dU_e} \). The reactor acts like two capacitors \( C_g \) and \( C_d \) in series. The total capacitance \( C_{tot} \) corresponds to following equation:

\[
C_{tot} = C_d + C_g
\]

At point 1 the displacement current through the reactor will be zero because \( dU_e/dt \) is zero. The zero crossing causes an interruption of the previous negative discharges because the voltage in the gap \( U_g \) decreases due to the negative displacement current. The gap voltage has to swing over to reach the positive discharge voltage during time interval 1→2. A conductive channel is formed in the gap during discharges in time interval 2→3 and 4→1. These slopes will correspond therefore only to the capacitance of the dielectric barrier \( C_p \). The external current I will substantially increase during the discharge intervals. Between 3 and 4 the voltage has to swing over again and the slope corresponds again to \( C_{tot} \). The negative discharges will occur during time interval 4→1. The width of the diagram \( 2 \, U_{min} \) corresponds to twice the magnitude of the required minimum external applied electrode voltage \( U_w \) which is necessary to reach the discharge inception voltage, because the gap voltage has to swing from negative to positive and vice versa. The actual gap voltage during discharges \( U_g = U_{disc} \) can be calculated by equation (2.3), because \( C_g \) and \( C_d \) acts as a capacitive divider between discharges (interval 1→2 and 3→4).

\[
U_{av} = U_{max} \frac{C_d}{C_d + C_g} = U_{max} \frac{1}{1 + \frac{C_g}{C_d}}
\]

\[\text{Figure 2.2: Typical SDBD waveforms} \]

\[\text{Figure 2.3: Typical DBD Q-U_e lissajous plot}\]

The gap voltage \( U_g \) and applied electrode voltage \( U_e \) are not in phase during interval 1→2 and 3→4 however the DBD acts like a capacitive divider in these intervals. This can easily be explained by the fact that each burst of micro discharges will accumulate a certain amount of charge on the dielectric barrier. Only a small portion of this charge is removed during voltage reversal (interval 1→2 and 3→4) because the displacement current is limited by the relative low capacitance of the gap. In other words, the voltage over the dielectric barrier will only slightly drop during voltage reversal.

Average power dissipated by the plasma can be estimated after the parameters of the model are determined. The surface of the lissajous plot resembles the dissipated energy per period because the surface of the parallelogram has units Coulomb x Volts = Joules. First derived by Manley [Man43], the total reactor power dissipation can be estimated by calculating the area of the lissajous plot and subsequently multiplying this value by the frequency (f) of the applied electrode voltage \( U_e \) (equation 2.4).

\[
P = 4 f C_e U_{av} \left( \dot{U}_e - \left(1 + \frac{C_e}{C_g} \right) U_{av} \right) , \dot{U}_e \geq \left(1 + \frac{C_e}{C_g} \right) U_{av}
\]

\[\text{Figure 2.4: Typical DBD Q-U_e lissajous plot}\]
2.2 Model development for a SDBD reactor

2.2.1 SDBD AC operation

The SDBD reactor differs from the traditional DBD because the high voltage electrode is placed directly on top of the dielectric barrier. The plasma isn't created between the barrier and the high voltage electrode, but alongside the electrode (figure 2.4b). The question arises if the introduced DBD model is feasible for the SDBD reactor. The model proved to be valid with an adjustment; the addition of the electrode capacitance $C_e$. The SDBD behaves similar when this capacitance is taken into account. Figure 2.4a shows a schematic overview of several reactor capacitances when no discharges occur.

![Figure 2.4: Schematic SDBD reactor](image)

There is a relative small capacitance $C_g$ (figure 2.4) from the high voltage electrode to the dielectric barrier. The charge accumulated on the surface of the dielectric during previous discharges is responsible for a voltage over capacitance $C_d$: a capacitance between the surface charge layer and the ground plane. This dielectric surface charge in combination with the applied electrode voltage $U_e$ will determine the electric field alongside the high voltage electrode. The field around the electrode is non-homogeneous so discharges will occur in the regions where the E field is high enough. The gap voltage (voltage between high voltage electrode and dielectric surface) will be more or less equal to the discharge inception voltage $U_{dis}$ during the intervals that discharges take place (figure 2.4b). The capacitance $C_d$ will subsequently be determined by the area of the discharge activity on the dielectric surface. The electric equivalent model of the SDBD reactor is shown in figure 2.5. The model is equal to figure 2.1b but with the addition of the electrode capacitance $C_e$.

![Figure 2.5: SDBD model](image)

![Figure 2.6: Typical SDBD waveforms](image)

![Figure 2.7: Typical SDBD Q-U_e and Q'-U_e lissajous plots](image)
A typical SDBD reactor charge \( (Q) \) - applied electrode voltage \( (U_e) \) lissajous figure of a single AC period is plotted in figure 2.7. Figure 2.6 shows the associated current and voltage waveforms. Only the current waveform differs from figure 2.2 because a continuous displacement current flows through the electrode capacitance \( C_e \). No discharges occur during time interval \( 1 \rightarrow 2 \) and \( 3 \rightarrow 4 \). Now the slope of the \( Q-U_e \) plot corresponds to the reactor capacitance \( C_{total} \).

\[
C_{total} = \frac{C_s + C_e}{C_s + C_e + C_r} \quad (2.5)
\]

This is equal to equation 2.2 only with the addition of the capacitance \( C_e \) (the capacitance between the high voltage electrode and the ground plane). During interval \( 2 \rightarrow 3 \) and \( 4 \rightarrow 1 \) discharges occur, the current \( I \) increases substantially and now the slopes correspond only to the sum of \( C_s \) and the dielectric surface capacitance \( C_d \) since capacitor \( C_e \) is bridged by the discharge.

\[
C_{total} = C_s + C_e \quad (2.6)
\]

The electrode capacitance \( C_e \) can easily be calculated or measured using a LCR meter. Equation (2.7) can be applied to estimate \( C_e \) because the electrodes act like a parallel plate capacitor. \( A_e \) is the total high voltage electrode surface, \( d \) the thickness and \( \varepsilon_r \) the relative permittivity of the dielectric barrier.

\[
C_e = \varepsilon_r \frac{A_e}{d} \quad (2.7)
\]

The last parameter \( U_{dis} \) cannot directly be estimated from this lissajous plot because the electrode capacitance \( C_e \) has to be taken into account. The electrode charge can easily be subtracted from the total reactor charge because the applied electrode voltage and electrode capacitance \( C_s \) are known. The electrode charge can be calculated with equation (2.8).

\[
Q_e = C_e U_e \quad (2.8)
\]

The corrected instantaneous charge can subsequently be calculated with the following equation.

\[
q(t) = \int_i(t) dt + q(0) - C_e U_e(t) \quad (2.9)
\]

Figure 2.7 shows the resulting lissajous plot (dotted figure). The width of the diagram will now correspond to twice \( U_{max} \). Formula 2.3 can be applied to determine the actual discharge inception voltage \( U_{dis} \). The SDBD's power dissipation can subsequently be estimated for any applied AC electrode voltage by equation 2.4.

### 2.2.2 SDBD pulsed operation

The AC excited plasma consists of small short live local discharges which extinguish almost immediately due to the voltage drop in the gap. For uni-polar ns pulses the SDBD reactor behaves differently. The high \( dU/dt \) of the pulse slopes results in a larger discharge current, which results in a single discharge on the rising edge and a second discharge on the falling edge of the pulse. For DBD, the gap voltage is also able to exceed the static discharge inception voltage of the gap [Ble03].

![Figure 2.8: Pulsed push pull circuit](image)

![Figure 2.9: Schematic pulse waveform](image)

Figure 2.8 shows a SDBD equivalent model connected to a push-pull circuit, which is required to initiate the primary and secondary discharge. The voltage over the gap \( (U_g) \) increases until discharge inception, after switch \( S_1 \) is closed (figure 2.9). A large current is able to flow through the discharge which ideally continues to exist until the \( dU/dt \) of the voltage over the dielectric barrier \( (U_d) \) becomes zero. So the transition of the discharges into a spark is prevented by the accumulation of charges on the dielectric surface, which reduces the electric field in the gap and eventually quenches the discharge.
Capacitance \( C_e \) and \( C_d \) will be charged to \( U_e \); \( C_e \) at point 1 and \( C_d \) at point 2. The gap voltage will become negative when \( S_1 \) is opened and \( S_2 \) is closed which pulls the electrode voltage towards ground level. The energy which is stored on the dielectric surface (capacitance \( C_d \)) will be dissipated in the plasma after the negative discharge is initiated. Ideally all energy is dissipated but a charge is left on the dielectric surface if the discharge quenches earlier. The discharge behavior cannot be modeled by zener diodes because the gap voltage \( U_g \) does not remain constant during the discharge. A current source is for this reason admitted in the equivalent model. Consequently the discharge behavior cannot be predicted for pulsed operation with this model. Beside the modeling problem a main disadvantage of pulsed operation is the dissipation of the energy stored in electrode capacitance \( C_e \) in \( S_2 \) during the falling edge of the pulse. The same capacitance has to be charged in nano seconds during the rising edge. Consequently the pulse source has to source and sink high currents.

### 2.3 Analytic SDBD model

Some measurements in chapter 4 will show that the DBD model is feasible for a SDBD if the electrode capacitance is added. Capacitances \( C_e \) and \( C_d \) can be estimated with the lissajous figure and proved to have nearly constant values. Liu and Neiger introduced an analytic model to calculate the actual gap voltage \( U_g \) and discharge current \( i_{p,g} \) out of the measured applied voltage and current for a DBD [Liu03]. The electrode capacitance \( C_e \) is admitted in the analytic expressions for gap voltage and discharge current of the DBD model which is shown in figure 2.10 (within dotted lines). The discharge plasma is modeled by a current source, the capacitance \( C_g \) is assumed to be constant. The model can be applied for AC but also for pulse plasma excitation if assumed that the parasitic inductance of the electrode strips is negligible for high frequency pulsed operation.

\[
i_{s,a} \text{ can easily be calculated by subtracting the electrode capacitance displacement current of the total external measured current } (i(t)):\n\]

\[
i_{s,a} = i(t) - C_e \frac{du_e(t)}{dt}
\]

(2.10)

First the discharge current \( i_{p,g}(t) \) will be determined. The following equations can derived by applying kirchoff’s theorem.

\[
i_{s,a}(t) = C_g \frac{du_g(t)}{dt} \quad \Rightarrow \quad \frac{du_g(t)}{dt} = \frac{i_{s,a}(t)}{C_g}
\]

(2.11)

\[
i_{s,a}(t) = C_g \frac{du_g(t)}{dt} + i_{p,g}(t) \quad \Rightarrow \quad \frac{du_g(t)}{dt} = \frac{1}{C_g} \left( i_{s,a}(t) - i_{p,g}(t) \right)
\]

(2.12)

\[
u_e(t) = u_e(t) + u_g(t) \quad \Rightarrow \quad \frac{du_e(t)}{dt} = \frac{du_e(t)}{dt} + \frac{du_g(t)}{dt}
\]

(2.13)

Substitution of (2.11) and (2.12) into (2.13) results in:

\[
\frac{du_e(t)}{dt} = \frac{1}{C_g} \left( i_{s,a}(t) - i_{p,g}(t) \right) + \frac{i_{p,g}(t)}{C_g} = \left( \frac{1}{C_s} + \frac{1}{C_g} \right) i_{s,a}(t) - \frac{i_{p,g}(t)}{C_s}
\]

(2.14)

Rearranging (2.14) will result in the solution for \( i_{p,g}(t) \):

\[
i_{p,g}(t) = \left( \frac{1}{C_s} + \frac{1}{C_g} \right) i_{s,a}(t) - C_s \frac{du_e(t)}{dt}
\]

(2.15)
The discharge current as function of the external current can be obtained by substituting (2.10) into (2.15) and rearranging the equation.

\[ i_{p}(t) = \left( 1 + \frac{C_{e}}{C_{d}} \right) i(t) - \left( C_{e} + C_{d} + \frac{C_{d} C_{e}}{C_{d}} \right) \frac{d u_{g}(t)}{d t} \]  

(2.16)

The voltage over the gap can be determined by subtracting the voltage over the barrier \( U_{d} \) of the electrode voltage \( U_{e} \). The instantaneous voltage \( u_{g}(t) \) can be calculated by equation (2.17).

\[ u_{g}(t) = \frac{1}{C_{d} g} \int_{0}^{t} i_{p}(\tau) d\tau + u_{g}(0) \]  

(2.17)

**AC gap voltage calculation**

Now a problem arises for AC excitation because the initial voltage over the dielectric barrier (\( U_{d}(0) \)) has to be known on \( t = 0 \). It is possible to calculate this value if assumed that the voltage waveform over the barrier is strictly symmetric (2.18), where \( T \) is the period time of the applied voltage \( U_{e} \).

\[ u_{g}(t + \frac{T}{2}) = -u_{g}(t) \]  

(2.18)

An expression for \( U_{d}(0) \) can be derived if (2.17) is substituted in (2.18) and subsequently rearranged into equation (2.19)

\[ u_{g}(0) = \frac{1}{2C_{d}} \int_{0}^{r/2} i_{p}(\tau) d\tau \]  

(2.19)

The voltage waveform over the barrier won't be strictly symmetric in practice but equation 2.19 will give a good estimate of \( U_{d}(0) \). An error in this voltage will only result in a DC offset in the barrier voltage and subsequently in the gap voltage. The gap voltage can subsequently be calculated by equation (2.20).

\[ u_{g}(t) = u_{e}(t) - u_{g}(t) = u_{e}(t) - \frac{1}{C_{d} g} \int_{0}^{t} i_{p}(\tau) d\tau - u_{g}(0) \]  

(2.20)

By substituting (2.10) and (2.19) into (2.20) the following expression for gap voltage as function of total external electrode voltage and current can be obtained:

\[ u_{g}(t) = u_{e}(t) - \frac{1}{C_{d} g} \left( \int_{0}^{t} i(\tau) d\tau + C_{e} \left( u_{e}(t) - u_{g}(0) \right) \right) + \frac{1}{2C_{d}} \left( \int_{0}^{T/2} i(\tau) d\tau - C_{e} \left( u_{e}(T/2) - u_{g}(0) \right) \right) \]  

(2.21)

This equation can be rearranged into equation (2.22)

\[ u_{g}(t) = u_{e}(t) - \frac{1}{2C_{d}} \left( 2 \int_{0}^{t} i(\tau) d\tau + \int_{0}^{T/2} i(\tau) d\tau + C_{e} \left( 2u_{e}(t) - u_{e}(T/2) - u_{g}(0) \right) \right) \]  

(2.22)

The time zero can be an arbitrary point in time because the calculation of the initial barrier voltage is included.

**Pulsed gap voltage calculation**

Gap voltage \( u_{g}(t) \) is more difficult to determine for pulse excitation because the initial surface dielectric charge before the pulse is unknown (voltage over the dielectric barrier; \( U_{d}(0) \)). It has to be estimated or assumed to be negligible. Equation (2.23) is obtained if (2.10) is substituted into (2.17).  

\[ u_{g}(t) = u_{e}(t) - \frac{1}{C_{d} g} \left( \int_{0}^{t} i(\tau) d\tau - C_{e} \left( u_{e}(t) - u_{g}(0) \right) \right) - u_{g}(0) \]  

(2.23)

This can be rearranged into (2.24) if the time zero is chosen before the pulse when the electrode voltage \( u_{e}(t) \) is zero.

\[ u_{g}(t) = u_{e}(t) \left( 1 + \frac{C_{e}}{C_{d}} \right) - \frac{1}{C_{d} g} \int_{0}^{t} i(\tau) d\tau - u_{g}(0) \]  

(2.24)
3 Experimental setup

This chapter provides information about the equipment which is used during experiments. The SDBD reactor and two different power modulators (AC and pulse) will first be introduced. Electrical measuring equipment will subsequently be discussed. Information about the setup which is used to measure ozone yields can be found in section 3.5. An ICCD camera setup is introduced which was used to study the pulsed and AC excited plasma optically.

### 3.1 SDBD reactor

The dielectric barrier of the reactor used during experiments is constructed of a 1 mm thick 200mm x 100mm aluminum oxide (Al₂O₃) plate. This ceramic material has a ϵᵣ of 9.8 [Rot06] and a very low loss factor. The high voltage electrode consists of 20 parallel platinum strips which are printed on top of the dielectric barrier. The 1 mm wide strips are 180mm long and are printed with a mutual distance of 3 mm. Platinum is used for the electrode to prevent oxidation. A platinum ground plane is printed on the back of the plate. Total capacitance between ground plane and electrode is ≈ 700pF.

![Figure 3.1: SDBD reactor](image)

### 3.2 Power modulators

#### 3.2.1 AC power modulator

The basic circuit of the AC power modulator is shown in figure 3.2. The power source is energized by a single phase main supply. D₁-D₄ rectifies the AC current to enable charging of buffer capacitor C₁. Thyristors T₁ and T₂ provide phase proportioning to regulate the voltage over C₁. This enables the control circuit of the modulator to regulate the output voltage of the inverter, and thereby the output power.

![Figure 3.2: AC modulator circuit](image)

IGBTs S₁ and S₂ are switched-on during alternate half cycles, each with a conduction cycle approaching 180°, creating a square wave voltage over C₂-T₁ (figure 3.3). Capacitor C₂ blocks the DC voltage of the square wave.

![Figure 3.3: AC modulator waveforms](image)
The transformer has multiple primary and secondary taps. For these experiments, the taps are connected to obtain a 1:25 winding ratio. The stray inductance of the transformer forms a resonant circuit with the capacitance of the SDBD reactor which results into a sinusoidal load current. The control circuit tunes the frequency of the square wave to the resonance frequency of this LC circuit. Optimally the reactor current will be in phase with the square wave over C2-T1. The IGBT’s operate with zero current switching (ZCS), turning on and off as the load current crosses zero. Apparently the output voltage of the transformer depends not only on the turn ratio of the transformer but also on the Q of the LC circuit which is determined by the discharge activity of the reactor. Since the SDBD reactor has a relative high capacitance the modulator always operates at its minimum frequency of 22 kHz. This means the circuit is out of resonance and the transistors do not switch at the zero crossings because the load current is out of phase. Diodes over the IGBT’s which are omitted in figure 3.2 enable the load current to freewheel in the circuit.

3.2.2 Pulse power modulator

The pulse source used during experiments is an unconventional switching system which is described in detail in [Pem03]. Switching is performed by very fast recovery drift step recovery diodes (DSRD) which act as opening switches in combination with inductive stored energy. The diode uses super fast recovery in silicon p-n junctions during forward to reverse conduction of high currents. Recovery occurs when the charge injected during forward current conduction equals the charge extracted during reverse operation.

Resonant circuits are applied to supply the forward, reverse current and the inductive storage of energy. The principle of the DSRD pulse generator is shown in figure 3.4.

![Figure 3.4: DSRD principle](image)

![Figure 3.5: DSRD current and output voltage waveform](image)

Capacitors C1 and C2 have the same value and are initially charged: C1 to a negative voltage and C2 to a positive voltage. A forward current If flows through the diode via C1-DSRD-L1-S1 when switch S1 is closed (figure 3.5). Electron hole plasma is pumped into the diode junction during this step. On the zero crossing of the current the voltage over C1 has been inverted and S2 will be closed. The resulting currents through L1 and L2 will flow in the reverse direction through the diode via C2-S2-L2-DSRD and C1-S1-L1-DSRD. The plasma is gradually pulled out of the p-n regions of the diode. The charge carriers are wiped out of the diode twice as fast because the current has doubled. At the top of the current all energy is stored in the inductors and the voltage over C1 and C2 will be zero. The diode recovers and the inductor currents are commutated into the load resistor, forming a high voltage pulse. The recovery time of the diode determines the rise time of the pulse. The voltage amplitude of the pulse is determined by the peak diode current and the value of the load resistor. The pulse width is determined by the time constant \( \tau = L/R_{\text{load}} \), where \( L = L_1/L_2 \).

The actual circuit of the pulse source and reactor which has been used during experiments is shown in figure 3.6. Magnetic switches and a saturable transformer is applied to switch the high voltages and currents.

![Figure 3.6: DSRD power modulator circuit](image)
At initial state the transformer $T_{r1}$ is unsaturated; inductances $L_1$ and $L_2$ are saturated. Capacitor $C_1$ is charged to 0.9kV. $C_2$ is resonantly charged to 28kV via $C_1$-RSD-D1-$T_{r1}$-$C_2$-$L_1$-$L_2$ after the RSD (Reverse Switch-on Dynistor) switch is triggered. Transformer $T_{r1}$ is saturated after this 3.5μs charging cycle and subsequently $C_3$ is charged via $C_2$-$C_3$-$T_{r1}$, $L_1$ and $L_2$ are unsaturated during this cycle. $L_3$ saturates subsequently and $C_4$ is charged via $C_3$-DSRD-$C_4$-$L_3$ in 300ns. The resulting forward current $I_f$ through the DSRD is called the pumping cycle, as result of the current plasma is pulled into the diode. Inductor $L_2$ saturates when the total charge has been transferred from $C_3$ to $C_4$. The resulting reverse current $I_r$ will flow through the diode via $C_4$-DSRD-$L_2$. The maximum current is reached after 80ns, the voltage over $C_4$ is zero and all energy will be stored in the $L_2$. At this point the plasma is pulled off the DSRD again. The diode recovers and the current commutates in about 3ns into the 50Ω transmission line. The inductors peak current and the 50Ω impedance of the transmission line result in a 60kV pulse. The other side of the line is terminated by $R_1$ and $R_2$. The sum of these resistors is equal to 50Ω. The center tap of the series resistors is connected to the SDBD reactor. The peak voltage over the reactor can be controlled by varying $R_1$ and $R_2$. The current is divided between the reactor and $R_1$ during the rising edge. The reactor capacitance is charged to a certain voltage when the top of the pulse is reached. The reactor capacitance is able to discharge via $R_1$ on the falling edge of the pulse. The electrode charge and a part of the dielectric surface charge will be subsequently dissipated in $R_1$.

3.3 Equipment for electrical measurements

The AC and pulsed voltages were measured using a North Star PVM-1 high voltage probe. The bandwidth of the probe is 80MHz. The probe attenuates the voltage by a factor 1000. Current was measured with a Pearson 6600 current monitor. The monitor has a bandwidth of 120 MHz, is able to measure a maximum rise time up to 5ns, and has a sensitivity of the monitor is 0.05V/A when terminated with 50Ω. Data was recorded using a LT584L oscilloscope.

3.4 Setup for ozone measurements

Measurement of $O_3$ production was applied to compare chemical activity of pulsed and AC excited plasma. The $O_3$ concentration was measured with a technique called UV (Ultra Violet) absorption spectroscopy. A schematic overview of the setup is shown in figure 3.7.

![Schematic ozone yield measurement setup](image)

Figure 3.7: Schematic ozone yield measurement setup
Ozone (O₃) is a triatomic molecule consisting of three oxygen atoms. It is an allotropy of oxygen that is much less stable than O₂. It can be produced out of air under the influence of electrical discharges. Energetic electrons collide with the gas molecules during the discharge, creating O radicals. These radicals form O₃ when they combine with O₂. Only a part of the energy is converted into O radicals. Remainder energy is converted as result of elastic collisions, excitation, ionization, and dissociation of N₂ and H₂O molecules. A detailed overview of the chemistry and physics which occur during discharges can be found in [Han07].

The ozone is produced when air is flushed along the surface of the reactor. The amount of produced O₃ can be utilized to evaluate the quality of the plasma. Efficient plasma converts energy in radical production instead of heat, light emission, etc.

The SDBD reactor is placed in a gas tight chamber (figure 3.7). Compressed air is fed in at the bottom of the diagram. The flow rate can be controlled with a valve and measured by a flow meter. The gas is uniformly distributed over the width of the SDBD by a tube with a small slit. The chamber is covered with a glass plate. The distance between the surface of the SDBD reactor and the glass plate is 3mm. A part of the gas flows over the corona discharges because they only exist along the surface of the reactor. This side affect will probably lower the concentration O₃ because an unknown amount of the gas leaves the chamber untreated. However it won’t make a difference for the comparison.

The AC excited plasma produces heat which heats up the dielectric barrier of the reactor. The temperature also has an affect on O₃ production [Han07][Bau82]. The SDBD is placed on top of an aluminum water cooled heat sink to prevent heat up. The heat sink is fed with tap water, ensuring a dielectric barrier temperature which will be near the water temperature. The cooling is essential to make a good comparison because the pulsed excited plasma generates presumably less heat than the AC excited plasma.

The treated air is accumulated in the back of the setup and fed outside by a 35cm long, 40mm thick plastic hose. The hose is connected to a 30cm, 34mm (inner diameter) thick metal pipe. The purpose of the pipe is to ensure a laminar flow. The end of the pipe is connected to an air exhaust, because high concentrations O₃ are harmful to health.

Two quartz lenses with a mutual distance of 46mm (optical path: d) are mounted at the end of the pipe. An Ocean Optics UV deuterium lamp is connected to one of the lenses via an optical fiber. The other lens is via an optical fiber connected to an Ocean Optics HR2000 UV spectrometer. The spectrometer is connected to a PC to acquire the spectral data. A part of the UV light beam is absorbed when O₃ passes the lenses. The amplitude of the UV spectrum can used to calculate the O₃ concentration.

### 3.5 Setup for optical measurements

An intensified charged coupled device (ICCD) camera was used to study the pulsed and AC excited plasma optically. The Princeton Instruments 576G/RB camera (180-800nm, 576x384) with a Sigma 180 lens has the ability to take pictures with a minimum shutter speed of 5 ns. The camera was used to photograph single pulse plasma and plasma discharges during multiple pulses/AC periods. The images should answer some questions about homogeneousness of the plasma and if there’s pulse/AC parameter dependency on the plasma coverage of the reactor.
Figure 3.8 shows a schematic overview of the setup which was used during the experiments. Actually the same setup is used which was constructed for the ozone yield measurement. A surface mirror placed under an angle of 45° had to be used since the SDBD reactor and camera are placed horizontally. The pictures were taken through the glass plate although the window-glass is omitted in this figure.

The camera is able to operate in two modes. In the triggered mode, the camera’s shutter speed and moment is controlled by an external circuit. In the software controlled mode, the PC controls the shutter. The first mode was used to make images of single shot pulsed excited plasma. The DSRD power modulator delivers an advanced sync signal of 15 μs prior to the actual high voltage pulse. The camera’s control circuit has a 75ns delay between the moment of triggering the shutter control and the actual opening of the camera’s gate. So the adjustable delay (figure 3.8) could be set to a maximum of 14.925 μs (15 μs - 75ns) if the gate should be opened at the beginning of the HV pulse. The shutter speed can be set to a maximum of 2μs.

Triggering of the camera for AC excited plasma images was less difficult because of the larger timescale. The delay of the camera and controller can be neglected. The camera was triggered with the trigger-out of the oscilloscope. The trigger moment can be adjusted by adjusting the trigger level on the oscilloscope.
4 Experimental results

This chapter describes several methods to measure energy dissipation of the SDBD’s pulsed and AC excited plasma. The lissajous method is applied to determine several parameters of the earlier introduced SDBD model.
Chemical activity of the AC and pulsed excited plasma is observed by comparing power dissipation and ozone production of the two different plasma excitations.
Several images of the plasma were made with the ICCD camera. The images reveal information about length of streamers and homogeneity of the plasma during a single pulse.

4.1 Electrical measurements

4.1.1 AC Plasma power dissipation

Power dissipation of the AC excited plasma can be measured with several methods. The earlier described lissajous method can be applied to calculate the energy dissipation of a single period, by determining the surface of the lissajous plot. The total power dissipation can subsequently be calculated by multiplying the surface value by the frequency of the applied electrode voltage. The lissajous figure is created by plotting the reactor charge (Q) vs. the applied electrode voltage (Ud).
The instantaneous charge of the reactor can be calculated by integrating the current through the reactor (equation 4.1).

\[
q_{sDBD}(t) = \int_{0}^{t} i(\tau) d\tau + q_{sDBD}(0) \quad 0 < t < T
\]

(4.1)

The current can be measured with a current monitor (figure 4.1b) and integrated afterwards.

A second option is to insert a measuring capacitor Cm in series with the reactor (figure 4.1a). The measuring capacitor integrates the current directly since:

\[
u_{Cm}(t) = \int_{0}^{t} i(\tau) d\tau + u_{Cm}(0)
\]

(4.2)

The instantaneous reactor charge \(q_{sDBD}(t)\) can be determined by measuring the voltage over the capacitor and multiplying the voltage by the capacitance of the Cm. The charge accumulated on the reactor will be equal to the charge in the capacitor.

\[
q_{sDBD}(t) = q_{Cm}(t) = C_m u_{Cm}(t)
\]

(4.3)

The series reactor and measure capacitances act as a voltage divider. The value of Cm needs to be much higher than the reactor capacitance in order to minimize the voltage over Cm and to maximize the reactor voltage. The reactor capacitance has values between 700pF and 1300pF; a typical value for Cm would be for instance 30nF. Two voltage probes are needed, the voltage over the reactor can be calculated by subtracted the two measured voltages. Disadvantage of this configuration is that the reactor has a floating ground potential. Placing the capacitor in series with the high voltage line is also possible, but two 'high' voltages have to be subtracted to obtain the voltage over the capacitor resulting in low measuring resolution. Second disadvantage is the uncertain frequency response of Cm resulting in possible measurement errors.
Second possibility to calculate the power dissipation is integration of the instantaneous power over a single or multiple AC period(s). Voltage and current are measured as shown in figure 4.1b. Disadvantage is that offset in current and voltage measurement can result in relative large errors, because the offset is integrated.

\[
P = \frac{1}{T} \int_{T_0}^{T} u(\tau)i(\tau) d\tau
\]  

(4.4)

Typical measured AC waveforms of the applied electrode voltage and current are shown in figure 4.2. The spikes on the top of the current waveform are the result of the positive burst of micro discharges. Figure 4.2b shows a low frequent modulation of the current and voltage waveform. The AC modulator is power controlled; the control unit presumably causes the jittering of the amplitude. To obtain an accurate power measurement the dissipation per period during time interval \(t_1\) to \(t_2\) has to be averaged. The sample rate of the oscilloscope is limited to 10Msamples/s by the relative large (typical 10ms) record length. Sampling of the 22kHz waveform corresponds to \(\approx 450\) samples per period.

![Figure 4.2: Typical AC waveforms of the reactor voltage and current](image)

A matlab script is added in appendix A. which is used to calculate the surface of the lissajous plot. The boundaries \(t_1\) and \(t_2\) are set by adjusting a threshold level within the modulation ripple. The charge on the reactor was determined by integrating the measured current. For each period within this range the surface of the plot is calculated and subsequently averaged.

Calculation by integration of power is also added in the script. The average power is calculated using equation 4.5. The offset is removed by subtracting the mean value of the voltage and current calculated from \(t_1\) to \(t_2\) (complete number of periods).

\[
P = \frac{1}{T} \int_{t_1}^{t_2} (u(\tau) - \bar{u})(i(\tau) - \bar{i}) d\tau
\]  

(4.5)

Both calculations gave similar results with deviations up to 10%. For further power calculations only the last method was used, because it proved to be difficult to determine the surface of the lissajous plot accurately and to create a floating reactor ground in the setup.

The dielectric losses of the reactor should be taken into account if the exact power dissipation of the plasma has to be determined. The losses can be split into two parts, the losses of the dielectric material under the electrode and the losses of the dielectric discharge area when discharges occur. Equation 4.6 can be used to calculate the dielectric losses of a parallel plate capacitor. It is applied to determine the losses of the dielectric material between ground plane and electrode of the SDBD.

\[
P = \frac{2\pi fA}{d} \varepsilon_0 \varepsilon_r \tan \delta
\]  

(4.6)

\(A\) is the surface of the electrodes and \(d\) the thickness of the dielectric material. The loss factor \(\tan \delta\) of aluminum oxide can be found in literature and has a value of 0.0004 (1MHz) [Rot06]. \(U_{\text{rms}}\) was calculated with equation 4.7.

\[
U_{\text{rms}} = \sqrt{\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} U(\tau)^2 d\tau}
\]  

(4.7)
The losses proved to be negligible; for instance, the dielectric dissipation is 136µW for 3.5kV RMS voltage, during a total power dissipation of 300W. No effort was made to determine the losses of the dielectric during discharges, because the discharge area is even smaller than the electrode area. The heat up of the dielectric is apparently only caused by the plasma.

Figure 4.3 shows the plasma's power dissipation (equation 4.5) as function of the RMS voltage (equation 4.7). This particular measurement is made during the ozone yield measurements which will be described in the next paragraph. The reactor power dissipation appears to be linear with the amplitude of the applied RMS electrode voltage.

4.1.2 Pulsed plasma power dissipation

The reactor voltage and current have to be measured in order to determine the instantaneous power of the pulse (equation 4.8). The instantaneous energy can subsequently be determined by integrating the power waveform (equation 4.9). The length of the probes coaxial cables have to be equal, because the cables have a non negligible typical distance-velocity lag of 5ns. An unequal length can cause phase shift of the signals resulting in power calculation errors.

\[ p(t) = u(t)i(t), t \geq 0 \]  
\[ E(t) = \int_0^t p(\tau)d\tau \]  

The energy per pulse during the ozone yield measurements was varied by setting four different peak voltages with the resistive divider. The power was subsequently controlled by adjusting the repetition rate (0 - 1200Hz) of the pulses. An overview of the averaged pulse parameters is shown in table 4.1. The corresponding typical waveforms are shown in figure 4.4. Rise time of the pulses is approximately 20ns. The amount of energy dissipated in the plasma can be determined from the stable value at the end of the energy waveform. The difference between this value and the peak value of the energy waveform is capacitive stored reactor energy which will be dissipated in the parallel resistor (R₁ figure 3.6) during the falling edge of the pulse.

![Figure 4.3: RMS reactor voltage level versus power dissipation](image)

![Figure 4.4: Typical pulse waveforms](image)
Multiple pulses were recorded during experiments. The value for energy dissipation was calculated for each measurement, the resulting values were averaged afterwards for higher accuracy. Power dissipation was subsequently calculated by multiplying this mean value by the repetition rate of the pulses. The repetition rate was measured with a counter. The amount of power which can be dissipated in the plasma is limited by the repetition rate, resulting in a maximum of 13.8W (11.5mJ · 1200Hz). So ozone yields can unfortunately only be compared at low power levels, since the AC excited plasma reaches a power dissipation of 300W (figure 4.3).

### 4.1.3 Model verification

The lissajous method was applied to determine the capacitances $C_d$ and $C_g$ for the earlier proposed SDBD model (figure 4.5). Figure 4.6 shows two typical lissajous plots of the same single 4.8kV (peak) AC period. First the total reactor charge is plotted, second by the electrode charge is subtracted of the total charge according to equation 2.9. The electrode capacitance used for this calculation was measured with a LCR meter and had a value of $\approx 700\, \mu F$. The slopes of the second plot subsequently correspond to capacitances $C_d$ and equivalent series capacitance of $C_d$ and $C_g$. The positive discharges occur during time interval $2 \rightarrow 3$. Negative discharges take place during interval $4 \rightarrow 1$. The discharge inception voltage can be calculated by equation 2.3. $U_{\text{in}}$ will be near $U_{\text{dis}}$, because the gap capacitance has a relative low value. The width of the plot corresponds to twice $U_{\text{in}}$; the resulting discharge voltage is approximately 2.5kV.

The value of $C_d$ depends on the amount of discharges covering the surface of the SDBD. The plasma is non homogeneous at relative low applied reactor voltages, a lower value of $C_d$ is then expected. Several measurements were done to investigate the dependency of reactor voltage/power on the capacitance $C_d$. The matlab script added in appendix A is able to calculate the average power dissipation, applied RMS electrode voltage and average value of each slope during a single period. The values of the slopes of $\approx 220$ periods during time interval $t_1 \rightarrow t_2$ were subsequently averaged to obtain accurate values, and are used to calculate the capacitances $C_d$ and $C_g$. Figure 4.7 shows the resulting capacitances for 15 different applied RMS electrode voltages. The capacitance $C_d$ seems to have a lower value for relative low voltages because the surface of the reactor isn’t completely covered with discharges (figure 4.8). When the voltage is increased to 3kV ($\approx 225\, \text{W}$) the value of $C_d$ stabilizes. At this point the plasma is visually also homogeneous (figure 4.9). $C_d$ appears to be a fixed parameter for homogeneous plasma. Second observation is the overall lower value of $C_d$ for the negative discharges. These discharges seem to be initiated differently compared to the positive discharges.

The value of $C_g$ is very low because the electrode is very thin and placed on top of the dielectric. The value should be a fixed parameter, spreading is presumably caused by measuring/calculation errors.
4.1.4 AC model simulation

The model as in figure 4.5 was implemented in Pspice to compare the measurements with simulations. These simulations should give information about the validity of the model. The Pspice model is shown in Appendix B. The model doesn't provide two dielectric capacitances for positive and negative discharges. For this reason the average value for \( C_d \) of 550pF is chosen, since the applied voltage is high enough to initiate completely homogenous plasma. For this particular simulation capacitance \( C_g \) was chosen to be 40pF. Applied electrode voltage \( U_e \) and current (figure 4.11) are the actual measured waveforms, which were used to plot the measured lissajous plot in figure 4.6 and 4.10.

High frequency noise is rejected from the voltage waveform by applying a moving average filter. This is necessary because Pspice utilizes numerical calculations, noise can cause simulation problems when for instance calculating derivatives. The filtered measured data has subsequently been converted to a format which Pspice is able to handle. The simulated current waveform is integrated and a single period is also plotted versus the measured applied electrode voltage \( U_e \) in figure 4.10. The diagrams appear to be almost identical. Corners 2 and 4 of the measured plot are less abrupt, the burst of discharges appear to be initiated slowly. The measured and simulated current waveforms are
plotted in figure 4.11. It is clearly visible that the start of the simulated and measures positive discharge interval correspond to each other. The oscillation of the current during discharge is the result of the non pure sinusoidal electrode voltage waveform. Nevertheless the current waveform is a good approach because the simulated lissajous plot is a good estimation of the measured plot. The approximately equal surface of the lissajous plots confirms that the model can be used to estimate power dissipation.

4.1.5 Analytical gap voltage and discharge current calculation

Capacitances $C_d (=550\,\text{pF})$ and $C_g (=40\,\text{pF})$ are assumed to have fixed values for homogeneous plasma. This means that the analytical model as derived in section 2.3 can be applied to estimate the actual gap voltage and discharge current. Equations 2.18 and 2.12 are implemented in a Matlab script to plot figure 4.12 utilizing the measured current and filtered applied electrode voltage of figure 4.11. The $\approx 5\,\text{kV}$ voltage swing of the gap voltage between discharges seems to correspond to the voltage swing which was earlier determined by the lissajous figure. Care should be taken with interpreting these waveforms because the capacitance $C_d$ does not have a constant value at corners 2 and 3 of the lissajous plot (figure 4.10), because the discharges are initiated relative slow. Another problem is that the model doesn’t provide two dielectric capacitances for positive and negative discharges. The gap voltage spike which can be seen at point 2 in figure 4.12 is presumably a consequence of these deficiencies in the analytic model.

Figure 4.12: Typical AC gap voltage and discharge current

The instantaneous discharge impedance (figure 4.13) is calculated by dividing the gap voltage by the discharge current. During the time intervals that no discharges occur, the impedance is given a value of $r(t)=0$ for convenience. A moving average filter is subsequently applied to smooth the plasma impedance waveform.

Expressions 3.15 and 3.24 are applied to calculate the actual gap voltage and discharge current during ns pulsed operation. Capacitances $C_d$ and $C_g$ cannot be estimated from a single pulse lissajous plot because the gap voltage does not have a constant value during discharges as explained in section 2.2.2. For this reason the capacitance $C_d$ is assumed to be $550\,\text{pF}$ and $C_g$ $40\,\text{pF}$. The external applied voltage $U_e$ and current $I$ of pulse 2 (table 4.1) are used to calculate the gap voltage $U_g$ and discharge current $I_{dis} (= I_{p,k})$ which are shown in figure 4.14.

Figure 4.13: Typical AC discharge impedance

Figure 4.14: Typical pulsed reactor waveforms
The gap voltage has a constant offset of \(-1800\text{V}\) at \(t=300\text{ns}\); there appears to be a residual charge on the dielectric barrier (voltage over \(C_d\)) after the pulse since the applied electrode voltage \(U_e\) is zero at this point. This charge is presumably lost before the next pulse because the gap voltage \(U_g\) at \(t=0\) is unequal to \(U_g\) at \(t=300\text{ns}\). For this reason the initial voltage over the dielectric barrier \(u_d(0)\) is set to zero in this figure.

The positive discharge inception voltage appears to be reached at about \(4\text{kV}\). The negative gap voltage reaches almost \(5\text{kV}\). However, the discharge voltage is able to exceed the static discharge inception voltage of the gap for DBD [Ble03], it is questionable that these values are correct because a pulsed applied electrode voltage \(U_e\) of \(3.5\text{kV}\) is already enough to initiate discharges.

Further research is needed to determine the actual dielectric surface capacitance \(C_d\). Possibly this value isn’t constant during the discharge. Furthermore should be investigated if the parasitic inductance of the strips can be neglected.

4.2 Ozone yield measurement

The conditions under which the experiments were performed will first be clarified. How the spectral measurements can be converted into \(\text{O}_3\) concentrations will subsequently be discussed. Several \(\text{O}_3\) yield measurements of pulsed and AC excited plasma can be found in section 4.2.2.

4.2.1 Experiments

Flow and gas temperature

All experiments were performed at a gas flow rate of \(10\ \text{l/min}\). Dried synthetic air was used to eliminate deviations in humidity, which affects \(\text{O}_3\) production. Heat up of the processed gas due to the plasma was neglected because the temperature difference between in and outgoing air was less than \(3\ \text{°C}\) during the worst case situation (300W AC excited plasma), measured near the reactor. The increase of temperature wasn’t noticeable at the exhaust. Ambient temperature was 20-21°C.

Spectral measurements

The \(\text{O}_3\) concentration (\(\text{cmolecules/m}^3\)) can be calculated by applying Beer’s Law:

\[
\ln \left( \frac{I(\lambda)}{I_0(\lambda)} \right) = c_o \cdot \varepsilon(\lambda) \cdot d \tag{4.10}
\]

Where \(I(\lambda)\) is the absorption spectrum, \(I_0(\lambda)\) the background spectrum (gas flow without \(\text{O}_3\)), \(\varepsilon(\lambda)\) is the absorption cross-section (m²/molecule) of \(\text{O}_3\) as function of wavelength and \(d\) is the distance between the quartz lenses. The values for \(\varepsilon(\lambda)\) can be found in literature [Sei86]. The ozone yield is determined for 17 different wavelengths in the Hartley-band (230-290nm), where ozone absorption is maximum. These values are subsequently averaged to obtain an accurate \(\text{O}_3\) concentration. The result is divided by Avogadro’s number \((N_o)\) to determine the concentration \(\text{O}_3\) in mol/m³. This \(\text{O}_3\) concentration value is converted into ppm (parts per million) by applying the ideal gas law.

\[
n = \frac{PV}{RT} \tag{4.11}
\]

\[
R = k_o N_o J \text{mol}^{-1} \text{K}^{-1} \tag{4.12}
\]

The total amount of mol/m³ \((n)\) in ideal gas is determined at \(P=1\text{e}5 \text{pascal} (=1 \text{bar}), 294\text{K} (=21\text{°C})\) and \(V=1\text{m}^3\), using equations 4.11 and 4.12 with Avogadro’s number and Boltzmann’s constant. Equation 4.13 is subsequently applied to determine the \(\text{O}_3\) concentration in ppm.

\[
c_{\text{O}_3,\text{ppm}} = \frac{10^6 c_{\text{O}_3\text{mol/m}^3}}{n_{\text{mol/m}^3}} \tag{4.13}
\]

For each power setting the background spectrum \(I_0(\lambda)\) was recorded. The absorption spectrum \(I(\lambda)\) was recorded after the power source was switched-on and the spectrum stabilized. Subsequently the power supply was switched-off and the system was flushed (spectrum stabilized again). This sequence was repeated two times for accuracy. The spectral data was processed using Matlab, the equations above
and the absorption coefficients $\varepsilon(\lambda)$. The three $O_3$ yield measurements were averaged. Deviation between separate concentration measurements was usually less than 1%.

The earlier described power measurements were performed simultaneously with the concentration measurements. The power dissipation is converted into joule/liter to get some notion of energy which is needed to produce a certain amount of $O_3$. For instance with a flow of 10 l/min, 600 J/l corresponds to 100W reactor power.

### 4.2.2 Results

Figure 4.15a shows the $O_3$ yields for the pulsed and AC excited plasma. Figure 4.15b shows a close-up, because only relative low power dissipations for pulsed plasma excitation could be reached. The pulse parameters can be found in table 4.1.

![Figure 4.15: Ozone yield measurements](image)

#### $O_3$ yield AC excited plasma

The AC plasma produces almost no $O_3$ for energy densities smaller than 150 J/l (region 1, figure 4.15a). The applied voltage is relative low; the discharges occur only on small spots on the reactor, resulting in large amounts of untreated gas passing the reactor. The $O_3$ yield increases subsequently linear with the power dissipation in region 2. The yield levels out as the power and the plasma covered area increases (region 3) and saturates in region 4. The $O_3$ yield drops for energy densities larger than 1200 J/l (region 5). Two mechanisms can be responsible for the ozone destruction. Ozone destruction by chemical reactions; produced ozone rapidly reacts with almost all species in the reactor. Second, ozone destruction by thermal decomposition; the destruction process is greatly enhanced for increasing gas temperatures in the streamer channels [han07][Bau82]. The capacitance calculations (figure 4.7a) show that a minimum of ~3kV (corresponds to ~1400 J/l) is required to create a completely homogeneous plasma. Possibly, the extra energy (energy densities larger than ~1400 J/l) results in stronger, more thermal discharges in this experiment which could enhance the second ozone destruction mechanism. The reactor temperature rises significantly for large energy densities if no cooling is applied.

#### $O_3$ yield pulse excited plasma

The main advantage of pulsed operation is the fact that the plasma is very homogenous over the whole surface of the SDBD during each pulse. Pulse 2-4 created, in contrast to Pulse 1, visually homogenous plasma. Nevertheless Pulse1 has the highest efficiency (highest yield at the lowest power). Pulse 4 has the worst performance but a higher energy density could be reached because it had the highest energy per pulse. However, the $O_3$ yield differences are very small for pulse 1-4.

### Comparison and conclusions

Comparison of the pulsed and AC excited plasma is difficult because the $O_3$ yields can’t be compared at high power. The yield can only be compared in an area where the AC plasma is non homogenous and where large amounts of gas leave the reactor chamber untreated. A pulse source which is able run
on very high repetition rates or an AC source with a lower resonance frequency is needed for an unambiguous comparison.
The pulsed excited plasma appears to obtain relative higher O₃ yields with less energy per pulse. Because the O₃ yield differences between pulses 1-4 are small, the efficiency of the pulse source for a certain pulse should be taken into account to determine the most appropriate pulse parameters. This would be senseless in this experimental setup since most of the energy is dissipated in resistors R₁ and R₂ (figure 3.6).
The ozone yield saturates at 300ppm for the AC excited plasma. Ozone destruction mechanisms limit the O₃ yield. Presumably the pulsed excited plasma could have a much higher ozone saturation level, if thermal decomposition of ozone is the main cause of the ozone saturation limit for AC excitation.

4.3 Optical measurement

The camera was used to photograph single pulse plasma and plasma existing out of multiple pulses/AC periods. The images should answer some questions about homogeneity of single shot pulsed excited plasma and if there’s pulse/AC parameter dependency on the plasma surface coverage.

4.3.1 Pulsed single shot images

Jittering of the modulators sync pulse and different distance-velocity lag of several control/measure cables have be taken into account for triggering the camera. Since premature triggering isn’t a problem, the camera is triggered an extra 100ns earlier than the start of the pulse. The width of the high voltage pulse is ≈100ns so the shutter speed was set to 350ns to ensure capture of the complete pulse. The shutter signal can be compared with the high voltage pulse on the oscilloscope to ensure that the shutter signal overlaps the high voltage pulse. The intensifier gain was set to 100% to make the discharges visible.

Single shot images were made with several pulse parameters but all images looked similar to figure 4.16. This particular image was taken from a 7.2kV (pulse 4 as in table 4.1) pulse. The actual grayscale image is converted using a blue color grid. So the colors can deviate from reality. The image shows that the discharges do not fully bridge the gap between the high voltage electrode strips. The major conclusion which can be made from this picture is that the discharges seem to originate over the complete surface of the SDBD. Images of the 3.5kV (pulse 1 as in table 4.1) pulse show similar pictures although non plasma covered spots are visible outside the view of the camera. Increasing the peak voltage of the pulse further than 4kV has only effect on the plasmas intensity.

![Figure 4.16: Single pulse image, 3.5kV (pulse 3 table 4.1)](image)

4.3.2 AC single period images

An attempt was made to make images of a single AC period. The aim was to find out if the discharges also cover the entire surface of the SDBD. Making the images proved to be difficult because the camera’s maximum shutter speed in the triggered mode is 2µs. The AC period has a period length of 45µs. So it is impossible to capture a complete AC period. Using the camera in the software controlled mode by making 45 µs shutter speed images at random moments was also not possible because the minimum speed is 5ns in this mode. Therefore attempts were made to make 2µs shutter speed images. The camera was triggered on the positive peak of AC current (figure 4.2a). At this point the discharges...
should reach maximal intensity (evaluating from the current waveform). The plasma wasn’t visible at all on the images although the camera’s intensifier was set to 100%. These discharges seem to be much weaker than the pulsed discharges since the shutter speed was set almost 6 times longer.

### 4.3.3 Integrated images

The camera had to be used in the software controlled mode with the minimum shutter speed of 5ms in order to make the AC excited discharges visible. All images were made in the dark to eliminate background light. Figure 4.17a shows apparently homogenous plasma. Total reactor power was 160W. It does not give information about the homogeneity of the discharges during a single period because in this case 110 periods (5ms / 45us) are integrated on the CCD of the camera. The bright spots along the strips show that discharges occur at preferred locations. Figure 4.17b shows an image of 100 pulses of the pulse excited plasma. The shutter speed was set to 100ms with a pulse repetition rate of 1kHz. Peak voltage was set to 5.9kV (pulse 3 as in table 4.1). These images show more clearly that the discharges do not fully bridge the gap between the high voltage electrode strips.

![Figure 4.17: Multiple period/pulse images](image)

**Figure 4.17: Multiple period/pulse images**

### 4.3.4 Observation of streamer length

Several images of pulsed and AC excited plasma were made to study the total length of the streamers along the dielectric surface. Possibly the streamers can grow longer if a larger voltage or higher $dU/dt$ is applied to the reactor; reducing the uncovered plasma area between the high voltage electrode strips.

**Procedure**

Discharges originate at the edges of the high voltage strips, high intensity values are expected in these regions. Relative small intensities are expected between the strips; where the discharges do not fully bridge the gap. The intensity values are used to plot an intensity profile which should provide information about the discharge activity along the high voltage strips. These AC and pulsed profiles are compared to investigate differences in discharge activity/intensity, and total length of the streamers. Images like figure 4.18a were made and processed to calculate the average intensity $I_x$ of the plasma.

![Figure 4.18: Plasma intensity figures](image)

**Figure 4.18: Plasma intensity figures**
Matlab was used to load the images in a xy matrix (380x569 pixels). All samples in the y direction were averaged to calculate an average intensity $I(x)$ along the electrode strips and dielectric surface.

$$I(x) = \frac{1}{569} \sum_{y=1}^{569} i(x, y)$$

(4.14)

The result is plotted in figure 4.18b. The intensity of the plasma seems to be higher at the right side of the image. Some complementary images were made to explain this unlikely observation. The camera was turned 90 degrees and the effect was noticed the other way around. The problem seemed to be in the optical path. The window-glass on top of the reactor and possibly the alignment of the mirror and camera causes distortion on intensity. Mutual comparison of images isn’t a problem because they were made under the same circumstances. The intensity of the plasma along the middle three high voltage strips is averaged for even higher accuracy and subsequently multiplied by the actual width per pixel. This intensity ($I(d)$) as function of the distance $d$ is plotted in figure 4.18c.

**Pulsed excited plasma profiles**

Pulsed excited plasma images were made for 5 different peak voltages; pulse 1-4 can be found in table 4.1, the amplitude of pulse 5 is 9.8kV ($R_1/R_2$ divider = 25/50) The shutter speed was set to 100ms and the intensifier was set to 68%. The pulse repetition rate of the power modulator was fixed at 1kHz. Settings were used for all images because the intensity’s of the plasma is compared. Figure 4.19a shows the intensity plots of the five different pulses. The profile of the plasma around the strips looks similar for the five various peak voltage levels. Only the intensity increases with increasing voltage, because more energy is fed into the plasma. Figure 4.19b shows the same plot with scaled intensities. The scaling improves comparison of the profile around the strip. First the offset of the strip intensity is removed; the intensity is subsequently scaled on the maximum intensity (equation 4.16).

$$I(d)_{scaled} = \frac{I(d) - \min(I(d))}{\max(I(d)) - \min(I(d))}$$

(4.16)

The intensity profiles for the five different peak voltages are similar. There seems to be no relations between the peak voltage and the length of the streamers. The higher voltage results only in more intense plasma which also was concluded during the ozone yield measurements.

![Figure 4.19: Pulsed plasma intensity profile](image)

**AC excited plasma profile**

AC excited plasma images were made for four different RMS voltages with the 22kHz oscillation frequency. A minimum of 3kV (~225W) is required to create homogeneous plasma. Two of the voltages in the figure are below or near this minimum. The camera’s shutter speed was set to 5ms to capture about 110 periods.
Figures 4.20 a and b show the plasma profile plots of the processed images. There appears to be two modes of plasma profile along the high voltage strip. The intensity and profile changes when the 3kV boundary is passed. For voltages larger than 3kV, the entire surface of the reactor is covered with discharges. Apparently, the energy cannot be converted into a larger plasma surface coverage, resulting into more intense or faster repetitive discharges. This would explain the increase in intensity of the image in the second mode. The different offset of the strip intensity (-0.5<d<0.5 mm) between the images is presumably caused by plasma which lights up the high voltage strip. This effect can also be seen in figure 4.19a.

**Comparison and conclusions**

Figure 4.21 show several scaled plots of pulse and AC plasma profiles. Only one pulsed plasma profile is plotted because all pulsed profiles are similar. Two plots of the two AC plasma profile modes are also plotted in the figure.

The AC 3.47kV and Pulse 5.90kV plot look very similar. There appears to be no significant difference in streamer length or scaled intensity near the high voltage electrode strip. A persistent mechanism controls the expansion of the streamers. Presumably the interacting E field around the strips and the electron fronts in the head of the streamers from opposite side determine the length of the discharges. More research is needed to determine the exact cause of this effect.

**4.4 Pulse and AC excited plasma comparison**

Although the ozone measurement did not give a conclusive answer, it appeared that the pulsed excited plasma performed better. Ozone destruction mechanisms limit the O₃ yield. Presumably the pulsed excited plasma could have a much higher ozone saturation level, if thermal decomposition of ozone is the main cause of the ozone saturation limit for AC excitation.

The high speed images showed single shot homogeneous pulsed excited plasma. The streamer length appeared to be similar for both plasmas.
Pulse operation would be preferred. However, a solution must be found to recycle the energy in the reactor capacitance, which is not fully used by the discharge. Only then, the full advantage of a high efficiency pulse source can be benefited from. For pulsed operation, it is easy to control the average plasma power by adjusting the repetition rate. The single shot homogeneous plasma ensures homogeneous plasma over the complete power range of the source. Second reason for choosing a pulse source would be the ability to compare the chemical efficiency of the pulsed and AC source at equal power levels and to find the ozone saturation level for pulsed operation. Both concepts suffer from the electrode capacitance $C_e$ which increases reactive power for AC operation and which absorbs energy which is difficult to recycle during ns pulse operation. This problem can probably be reduced by narrowing the strips or eliminated by modifying the reactor. An example with embedded ground electrodes is shown in figure 4.22.

![Figure 4.22: Modified SDBD reactor, imbedded ground electrode](image)

Second alternative SDBD reactor is shown in figure 4.23. Ground and high voltage electrodes are both imbedded in the dielectric. This co-planar SDBD solution will also reduce the capacitance between the electrodes significantly. The thickness of the dielectric between upper surface and electrodes must be larger than the thickness between lower surface and the electrodes to ensure that the discharges occur on the upper surface.

![Figure 4.23: Modified SDBD reactor, imbedded ground and high voltage electrode](image)

The SDBD has to be mounted on top of a heat sink if cooling is required. Drawback of both versions is that there will be a capacitance between the electrodes and the heat sink. However, this capacitance can be reduced by enlarging the thickness of the dielectric material, or by using a low $\varepsilon_r$ dielectric material between the electrodes and the heat sink.
5 Developed pulse sources

Two realized pulse modulators are described in this chapter. The first power source is based on the earlier described DSRD. Desirable output voltage could unfortunately not be reached with this concept. The second source is based on a low stray inductance pulse transformer and is able to create quasi resonant 6.2kV pulses.

5.1 DSRD based pulse source

The Drift Step Recovery Diode (DSRD) concept was chosen because no high voltage switches are required. A relative low voltage is switched in a resonant circuit. The DSRD interrupts the resulting current in the circuit when all energy is inductively stored, similar like a boost converter creating high voltage gain. The developed pulse source is based on the same principle as in 2.3.3. Five 1300V 2.8kA DSRD’s were taken out of the original diode stack of the pulse source described in that section. The aim was to design a new high repetition rate pulse source with adjustable output voltage. Some design considerations will first be discussed. The practical implementation and electrical measurements will be discussed later.

5.1.1 Circuit and design considerations

Electrical measurements on the pulse source described in 2.3.3 showed that the forward pumping time of the DSRD stack takes approximately 300ns. The reverse peak current should be reached in about 80ns. These forward and reverse pumping times should not be exceeded because the charge carriers in the diodes have a limited lifetime. These time values are applied in the new pulse source to ensure correct recovery behavior of the DSRD’s. The basic circuit in figure 4.1 is used to create these unequal forward and reverse conduction times.

![DSRD basic circuit](image)

**Figure 4.1: DSRD basic circuit**

Capacitor $C_1$ is initially charged to the supply voltage (see figure 4.2). Upon closing of switch $S_1$ at $t=0$, a forward current will flow through the diode via $C_1-S_1-DSRD-L_1-C_2$. All energy will be transferred from $C_1$ to $C_2$ on $t = 1/2 T$. This half period time must be 300ns (forward pumping time of the DSRD), and can easily be calculated by following equation (appendix D).

$$\frac{1}{2} T = \pi \sqrt{\frac{(L_1 + L_2) C}{2}} , C_1 = C_2 = C$$

(4.1)

After this half period, $C_1$ is discharged and $C_2$ is charged to the initial voltage of $C_1$ at $t=0$. At the zero crossing of the current (at $t=1/2 T$), switch $S_1$ is opened while $S_2$ is subsequently closed. The resulting reverse current will flow via $C_2-S_2-DSRD-L_2$. The peak of the 80ns reverse current should be set at $t' = \frac{1}{4} T'$ (starting at the zero crossing of the current), using equation 4.2.
The diode will in theory always recover at the top of the current when the voltage over \( C_z \) is zero, regardless the values of \( L_1 \) and \( L_2 \) (of course meeting the time constraints). This can be explained by the fact that the forward and reverse diode current also charges and discharges \( C_z \). The charges accumulated in the diode and capacitor during forward conduction must be pushed out at the same time during reverse conduction. The current through \( L_2 \) will be commutated in resistance \( R_{\text{load}} \) after the recovery of the diode. The peak current can be estimated using equation 4.3 (appendix D). Peak output voltage is subsequently determined by the load impedance.

\[
I(\frac{1}{4}T') = \frac{\dot{U}}{L_z} \frac{L_z}{C_z}
\]

(4.3)

5.1.2 Practical implementation

Switches \( S_1 \) and \( S_2 \) were first selected. Magnetic switches (saturable inductors) couldn't be applied to switch the forward and reverse current because an adjustable output voltage is desired. These switches have to be designed to saturate (switch) at a certain core flux. Adjustment of the supply voltage to regulate the output voltage of the pulse source will result in core saturation in a different moment in time. Solid state semiconductor switches can be chosen for this application. The switching time must be much faster than 80ns to avoid large energy dissipation. This reduces the possibilities to IGBT'S (Insulated Gate Bipolar Transistor) and Mosfets. IGBT's are capable of switching much higher currents than mosfets. The current handling capability of mosfets becomes less for high voltage models because of increasing Rds-on. Standard models are available up to 1500V, but are expensive and have very poor specs. Only ultra fast IGBT's with current rise times under 20ns, current handling up to 200A and a switching voltage of 1200V appeared to be suitable. Disadvantage of these devices is the long switch-off time, typical >200ns. These semiconductors proved to be not so suitable after the initial test with the realized pulse source. The initial switching speed seem to be fast enough but it took far too long to reach the saturation voltage of the device, resulting in very poor performance. The IGBT's had to be replaced by 600V mosfets which are able to switch 180A (peak) with a rise time under 10ns, and 0.09Ω Rds-on.

The practical implementation of the circuit is shown in figure 4.3. The voltage over \( C_1 \) is initially zero and the buffer capacitor \( (C_3) \) of the power supply is charged to \( U_{\text{DC}} \). \( C_1 \) will resonantly be charged via \( C_3-C_1-L_3-D_1 \) to \( 2U_{\text{DC}} \) because \( C_3>>C_1 \) (appendix D). Diode \( D_1 \) will block after this 13μs charging cycle. \( L_3 \) has a value of 275μH; this relative large value ensures that only a small leakage current can flow from the power supply in the circuit when \( M_1 \) and \( M_2 \) are switched-on. \( C_1 \) will recharge again after \( C_1 \) is discharged and \( M_1 \) is opened again. \( C_1 \) and \( C_2 \) are chosen to be as large as possible to maximize the energy per pulse, taking the forward and reverse current time constraints into account. The resulting values for \( C_1 \) and \( C_2 \): 23.5nF, \( L_1 \): 667nH and \( L_2 \): 110nH. The circuit is constructed using copper strips to obtain very low stray inductance (figure 4.5). \( L_1 \) and \( L_2 \) are air core inductors wound of 1mm enameled copper wire.

Two mosfets are placed in parallel to reduce the conduction losses during the higher reverse current. Two galvanic isolated floating gate drive circuits are implemented to drive the mosfets. A 12A mosfet driver is used for each circuit. The drivers are able to charge the mosfet gates to 18V in ~25ns, which is
essential for very fast switching speeds. Both driver circuits are connected to a control circuit via an optical link. Each driver has its own galvanic isolated power supply.

![Figure 4.4: Schematic control circuit](image)

The control circuit (figure 4.4) consists out of several digital cmos IC’s. The repetition rate of the pulse source is controlled by the frequency of the oscillator (70 Hz - 15kHz). The 300ns switching delay between $M_1$ and $M_2$ can be set by the adjustable delay. A schmitttrigger IC is used to create the oscillator and delay. The on-time of the mosfets can be controlled by two monostable multivibrators. Complete circuits of the control circuit, gate drivers and galvanic isolated power supply can be found in appendix D. The entire pulse source is shown in figure 4.5.

![Figure 4.5: Complete DSRD based pulse source](image)

### 5.1.3 Electrical measurements

The pulse source is initially tested with a 50 ohm low inductance load resistor. The circuit was fed by a 0-300V adjustable power supply. The voltage was set to 200V during the following measurements. $C_1$ should initially be charged to twice the supply voltage, but is charged to $-450V$. The reason for this will be explained later. The DSRD forward peak current is expected to be 55A during resonantly charging of $C_2$. A peak current of 208A in $L_2$ is expected (equation 4.3) just before recovery, if all energy in $C_1$ is transferred to this inductor. This would result in the output pulse amplitude of 10.4kV after recovery.

The actual measurements are shown in figure 4.6. Figure 4.6a shows the voltages on $C_1$, $C_2$, $R_{load}$, and the current through the DSRD. Figure 4.6b shows the voltages over $M_1$, $M_2$, $R_{load}$, and also the current though the DSRD. $C_2$ is resonantly charged to $-280V$ after $M_1$ has been closed. The forward peak current in figure 4.6a and b is only half of the expected value. The damping in the resonant circuit seems to be high. The damping is similar as during the reverse current. This would result in a 3.5kV pulse after recovery, but most of the energy is absorbed by the unexpected large parasitic capacitance of the DSRD stack. As result, a peak voltage of only $-950V$, with 20ns rise-time and 50ns duration is generated over the load. Each diode has a capacitance of $\approx 15nF$. Five diodes in series results in 3nF equivalent parasitic capacitance. The charging of this capacitance limits the rise time of the pulse to $\approx 20ns$. The DSRD capacitance forms a resonant circuit with $L_2$, resulting in an oscillation which is damped by the load resistor. The original pulse source from which these diodes were taken does not suffer from this problem; the total stack consists of 60 diodes, reducing the capacitance to 250pF.

The mosfets are switched-off after all energy is out of the circuit. $C_1$ will subsequently recharge (figure 4.7). A small current is able to flow via $C_2$-$M_2$-$L_1$-$M_1$-$L_3$-$D_1$ during on time of the mosfets. Energy is stored in $L_3$ en subsequently pushed into $C_1$ after turn-off of the mosfets. For this reason the voltage over $C_1$ can exceed twice the supply voltage.
The damping during forward and reverse current is primarily caused by the conduction losses of the mosfets and DSRD. Figure 4.6b shows that the mosfets switch very fast (under 10 ns) but a relative large voltage is measured over mosfets after turn-on. The specified Rds-on of 0.09 Ω is certainly not reached just after turn-on.

Figure 4.8 shows an energy balance to get some insight in the power dissipation of several components in the circuit. About two third of the energy is transferred to C2 after the forward current. The lost energy is primarily dissipated in the DSRD and M1. A larger amount of energy is dissipated in the DSRD during the reverse current cycle. The DSRD’s are known to suffer from skin effect. M2 (2 parallel mosfets) dissipate about the same amount of energy as M1. The energy in L2 is pushed into the load resistor and parasitic capacitance of the diode after recovery. The parasitic capacitance is subsequently discharged into the load. About one quarter of the energy is eventually dissipated in the load.

5.1.4 Conclusion

Realizing this circuit using mosfets and operation at low supply voltage is possible (with low parasitic capacitance DSRD’s) but the efficiency appears to be unacceptable. The damping coefficient of the DSRD forward and reverse current waveform is determined by R12L, where R is primarily determined by the resistance of the switches and DSRD, and L is the inductance in the current path. Increasing the value of L1 and L2 would reduce damping and increase efficiency but the value of C1 and C2 have to be reduced to meet the timing constraints. Increasing the supply voltage is subsequently required to charge C1 to the same energy level. The mosfets must be able to hold off this higher voltage. A complete solid state design seems difficult to realize, the usage of magnetic switches appears to be inevitable.
5.2 Quasi resonant pulse modulator

A new concept based on a pulse transformer was developed to step up the output voltage, because switching high voltages proves to be difficult. Creating ns pulses will be almost impossible, because of stray inductance in these transformers. The general idea behind the concept is to create uni-polar high frequency (quasi) resonant pulses; charging and discharging the reactor capacitance resonantly via a pulse transformer. The output voltage can be adjusted to the point that the dielectric surface capacitance \( C_d \) just reaches the maximum value during discharge activity. Under this condition, optimal chemical efficiency and homogeneous plasma can presumably be obtained. The power dissipation can be controlled by adjustment of the repetition rate, and by choosing a certain period time of the resonant pulse.

Main advantages of such a circuit topology are the minimum requirement of high voltage components (only the pulse transformer), ability to recycle the energy stored in the electrode and dielectric surface capacitance, and creation of homogeneous plasma at low power levels. Disadvantages are the uncertain discharge behavior. It is not certain if micro or single discharges are triggered. This will affect chemical activity.

The concept will first be further explored, practical implementation and several electrical and chemical measurements will be discussed later.

5.2.1 Basic concept

Figure 4.9 shows the basic circuit and the typical voltage and current waveforms are shown in figure 4.10. The stray inductance of the transformer and the reactor capacitance form a resonant circuit. Power supply buffer capacitor \( C \) should have a value much larger than the reactor capacitance \( C_{SOBO} \) to minimize the voltage drop over \( C \) during charging. The reactor capacitance is resonantly charged to a maximum of \( 2U_{c0} \) after \( S \) is closed. The factor two is caused by the resonant charging under the condition that \( C >> a^2C_{SOBO} \) (appendix D). The energy will subsequently completely swing back to the power supply if the reactor behaves as a pure capacitance. Switch \( S \) is subsequently closed on the zero crossing of the current. The resonant current will be damped if there's discharge activity on the reactor, because a part of the energy will be dissipated by the discharges. This will result in a reactor peak voltage \( < 2U_{c0} \) and the unfavorable effect that the reactor voltage does not completely drop back to zero, as can be seen in figure 4.10.

\[
M = k \sqrt{L_1L_2}
\]  
(4.4)

Figure 4.11 shows the basic concept with an equivalent transformer circuit. All component values are scaled to the primary side of the transformer by applying equations 4.4-4.9.
\[ a = \sqrt{\frac{L_2}{L_1}} = \frac{N_1}{N_2} \]  
(4.5)

\[ S_1^* = L_1 - \frac{M}{a} \]  
(4.6)

\[ S_2^* = L_2 - \frac{M}{a} \]  
(4.7)

\[ M' = \frac{M}{a} \]  
(4.8)

\[ C_{\text{sDBD}} = a^2 C_{\text{sDBD}} \]  
(4.9)

The worst case period time of the pulse can be estimated by equation 4.10 (appendix D). The capacitance \( C_{\text{sDBD}} \) is the maximum capacitance of the reactor; so the capacitance when the plasma is fully ignited (see section 2.2.1). The period time will in practice be smaller.

\[ T = 2\pi \sqrt{(S_1^* + S_2^*) C_{\text{sDBD}}}, C >> C_{\text{sDBD}} \]  
(4.10)

### 5.2.2 Practical implementation

The most difficult component is the pulse transformer. To design this, several trade-offs have to be made. A prototype of the transformer had to be constructed to investigate the feasibility of the concept. Designing an optimal transformer for this application wasn’t the aim; therefore core losses, proximity- and skin effect were neglected. The transformer should have a low stray inductance, but also a high mutual inductance (M) to minimize the magnetization current and core flux density. Low stray inductance can be obtained by minimizing the number of windings, by choosing a magnetic material with a large \( \mu_r \) and by placing the primary and secondary windings on top of each other. High mutual inductance can be obtained by maximizing the number windings and by also using a magnetic material with a large \( \mu_r \). The \( \mu_r \) of magnetic materials that can be used at higher frequencies, are relative low. Increasing the number of windings will reduce core losses but increase copper losses.

The switch \( S \) must be closed during at most the whole period \( T \). The core flux swing \( \Delta \Phi \) of the transformer can be calculated by equation 4.11. \( U_{\text{prim}} \) will be near the power supply voltage \( U_C \).

\[ \phi(t) = \frac{1}{N_i} \int U_{\text{prim}}(\tau)d\tau \]  
(4.11)

Equation 4.12 can be applied to calculate the flux density \( B \) in the core with cross-section \( A \).

\[ \phi = BA \]  
(4.12)

Inductance of the primary and secondary winding can be calculated by equation 4.13, \( N \) is number of windings and \( l \) is the mean magnetic path length of the core.

\[ L = \frac{\mu r A N^2}{l} \]  
(4.13)

First an easily available core material was selected, taking some of the earlier mentioned trade-offs into account. N97 ferrite from Epcos was selected because it can operate up to 500 kHz and has a reasonable \( \mu_r \) value of 1660. The largest available U-core was selected because; the high voltage winding has to fit, and the large core cross section \( (A) \) increases the primary and secondary winding induction.

<table>
<thead>
<tr>
<th>A</th>
<th>Core cross section</th>
<th>368mm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Core mean magnetic path length</td>
<td>139mm</td>
</tr>
<tr>
<td>( \mu_r )</td>
<td>Permeability</td>
<td>1660</td>
</tr>
<tr>
<td>( B_{\text{sat}} )</td>
<td>Saturation flux density</td>
<td>0.52T</td>
</tr>
</tbody>
</table>

Table 4.1: Specifications Epcos N97 ETD59 core

A 2\( \mu \)s period time was chosen to meet the 500kHz constraint and to minimize the number of turns. It proved to be difficult to find a good compromise between the required stray inductance and with the number of primary turns needed to avoid core saturation. Several transformers were constructed before
the required stray inductance and reactor voltage was reached. The final transformer has a winding ratio of 3:54. An extra circuit is added to pre-magnetize the core negatively, which provides more flux swing during the actual pulse. A 0.1 mm air gap had to be made in the core to decrease the residual flux which is introduced by the unbalanced magnetization current. The DC residual flux was large enough to cause core saturation. The air gap decreases the overall \( \mu \) of the core, because the magnetic field concentrates in the air gap. The magnetization current will increase, and primary and secondary inductance will decrease. Equivalent \( \mu \) of the core can be calculated by equation 4.14, presuming no flux fringing occurs in the gap (\( A_{\text{core}}=A_{\text{gap}} \)).

\[
\mu_{\text{eq}} = \frac{\mu_{\text{core}}}{\left(1 + \left(\frac{\mu_{\text{core}} A_{\text{gap}}}{\mu_{\text{core}} A_{\text{core}}}\right)\right)}
\]

(4.14)

A single layer high voltage winding was constructed to minimize the risk of breakdown. The single layer 54 turn secondary winding is put directly on top of the coil former (figure 4.12) using 0.75 mm enameled wire. The winding fits over the complete length of the coil former. Ten layers of 0.1mm polyethylene (PE) foil are wound around the secondary for insulation. A single layer of 25mm wide copper foil is placed on top of the insulator at one end of the coil former. This screen has a small slit at the top and is grounded. It eliminates parasitic capacitance between primary and secondary winding. Transients will be capacitive coupled to ground instead of to the other winding. In case of insulation breakdown the discharge should hopefully strike the screen. The three turn primary winding is constructed of 20mm wide 0.2mm thick copper strip which is insulated by heat-shrinkable tube. The strip is placed over the screen at the end of the coil former. The secondary winding is grounded at this side of the coil former. So there is a relative small potential between primary and secondary at this side. The high voltage is available at the other end of the coil former. The stray inductance could be reduced if the primary winding would be spread evenly over the complete width of the coil former, but this would increase the risk of breakdown between primary and secondary winding.

<table>
<thead>
<tr>
<th></th>
<th>Calculated</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_1 )</td>
<td>22.7 ( \mu )H</td>
<td>23.8 ( \mu )H</td>
</tr>
<tr>
<td>( L_2 )</td>
<td>7.34 mH</td>
<td>7.11 mH</td>
</tr>
<tr>
<td>( M )</td>
<td>-</td>
<td>408.9 ( \mu )H</td>
</tr>
<tr>
<td>( S_1 = S_2 )</td>
<td>-</td>
<td>140nH</td>
</tr>
<tr>
<td>( k )</td>
<td>-</td>
<td>0.994</td>
</tr>
<tr>
<td>( a )</td>
<td>18</td>
<td>17.28</td>
</tr>
</tbody>
</table>

Table 4.2: Transformer specification

The actual circuit used during measurements is shown in figure 4.14. The circuit contains a power supply buffer which is resonantly recharged to deliver the relative large primary winding current, and a transformer demagnetization circuit. Initially capacitors \( C_1 \) and \( C_2 \) are charged to the supply voltage. \( C_1 \) is a low-ESR elco, \( C_2 \) is a low loss MKP capacitor which is able to deliver the 160A peak current. The SDBD reactor will be charged to 6.1kV via \( C_2-T_{\text{p}}-M_2 \) after mosfet \( M_2 \) is switched-on. \( M_2 \) is switched-off after \( \approx 2\mu \)s on the zero-crossing of the current through \( M_2 \). The magnetization current is able to freewheel via \( T_{\text{p}}-D_2-C_3-R_4 \). The value of \( C_2 \) is much larger than \( C_{\text{SDBD}} \) to ensure that most of the magnetization energy is pushed into \( C_3 \) instead of into the reactor capacitance. The stored energy in the capacitor will be used to pre-magnetize
the core just before the next pulse. This enables the core to operate in the upper and lower half of the B-H curve. The voltage over C3 has a typical value of 25V after demagnetization. The core is resonantly magnetized in the lower half of the B-H curve after M1 is closed. Resistor R1 damps the oscillation which occurs during re-magnetization which is caused by the resonant circuit formed by the transformer stray inductance and reactor capacitance. Consequently not all magnetization energy can be recycled. M2 is opened just before M3 is closed on the zero crossing of the voltage over C3 when C3 is discharged. The resonant de- and pre-magnetization time can be calculated by equation 4.15.

\[ t' = \frac{\pi}{2} \sqrt{L_1 C_3} \]  

(4.15)

C2 is recharged after each pulse. The voltage over this capacitor will only slightly drop during the pulse. The capacitor voltage after recharge can be calculated by equation 4.16 (appendix D), \( u_{c0} (0) \) is the capacitor voltage before recharging.

\[ u_c (t') = 2u_{c0} (0) - u_{c0} (0) \]  

(4.16)

The voltage on capacitor C2 will increase a little bit each pulse until the capacitor can't be recharged because \( u_{c2} (0) \) exceeds the supply voltage. Equilibrium exists around this point. A voltage clamp formed by R1, Z4, and T1 should ensure that the voltage over C2 cannot exceed the supply voltage by 80V in case the capacitor is discharged further than intended (for instance when a breakdown occurs in the reactor).

RC snubber circuits are placed over the mosfets to dampen transients which occur after switch-off due to stray inductance in the circuit and the output capacitance of these devices.

![Practical implemented circuit](image)

The gate drive circuits, mosfets and control circuit are the same as used in the in the DSRD pulse source. M2 is mounted on a forced air-cooled heat sink. Rds-on of mosfets have a positive temperature coefficient; sufficient cooling will reduce conduction losses. Interconnections which carry high currents are constructed of copper strips to decrease parasitic inductance. The most important component values of the circuit are shown in table 4.3.

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_1 )</td>
<td>75 ( \mu )H</td>
</tr>
<tr>
<td>( C_1 )</td>
<td>150( \mu )F</td>
</tr>
<tr>
<td>( C_2 )</td>
<td>880nF</td>
</tr>
<tr>
<td>( C_3 )</td>
<td>6.6( \mu )F</td>
</tr>
<tr>
<td>( R_1 )</td>
<td>0.41( \Omega )</td>
</tr>
</tbody>
</table>

Table 4.3: Circuit component values

![Schematic control circuit](image)
The control circuit is slightly adapted (figure 4.15), because $M_1$ and $M_2$ have to be switched sequentially. A dead-time delay is triggered on the falling edge of the pulse which controls gate drive 1 ($M_1$). The delay output triggers subsequently the monostable multivibrator which controls gate drive 2. This ensures that $M_1$ and $M_2$ can never be switched-on at the same time, and are always sequentially switched, regardless the on-time of the mosfets. The schematic of the control circuit can be found in appendix C.

5.2.3 Electrical measurements

The pulse source is initially tested with the SDBD reactor. The circuit was fed by a 0-300V adjustable power supply. The voltage was set to 250V during the following measurements. $C_2$ is initially charged to $\approx 293$V and $C_3$ is charged to $\approx 25$V before the pulse cycle. $M_1$ is closed and the core is pre-magnetized in $\approx 20\mu$s. $M_1$ is switched-on and $M_2$ is subsequently switched-off. The peak current in the primary winding reaches 160A, the reactor current reaches 10A. The voltage over the primary winding is only $\approx 200$V because of the voltage drop over $M_1$ and the discharge of $C_3$ (figure 4.17). Reactor peak voltage reaches 6.1kV, discharges are initiated at 4.2kV (figure 4.18). A total voltage gain of 21 is reached, from the 293V supply voltage. $M_2$ is switched-off after $\approx 2\mu$s on the zero crossing of the primary winding current. The poor switch-off behavior is presumably caused by the possibility that the body diode of $M_2$ conducts a part of the negative current. Mosfet body diodes have poor reverse recovery times, typical several hundred ns. The reactor capacitance is still charged to $\approx 2.5$kV after the $M_2$ has been switched-off. The energy is subsequently resonantly transferred to the secondary inductance of the transformer, which increases the magnetization current and core flux. Diode $D_2$ starts conducting on the zero crossing of the primary voltage. The magnetization current is now able to freewheel via $T_{12}D_2-C_3-R_1$ in $\approx 20\mu$s. Most of the energy is stored in $C_3$ again, some energy is dissipated in $R_1$, and some energy is delivered to the reactor causing the oscillation ever since 25\mu s. The reactor is charged to $\approx 400$V, which corresponds to 560 µJ ($1/2 C_2 U^2$) energy loss.

![Figure 4.16: Complete setup](image)

![Figure 4.17: Typical primary transformer voltage/current.](image)
Figure 4.18: Typical applied reactor voltage/current

Capacitor C₂ is discharged to 171V and recharged again to 207V just before M₂ is opened. The 20 µs resonant recharge cycle of capacitor C₂ starts as soon as the voltage level drops below the supply voltage (250V). The capacitor recharges to 293V (equation 4.16) as expected.

Figure 4.19: Transformer core flux density

Figure 4.20: U₅ recharging

Figure 4.19 shows the core flux density of the transformer. Flux density is calculated by formulas 4.11 and 4.12. The pre-magnetization circuit provides about 180mT additional flux density swing (ΔB).

**Energy balance**

The energy balance of the circuit is shown in figure 4.21. About 16.5mJ of energy (E_supply) is needed to recharge capacitor C₂. This is the total amount of energy which is dissipated during each pulse in the reactor and circuit. Approximately 3mJ is dissipated in M₂, which suffers from severe conduction losses. The difference between the end value of the energy which is fed in at the primary side of the transformer (E_F(t > 25 µs) = 11mJ), and the energy consumed in the reactor (ES_RB(t > 25 µs) = 9mJ), equals the energy dissipated in the transformer. The total losses (core and copper) in the transformer are subsequently ≈2mJ per pulse.
The amount of energy dissipated in the de- and pre-magnetize circuit is equal to the difference between the energy which flows out of the transformer during demagnetization and the energy which flows in during pre-magnetization. So 1.4mJ of energy is dissipated in R₁ and M₁. About 560 μJ is delivered to the reactor during demagnetization, as calculated before. The remaining 0.54mJ is dissipated somewhere else in the circuit. The poor energy efficiency of the circuit is approximately 55%.

**Discharge behavior**

A single pulse lissajous plot is shown in figure 4.22., where the charge in the electrode capacitance is subtracted from the total reactor charge as in equation 2.9. Positive discharges are initiated during $1 \rightarrow 2$, the unsteady slope reveals a jittering gap voltage. The initial surface charge is unknown so the discharge inception voltage of the gap cannot directly be derived. The straight slope reveals that two bursts of micro discharges are initiated during $3 \rightarrow 5$ (constant gap voltage). A voltage swing of 3.7kV is required to initiate the first burst ($3 \rightarrow 4$), for AC excited plasma a voltage swing of 5kV was needed. Probably some conductivity remains in the gap after the positive discharge. The second burst ($4 \rightarrow 5$) requires a voltage swing (4.8kV) more similar to the AC discharge behavior. This discharge is unintentionally initiated during demagnetization of the core.

![Figure 4.22: Single pulse lissajous plot](image)

The actual gap voltage and discharge current are plotted in figure 4.23. These waveforms are calculated from the analytical model as described in section 2.3, by using equations 2.16 and 2.24. $C_0$ is assumed to be also 600pF during the positive discharge because it cannot be derived from the lissajous plot, the value for $u_0(0)$ is iteratively adjusted to 600V so that the negative voltage peak ($4 \rightarrow 5$) is equal to $\pm 2.5kV$. Following equation should be true for this value since there can only be energy dissipated in the gap. Resulting energy waveforms are shown in 4.24.

$$E_{gap} = \int_{-25\mu s}^{18\mu s} u_e(t)_p(t)dt = E_{in} = \int_{-25\mu s}^{18\mu s} u_e(t)i(t)dt$$

(4.16)

Interpretation of these figures must be done carefully because it is questionable if the analytical model is completely feasible for these discharges.

![Figure 4.23: Typical gap voltage and discharge current](image)

Possibly the discharge current is able to exceed the supply current due to space charges in the gap, as can be observed in figure 4.23b. Discharges seem to be initiated after the gap voltage has reached 4kV;
it is questionable that this value is really reached. A minimum external applied voltage of 4.2kV is required to initiate the positive discharges, so the discharge inception voltage should be approximately 3.6kV presuming that \( u(0) \) is 600V.

As can be seen in figure 4.24, roughly 6mJ is dissipated during the positive discharge; 2mJ is dissipated during the negative micro discharges. Largest part of the 2mJ energy is dissipated during the core demagnetization. The gap voltage decreases further after the negative discharge activity, this would mean that the dielectric surface charge decreases and about 1mJ is lost during the oscillation. The gap voltage stabilizes to \(-600V\) again at 80\( \mu \)s.

**5.2.4 Ozone yield measurements**

An ozone yield measurement has been performed to compare the chemical efficiency of the quasi resonant pulse source with the ns pulse and AC source as described in chapter 3. The experiment has been performed under exactly equal circumstances as during the AC and pulsed ozone yield measurements. Ozone concentrations have been measured with two different pulse amplitudes and repetition rates up to 15kHz. The yields of the 6.1kV and 6.5kV (270V supply voltage) pulses are shown in figure 4.25. Energy dissipation is determined by formula 3.9 and subsequently averaging five of these measurements.

The results show a rather poor performance. The ozone yield is lower than the AC plasma yield. Performance is only better for powers below 50W (300J/L), this can be explained by the fact that the quasi resonant pulse source is able to create homogeneous plasma in contradiction to the AC source for these low power levels. Although the energy dissipation per pulse is similar to the energy levels of the ns pulse discharges, the discharges are presumably more thermal; destroying the ozone by thermal decomposition.
The energy per pulse seems to decrease as the repetition rate increases (figure 4.26). This possibly confirms that the dielectric surface charge slowly decreases after each pulse. More surface charge is present before the pulse as the repetition rate increases and time between pulses decreases. The discharge inception voltage is consequently reached at a higher external applied voltage level because the initial gap voltage is more negative. This will result in less energy dissipation in the reactor.

5.2.5 Conclusion

The realized prototype is able to produce homogeneous plasma, with the ability to control the power dissipation up to 125W. Efficiency of about 55% is reached; mosfet conduction losses and transformer losses are the main reason for the poor performance. IGBTs with anti parallel diodes are possibly a better choice for this circuit.

About 6mJ of the energy per pulse is dissipated in the initial positive discharge, 2 mJ is dissipated by the negative discharges. Unintentionally discharges are initiated during demagnetization of the core. Some dielectric surface charge is presumably lost after the discharge activity.

Ozone yield measurements showed a poor performance.
6 Conclusions and recommendations

6.1 Conclusions

The widely used AC DBD model, can also be applied to describe AC behavior of a SDBD with one modification; the addition of the electrode capacitance $C_e$. The SDBD behaves similar as a homogeneous DBD, when this capacitance is taken into account. The parameters of the model ($C_d$, $C_g$ and $U_{in}$) can be estimated with a reactor charge ($Q$) – applied electrode voltage ($U_a$) lissajous figure if the electrode capacitance is known. The value for $C_d$ (dielectric surface capacitance) depends on the plasma coverage of the reactor. The value stabilizes to $\approx 600\text{pF}$ for positive discharges if the applied electrode voltage is large enough to create homogeneous plasma coverage ($U_a > 3\text{kV RMS}$). The overall value is smaller for negative discharges, and stabilizes to $\approx 500\text{pF}$. The discharge inception voltage $U_{in}$ has a value of approximately $2.5\text{kV}$, and $C_g$ (gap capacitance) a value of $\approx 40\text{pF}$. The SDBD's power dissipation can subsequently be estimated for any applied AC voltage.

An analytical SDBD model is introduced which can be used to calculate the actual gap voltage and discharge current out of the external measured applied voltage and external reactor current (for both pulse and AC operation). The model showed feasible calculated waveforms for AC excitation, but showed unlikely results for ns pulse operation. Possibly the dielectric surface capacitance $C_d$ isn’t constant during the discharge. Furthermore should be investigated if the parasitic inductance of the strips can be neglected.

Comparison of the pulsed and AC excited plasmas ability to produce ozone proved to be difficult because the $O_3$ yields couldn't be compared at high powers. The AC source is able to dissipate more than 300W in the plasma, but the pulse source only 13.8W. The yield could only be compared over a range where the AC plasma is non homogenous (relative low applied voltage) and where large amounts of gas leave the reactor chamber untreated. Compared to AC operation, the pulsed excited plasma appears to generate relative higher $O_3$ yields with less energy per pulse, although differences are small. The ozone yield saturates at 300ppm for the AC excited plasma. Ozone destruction mechanisms limit the $O_3$ yield. The AC excited plasma generates a large amount of heat. Presumably the pulsed excited plasma could have a much higher ozone saturation level, if thermal decomposition of ozone is the main cause of the ozone saturation limit for AC excitation.

The high speed images showed that, for pulsed operation, the plasma is already very homogeneous during one single shot. The plasma profile along the dielectric surface of the SDBD appeared to be similar for pulsed and AC excited plasma at different voltage/energy levels. A persistent mechanism controls the expansion of the streamers.

Pulse operation would be preferred. However, a solution must be found to recycle the energy in the reactor capacitance, which is not fully used by the discharge. Only then, the full advantage of a high efficiency pulse source can be benefited from. For pulsed operation, it is easy to control the average plasma power by adjusting the repetition rate. The single shot homogeneous plasma ensures homogeneous plasma over the complete power range of the source. The pulse source must able to run at high repetition rates ($> 10\text{kHz}$) to dissipate a reasonable amount of average power in the plasma.

The developed DSRD (Drift Step Recovery Diode) based ns pulse source wasn't able to reach the required output voltage. The damping in the resonant circuits introduced by the conduction losses of the mosfets and DSRD appeared to be unacceptable high. A large amount of energy is absorbed by the parasitic capacitance of the DSRD after recovery, resulting in a 950V pulse with a 20ns rise time on a 50Ω load resistor, whereas a peak voltage of about 10.4kV was expected (ideal circuit). The efficiency of the source is low; approximately 25%.

The developed pulse source based on a low stray inductance pulse transformer is able to produce 2μs wide quasi resonant 6.5kV (peak voltage) pulses with a repetition rate up to 15kHz. The circuit is able to recover a large part of the energy which is stored in the large reactor capacitance and that is not used by the plasma. Multiple discharges occur during the 2μs pulses. Homogeneous plasma is created with the ability to control the power dissipation between 0 and 125W, by means of varying the pulse repetition rate. An energy transfer efficiency of about 55% is reached; mosfet conduction losses and
transformer losses are the main reason for the poor performance. Ozone yield measurements showed an unfortunately low yield in comparison to AC and pulse excitation.

### 6.2 Recommendations

Pulsed and AC excited plasma O$_3$ yields should be compared at higher power levels to give a conclusive answer about the efficiency (chemical vs. power consumption) of both plasma's. A high repetition rate ns pulse source should be used to dissipate a reasonable amount of energy in the plasma. The ozone saturation limit for pulsed operation can subsequently be determined. An AC power modulator with a low resonance frequency could be used to possibly create homogeneous plasma at a lower power level. Ozone yields of pulsed and AC excited plasma can subsequently be compared at low power levels with homogenous plasma.

Increase of the reactors gas temperature and cooling water could be monitored to determine the amount of energy which is converted into heat. This can be used as a second measure to compare the AC and pulse excited plasma. These experiments should also be done at high power levels, and the setup should be well insulated to obtain accurate temperature measurements.

The DSRD based pulse source can be improved by using magnetic switches instead of mosfets. These switches are able to hold off higher voltages; capacitor values in the resonant circuits can subsequently be reduced and the pulse will still obtain an equal energy level. The smaller capacitance values will reduce damping in the circuit because inductances can be enlarged to meet the timing constraints, resulting in higher efficiency. Creating an adjustable output voltage would however be impossible with these switches.

The large electrode capacitance $C_e$ proves to be unfavorable for both pulse and AC operation. The capacitance increases reactive power for AC operation and it absorbs energy which is difficult to recycle during ns pulse operation. This problem can probably be reduced by narrowing the electrode strips or by modifying the reactor. An example with embedded ground electrodes is shown in figure 4.22. Another example of an alternative SDBD reactor is shown in figure 4.23. Ground and high voltage electrodes are both imbedded in the dielectric. This co-planar SDBD solution will also reduce the capacitance between the electrodes significantly.

The high speed images showed that the plasma profile along the high voltage strips appeared to be similar for pulsed and AC excited plasma at different voltage/energy levels. It is interesting to measure the charge accumulation on the dielectric barrier to learn more about the development of the streamers. Distance between the high voltage strips could be varied to investigate the effect on plasma surface coverage.
Bibliography


Acknowledgements

I would like to thank dr. Guus Pemen and prof. Jan Blom for creating the possibility to graduate at the Pulsed Power group. Secondly, I would like to thank dr. Paul Blom for providing the subject of the project, and his assistance. I would thank all people of the pulsed power group who helped during the project for sharing their expertise. Last but not least I would like to thank the students in our office for a very pleasant work environment.
Appendix A Lissajous Matlab script

The following matlab script is able to generate lissajous figures for each period within the integration bounds (figure 1). The surface and the slopes of each period are determined separately. The lissajous figure is quantized and divided into four parts (figure 2). The slope of each side and surface can subsequently be determined.

The script is able to reject failed calculations by setting a few rejection bounds. All capacitance values within the integration bounds are sorted so failed calculated values are very large or very small (figure 3). All values outside the reject bounds are rejected during averaging. The reject threshold for the energy calculations is estimated by a fitted polynomial curve with a user defined offset (figure 4). All values above the threshold are averaged.

Power calculation by integration of instantaneous power is also admitted in the script. RMS voltage of the waveform within the integration bounds can be found at the end of the script.
Matlab source code:

```matlab
%***********************************************%
%Auteur: F.J.C.M. Beckers
%SDBD (AC) energie/capaciteits meting
%***********************************************%

close all;
clear all;

%Zero crossing
tSkip=2e-6;    %s
zero_treshold=100;  %V

%Top crossing
tSkip_begin=2e-3;
tSkip_top=8e-3;
top_treshold=4500;

%Lissajous quantisatie
dV=300;  %V

%Reject grenzen
cap_reject_bounds=[25,1751];
E_reject_offset=1.5e-3;

pathname = uigetdir(pwd,'Please select the directory of files to be processed');

CH1 =load([pathname, '\C1.txt']);
CH2 =load([pathname, '\C2.txt']);

V(l,:) = CH1(:,2);
I(l,:) = CH2(:,2);
t(l,:) = CH1(:,1);

dt=t(2)-t(1);

skip_samples_zero = int32(tSkip/dt);
skip_samples_top = int32(tSkip_top/dt);
skip_samples_begin = int32(tSkip_begin/dt);

%Grenzen bepalen
i=skip_samples_begin;
j=1;

while(i <= size(V, 2))
    if(V(i) > top_treshold)
        t_top(j)=t(i);
sample_top(j)=i;
j=j+1;
i=i+skip_samples_top;
    else
        i=i+1;
    end
end

%Offset correctie
V=V-mean(V(sample_top(1) : sample_top(2)));
I=I-mean(I(sample_top(1) : sample_top(2)));

%Zero crossing detectie en frequentie bepaling
Vabs = abs(V);
i=sample_top(1);
j=1;

while(i <= sample_top(2))
    if(Vabs(i) < zero_treshold)
        t_zero(j)=t(i);
sample_zero(j)=i;
j=j+1;
i=i+skip_samples_zero;
    end
end
```

51
else
    i=i+1;
end

freq=1/(mean(diff(t_zero)) * 2);

figure;
plot(t, V, t, I*1000);
hold on;
plot(t(sample_top(1:2)), V(sample_top(1:2)), 'rs');
plot(t(sample_zero(1:size(sample_zero,2))), V(sample_zero(1:size(sample_zero,2))), 'ms');
hold off;
xlabel('t');
legend('Voltage (V)', 'Current * 1000 (A)', 'Integration bounds', 'Zero crossings');

%Electrode capaciteit gecorrigeerde lading bepalen
Q=cumsum(I)*dt;
Q=Q-V*700e-12;

%offset per periode corrigeren
for i=1: size(sample_zero,2)/2-2;
    period=sample_zero(i*2) : sample_zero((i*2)+2) -1;
    Q(period)=Q(period) - mean(Q(period));
    clear period;
end

figure;
plot(V(sample_zero(1) : sample_zero(size(sample_zero,2))),Q(sample_zero(1) : sample_zero(size(sample_zero,2))));

%Oppervlakte en capaciteiten per periode bepalen
for m=1: size(sample_zero(2)/2)-2;
    clear Qbound;
    clear Qav_up;
    clear Qav_down;
    clear Vdef;
    sample_up=1;
    sample_down=1;

    %Quantisatie om een x as met gelijke stappen te maken
    Vq = dV * round( V(sample_zero(m*2):sample_zero((m*2)+2))/dV);
    Q2 = Q(sample_zero(m*2):sample_zero((m*2)+2));
    Vmax=V(1);
    Vmin=V(1);
    Qmax=Q2(1);
    Qmin=Q2(1);

    %Hoekpunten links onder en rechtsboven zoeken
    for i=1: size(Vq,2)
        if((Vq(i)>Vmax) && (Q2(i)>Qmax))
            VMax=Vq(i);
            Qmax=Q2(i);
        end
        if((Vq(i)<Vmin) && (Q2(i)<Qmin))
            Vmin=Vq(i);
            Qmin=Q2(i);
        end
    end
    Vdef=linspace(Vmin,Vmax,((Vmax-Vmin)/dV)+1);

    %Virtuele lijn tussen deze punten trekken en het lissajous figuur opdelen in een onderste en bovenste stuk
for i=1 : size(Vdef,2)
    l=0;
    Qav=0;
    for j=1: size(Q2,2)
        if(Vdef(i)==Vq(j))
            Qav=Qav+Q2(j);
            l=l+1;
        end
    end
    Qbound(i)=Qav/l;
end

%Punten die door het quantiseren op elkaar zijn komen te liggen
%uitmidden
Qav_up = zeros(size(Vdef));
Qav_down = zeros(size(Vdef));
for i=1 : size(Qbound,2)
    l=0;
    k=0;
    Qv_up=0;
    Qv_down=0;
    for j=1 : size(Q2,2)
        if(Q2(j) >= Qbound(i) && (Vq(j) == Vdef(i))
            Qv_up=Qv_up+Q2(j);
            l=l+1;
        end
        if(Q2(j) < Qbound(i) && (Vq(j) == Vdef(i))
            Qv_down=Qv_down+Q2(j);
            k=k+1;
        end
    end
    if(l == 0)
        Qav_up(i)=Qv_up/l;
    end
    if(k == 0)
        Qav_down(i)=Qv_down/k;
    end
end

%Hoekpunten links en recht zoeken

dQ_dV=(Qmax-Qmin)/(Vmax-Vmin);
Qbound = Vdef * dQ_dV;
Qbound = Qbound + (Qmin-Qbound(1));
distance_down=0;
distance_up=0;
for i=1 : size(Vdef,2)
    a=Qbound(i)-Qbound(1);
    b=Qav_down(i)-Qav_down(1);
    c=Qbound(size(Vdef,2))=Qbound(i);
    d=Qav_up(size(Vdef,2))=Qav_up(1);
    if((a-b) > distance_down)
        distance_down=a-b;
        sample_down=i;
    end
    if((c-d) > distance_up)
        distance_up=c-d;
        sample_up=i;
end
end

% Af en toe een periode bekijken door deze te plotten
hold on;
if m==10
    plot(Vdef(2:size(Vdef,2), Qav_up(2:size(Qav_up,2), 'mo');
    plot(Vdef(2:size(Vdef,2), Qav_down(2:size(Qav_down,2)), 'ro');
    plot(V(sample_zero(m*2):sample_zero((m*2)+2),Q2);
    plot(Vdef(sample_down),Qav_down(sample_down), 'gs');
    plot(Vdef(sample_up),Qav_up(sample_up), 'gs');
    plot (Vdef (1) , Qav_down (1) , 'gs' );
    plot (Vdef (size (Vdef, 2) ) , Qav_up (size (Vdef, 2) ) , 'gs' );
end

%Aan de hand van de hoekpunten de gemiddelde helling van alle flanken berekenen
Cap.onder(m) = mean(diff(Qav_down(1:sample_down).diff(Vdef(1:sample_down)));
Cap.rechts(m) = mean(diff(Qav_down(sample_down:size(Qav_down,2)).diff(Vdef(sample_down:size(Qav_down,2))));
Cap.links(m) = mean(diff(Qav_up(1:sample_up)).diff(Vdef(1:sample_up)));
Cap.boven(m) = mean(diff(Qav_up(sample_up:size(Qav_up,2))).diff(Vdef(sample_up:size(Qav_up,2))));

%Oppervlakte van het lissajous figuur bepalen
E(m)=max(cumsum(Qav_up-Qav_down)*dV);
end

xlabel ('Voltage (V)');
ylabel('Charge (C) ');

%Weggooien van mislukte capaciteits bepalingen
Cap.onder = sort(Cap.onder);
Cap.boven = sort(Cap.boven);
Cap.links = sort(Cap.links);
Cap.rechts = sort(Cap.rechts);
figure;
hold on;
plot(Cap.onder, 'k');
plot(Cap.boven, 'b');
plot(Cap.links, 'm');
plot(Cap.rechts, 'g');
plot(cap_reject_bounds, Cap.onder(cap_reject_bounds), 'rs');
plot(cap_reject_bounds, Cap.boven(cap_reject_bounds), 'rs');
plot(cap_reject_bounds, Cap.links(cap_reject_bounds), 'rs');
plot(cap_reject_bounds, Cap.rechts(cap_reject_bounds), 'rs');
xlabel('Period number');
ylabel('Average slope (capacitance) ');
legend('Lower slope', 'Upper slope', 'Left slope', 'Right slope', 'Reject bounds');
hold off;

%Middelen van de overige capaciteits waarden
AvCap.onder = mean(Cap.onder(cap_reject_bounds(1):cap_reject_bounds));
AvCap.boven = mean(Cap.boven(cap_reject_bounds(1):cap_reject_bounds));
AvCap.links = mean(Cap.links(cap_reject_bounds(1):cap_reject_bounds));
AvCap.rechts = mean(Cap.rechts(cap_reject_bounds(1):cap_reject_bounds));
disp(['Average Capacitance down : ', num2str(AvCap.onder), ' F']);
disp(['Average Capacitance up : ', num2str(AvCap.boven), ' F']);
disp(['Average Capacitance left : ', num2str(AvCap.links), ' F']);
disp(['Average Capacitance right : ', num2str(AvCap.rechts), ' F']);

%RMS spanning bepalen
Tdiff = t(sample_top(2) - t(sample_top(1));
Urms=sqrt(max((1/Tdiff)*cumsum(V(sample_top(1) : sample_top(2))."2"*dt));
disp(['RMS Voltage: ', num2str(Urms), ' V']);

%Weggooien van van mislukte oppervlakte bepalingen
figure;
plot(E,'o');
hold on;

x=linspace(1,size(E,2),size(E,2));
p= polyfit(x,E,3);
Eest = polyval(p,x) - E_reject_offset;
plot(Eest,'r');

xlabel('Period number');
ylabel('Energy');
legend('Energy per period','Reject threshold');

% Middelen van de overige energie waarden
Eav=0;
j=0;
for i=1:size(E,2)
    if(E(m) > Eest(m))
        Eav=Eav+E(i);
        j=j+1;
    end
end
Eav=Eav/j;

% Vermogen bepalen, int(V*I)
Etot = cumsum(V(sample_top(1) : sample_top(2)).*I(sample_top(1) : sample_top(2)))*dt;
Pl = Etot(size(Etot,2))*(1/Tdiff);
disp(["Lissajous: ", num2str(Eav*freq), ' W']);
disp(["int(V*I): ", num2str(Pl), ' W']);
Appendix B Pspice SDBD model

The following Pspice model (Microsim Eval 8) is used to simulate the current waveform and lissajous plot. The actual measured voltage and current waveforms are loaded in respectively V1 and V2. The simulated and measured reactor charge is obtained by integrating the current waveforms. One integrator has an initial value to compensate the initial reactor charge.

![Pspice model diagram]

The measured oscilloscope ASCII files are converted to a format which Pspice is able to read by the following Matlab script. Only the voltage waveform is filtered by a moving average filter to reject high frequency noise.

Matlab source code:

```matlab
%Convertscope2spice
clear all;
close all;
N=10;

[filename, pathname] = uigetfile({'*.*';},'File Selector');
CH=importdata([pathname,filename]);
DataV(:,1)=CH.data(:,1)-CH.data(l,l);
DataV(:,2)=CH.data(:,2);
DataI(:,1)=CH.data(:,1)-CH.data(l,l);
DataI(:,2)=CH.data(:,3);

figure;
plot(DataV(:,1),DataV(:,2));
hold on;
DataV(:,2)=filter(ones(1,N)/N, 1, DataV(:,2));
hold off;

if(input('Save data to file? (y or n): ', 's')) == 'y'
    [file,path] = uiputfile('*.CSV','Save V file');
dlmwrite([path,file], DataV);

    [file,path] = uiputfile('*.CSV','Save I file');
dlmwrite([path,file], DataI);
end
```

Figure 5: Pspice model
Appendix C Schematics

Figure 1: Control circuit DSRD pulse source

Figure 2: Control circuit Quasi-resonant pulse source

Figure 3: Gate drive circuit
Figure 4: Gate driver and control circuit power supply

Figure 5: DSRD pulse source circuit

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C&lt;sub&gt;1&lt;/sub&gt;</td>
<td>23.5nF</td>
<td>5x 4n7 MKP375, 1700Vp-p</td>
</tr>
<tr>
<td>C&lt;sub&gt;2&lt;/sub&gt;</td>
<td>23.5nF</td>
<td>5x 4n7 MKP375, 1700Vp-p</td>
</tr>
<tr>
<td>C&lt;sub&gt;3&lt;/sub&gt;</td>
<td>33µF</td>
<td>Elco, 400V</td>
</tr>
<tr>
<td>D&lt;sub&gt;1&lt;/sub&gt;</td>
<td>-</td>
<td>PS3010R, 1000V, 3A</td>
</tr>
<tr>
<td>DSRD</td>
<td>-</td>
<td>5x, 1200V, 2800A</td>
</tr>
<tr>
<td>L&lt;sub&gt;1&lt;/sub&gt;</td>
<td>667nH</td>
<td>d = 9mm, l = 30mm, 20 windings, 1.5mm enameled copper wire</td>
</tr>
<tr>
<td>L&lt;sub&gt;2&lt;/sub&gt;</td>
<td>110nH</td>
<td>d = 5mm, l = 22.5mm, 15 windings, 1.5mm enameled copper wire</td>
</tr>
<tr>
<td>L&lt;sub&gt;3&lt;/sub&gt;</td>
<td>275µH</td>
<td>Metglass, MP4510 core, 44 windings</td>
</tr>
<tr>
<td>M&lt;sub&gt;1&lt;/sub&gt;</td>
<td>-</td>
<td>2x STW45NM60, 650V, I&lt;sub&gt;d&lt;/sub&gt; = 45A, I&lt;sub&gt;d, pulsed&lt;/sub&gt; = 180A</td>
</tr>
<tr>
<td>M&lt;sub&gt;2&lt;/sub&gt;</td>
<td>-</td>
<td>2x STW45NM60, 650V, I&lt;sub&gt;d&lt;/sub&gt; = 45A, I&lt;sub&gt;d, pulsed&lt;/sub&gt; = 180A</td>
</tr>
<tr>
<td>R&lt;sub&gt;load&lt;/sub&gt;</td>
<td>50Ω</td>
<td>Allen Bradley, 3kV, 3W</td>
</tr>
</tbody>
</table>

Table 1: DSRD pulse source component list
Figure 6: Quasi-resonant pulse source circuit

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₁</td>
<td>150μF</td>
<td>Elco, 400V</td>
</tr>
<tr>
<td>C₂</td>
<td>880nF</td>
<td>4x 220nF MKP378, 1000V</td>
</tr>
<tr>
<td>C₃</td>
<td>6.6μF</td>
<td>3x 2.2μF, PC, 100V</td>
</tr>
<tr>
<td>C₄</td>
<td>2.2nF</td>
<td>MKP385, 2000V</td>
</tr>
<tr>
<td>C₅</td>
<td>4.7nF</td>
<td>MKP375, 1700Vp-p</td>
</tr>
<tr>
<td>D₁</td>
<td>-</td>
<td>PS3010R, 1000V, 3A</td>
</tr>
<tr>
<td>D₂</td>
<td>-</td>
<td>ISL9R1560P2, 600V, 15A</td>
</tr>
<tr>
<td>D₃</td>
<td>-</td>
<td>ISL9R1560P2, 600V, 15A</td>
</tr>
<tr>
<td>M₁</td>
<td>-</td>
<td>STW45NM60, 650V, Iₕ = 45A, Iₜ,pulsed = 180A</td>
</tr>
<tr>
<td>M₂</td>
<td>-</td>
<td>2x STW45NM60, 650V, Iₕ = 45A, Iₜ,pulsed = 180A</td>
</tr>
<tr>
<td>L₁</td>
<td>75μH</td>
<td>Metglass, MP4510 core, 15 windings</td>
</tr>
<tr>
<td>R₁</td>
<td>0.41Ω</td>
<td>2x 0.82 Ω, 5W</td>
</tr>
<tr>
<td>R₂</td>
<td>10 Ω</td>
<td>Allen Bradley 3W</td>
</tr>
<tr>
<td>R₃</td>
<td>10.2 Ω</td>
<td>1x 22Ω Allen Bradley 3W, 1x 19Ω Allen Bradley 3W</td>
</tr>
<tr>
<td>T₁</td>
<td>-</td>
<td>Tip152, 400V, Iₑ = 7A</td>
</tr>
<tr>
<td>Z₁</td>
<td>86V</td>
<td>2x 43V</td>
</tr>
</tbody>
</table>

Table 2: Quasi-resonant pulse source component list
The instantaneous current in a RLC circuit with a capacitor charged to $U_c$ on $t=0$ can be derived by solving the following second order differential equation which is formulated by applying Kirchhoff's law.

$$i(t) = i_c(t) = i_L(t) = i_R(t)$$

$$0 = u_c(t) + u_L(t) + u_R(t)$$

$$0 = \frac{1}{C} \int_{0}^{t} i(\tau)d\tau + L \frac{di(t)}{dt} + R \frac{d}{dt} + \frac{1}{t}i(t)R$$

A solution of the equation is attempted

$$i(t) = e^{\omega t}$$

Substitution leads to:

$$0 = Lm^2 e^{\omega t} + Rm e^{\omega t} + \frac{1}{C} e^{\omega t}$$

$$0 = Lm^2 + Rm + \frac{1}{C}$$

$$m_{1,2} = \frac{-R \pm \sqrt{R^2 - \frac{4L}{C}}}{2L}$$

The case of under damping is examined further

$$\alpha^2 < \alpha_0^2$$

$$m_{1,2} = -\alpha \pm j\omega_d$$

$$\omega_d^2 = \omega_0^2 - \alpha^2$$

Substitution:

$$i(t) = A_1 e^{\omega_1 t} + A_2 e^{\omega_2 t}$$

Current $i(t)$ will be zero before the switch is closed so:

$$i(t \leq 0) = 0 \Rightarrow$$

$$A_1 + A_2 = 0$$

$$A_1 = -A_2$$
The voltage over the inductor will be near \( u_c(0) \) right after the switch is closed.

\[ u_c(0) = \frac{L}{\frac{d i(t)}{dt}} \]

\[ \left( \frac{d i(t)}{dt} \right)_{t=0} = \frac{u_c(0)}{L} \]

\[ \left( \frac{d i(t)}{dt} \right)_{t=0} = A_1 m_1 + A_2 m_2 \]

\[ A_1 (-\alpha + j \omega_d) + A_2 (-\alpha - j \omega_d) = \frac{u_c(0)}{L} \]

\[ A_1 (-\alpha + j \omega_d) - A_1 (-\alpha - j \omega_d) = \frac{u_c(0)}{L} \]

\[ A_1 = \frac{u_c(0)}{2 j A \omega_d L} \]

Substituting \( A_1 \) leads subsequently to:

\[ i(t) = \frac{u_c(0)}{2 j \omega_d L} \left( e^{(-\alpha + j \omega_d) t} - e^{(-\alpha - j \omega_d) t} \right) \]

\[ i(t) = \frac{u_c(0)}{2 j \omega_d L} e^{-\alpha t} \left( e^{j \omega_d t} - e^{-j \omega_d t} \right) \]

\[ i(t) = \frac{u_c(0)}{\omega_d L} e^{-\alpha t} \sin(\omega_d t) \]

With:

\[ \alpha = \frac{R}{2L} \]

\[ \omega_d = \sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2} \]

Figure 2: Typical under damped waveform

For negligible damping the current and oscillation frequency can be estimated by:

\[ i(t) = \frac{u_c(0)}{\sqrt{\frac{L}{C}}} \sin(\omega_0 t) \]

\[ \omega_0 = \sqrt{\frac{1}{LC}} \]

The period time \( T \) can subsequently be calculated by:

\[ T = 2\pi \sqrt{LC} \]
Resonant charging

The instantaneous current solution can be applied to calculate instantaneous capacitor voltages during resonant charging.

\[ i(t) = \frac{u_1(0) - u_2(0)}{\alpha L} e^{-\alpha t} \sin(\omega_d t) \]

For a negligible damping factor the capacitor voltages can be estimated by:

\[ u_{C1}(T/2) = u_{C1}(0) - \frac{2C_{1}}{C_{1} + C_{2}} (u_{C1}(0) - u_{C2}(0)) \]

\[ u_{C2}(T/2) = u_{C2}(0) + \frac{2C_{2}}{C_{1} + C_{2}} (u_{C1}(0) - u_{C2}(0)) \]

The final capacitor voltage at t = T/2 can be calculated by substituting the following value into previous equations:

\[ \frac{T}{2} = \frac{\pi}{\omega_d} \]

\[ u_{C1}(T/2) = u_{C1}(0) - \frac{1}{C_{1}} \left( u_{C1}(0) - u_{C2}(0) \right) \left( 1 + e^{\alpha T} \right) \]

\[ u_{C2}(T/2) = u_{C2}(0) + \frac{1}{C_{2}} \left( u_{C1}(0) - u_{C2}(0) \right) \left( 1 + e^{\alpha T} \right) \]