4. Unit step response of an impulse measuring system

SAFETY MEASURES: Interlocks are provided to prevent high voltage to be switched on while the gates/ doors are open. Despite these measures it is necessary to connect the safety earth stick to the HV parts before touching. (There could be some charge left on the capacitors). Special safety rules for the High Voltage laboratory must be read, understood, signed and always followed to every detail!

4.1 Objectives

The student must gain the following knowledge and comprehension in the following topics:

- General description of problems in the impulse voltage measurement derived from the dynamic behavior of measuring system;
- General description of unit step response (USR) method;
- Evaluation of measurements of transient voltages measured with a capacitive voltage divider system;
- Design of capacitive voltage divider impulse voltage measuring systems for specific cases.

4.2 General Description

4.2.1 Measuring system for impulse voltage

Impulse voltages are fast (ns-ms) transients with a relatively high (kV-MV) amplitude. To measure the impulse voltages, it will be necessary to reduce (downscale) the amplitude to a magnitude recordable by the chosen measuring equipment, normally an oscilloscope or an impulse voltmeter. The reduced voltage should ideally be an accurate, downscaled copy of the physical high voltage impulse impressed to the test object with a known, non-varying transfer ratio against all frequency components and other parameter. For practical applications one should be aware of the fact that the measured voltage (on the oscilloscope) would differ from the "real" high voltage because:

– Limitations in the transfer function of the measuring system;
– Noise signals induced/influenced to the measuring system.

Generally speaking measuring problems grows worse the larger and faster the voltages are.

Figure 1 shows the principle layout and components of the impulse voltage measuring system. Every possible current and voltage waveform present in the connection (supply) lead can be resolved into two waves travelling in each direction with a speed of $v[m/s]$. The waves would, in the case of a lossless conductor, satisfy the condition stating that the ratio of the voltage and current in any point of the conductor would be constant and equal to the characteristic impedance of the supply conductor. This characteristic impedance is pronounced Z_B and can be determined on the basis of inductance and capacitance per unit length according to:

$$Z_B = \sqrt{L/C}, \quad v = \sqrt{1/LC} \tag{1}$$

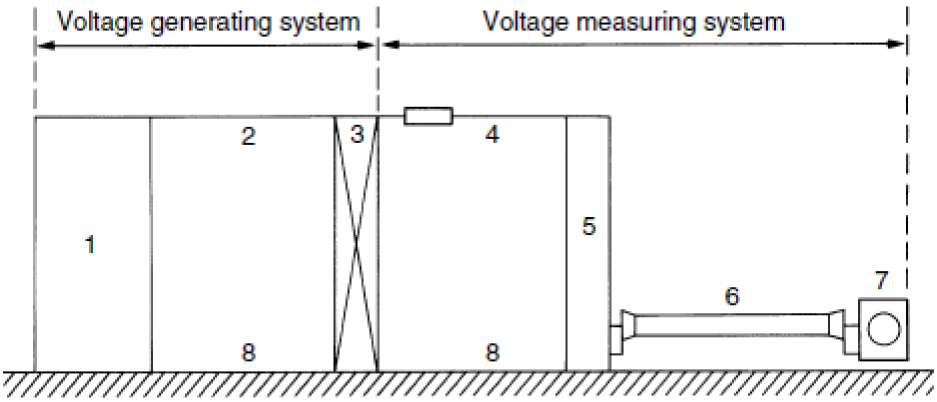


Fig.1 Impulse voltage test setup (principle drawing), 1. Impulse voltage generator (IVG), 2. Conductor between IVG and EUT, 3. Equipment under test (EUT), 4. Conductor for voltage divider, 5. Voltage divider, 6.measuring cable, 7. Oscilloscope, 8. Ground return conductor

The speed of the waves (wave propagation speed) would for a lossless conductor in the air be equal to the speed of light, $v_{light} = 30\ cm/ns$. The characteristics impedance Z_B would normally equal approximately 400 -500Ω.

The voltage $u(t)$ at the top (HV terminal) of the voltage divider would be given by the impressed impulse voltage and the reflection / transmission of the waves propagating in time on the supply conductor.

This voltage $u(t)$ at the HV terminal of the voltage divider will be divided into a lower voltage impressed to the measuring cable. The voltage divider is in principle constructed be means of two serial connected impedances.

The primary HV impedance Z_1 is normally of a high value while the secondary LV impedance Z_2 is very small in comparison to Z_1. Sometimes one uses the simple method by using the characteristic impedance of the measuring cable as LV impedance.

The transfer ratio of the voltage divider can be calculated by:

$$n = (Z_1 + Z_2)/Z_2$$

This value, n, will be practical applications normally be equal to the ratio of the input-to-output voltage and could be pronounced nominal transfer ratio.

4.2.2 Unit step response

The measuring system can be analyzed in the laboratory by means of the transfer function (amplitude and phase frequency characteristics) or the **unit step response**.

Fig. 2 below shows the principles of the unit step response method for analyzing the dynamic behavior of the impulse measuring system.

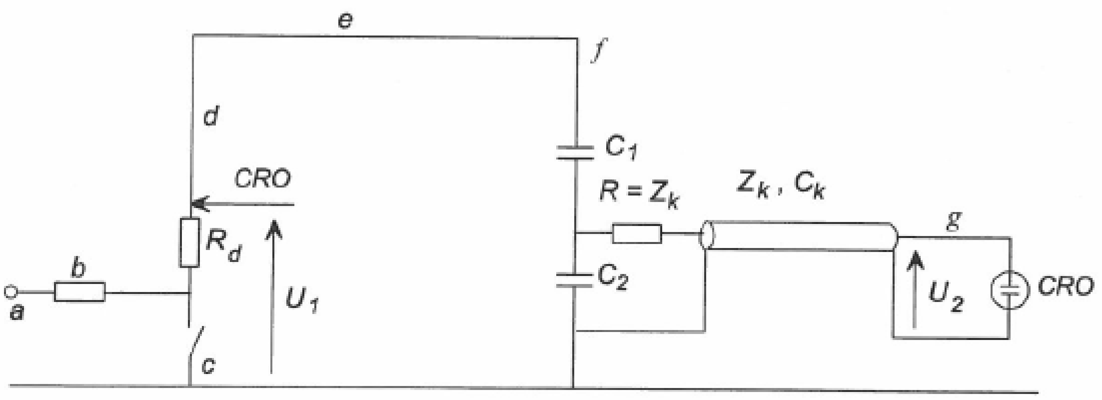


Fig.2 Experimental setup for the determination of the unit step response of an impulse measuring system. a. DC supply; b, charging resistor; c. mercury relay; d. vertical conductor with impedance matching R_d; e. supply conductor with length l and height h above ground; f. capacitive voltage divider; g. to oscilloscope.

An unit step voltage is impressed on the measuring system via resistor b. This unit step voltage is present at point d and will be the reference input signal for the unit step response test. The reply of the measuring system on this unit step unit is pronounced the step response of the measuring system and can be recorded with the oscilloscope connected in g. By means of the step response it will be possible to predict the transfer function of the measuring system and thereby be able to estimate the measuring error for an arbitrary input voltage.

The step response of the measuring system provides information on the following characteristic parameters:

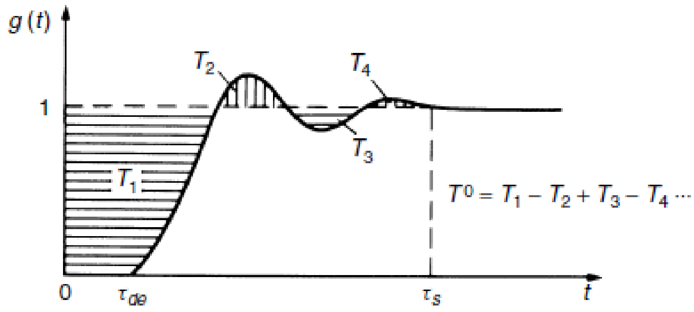
- The rise time of the step response reflects the upper frequency limit of the measuring system.
- Oscillations in the step response reflects the resonant frequency of the measuring system.
- The area between the unit (amplitude =1) step unit voltage and the normalized step response (limiting value) is pronounced response time T and defined in the following way:

$$T = \int_0^{\infty} (1 - g(t))dt$$

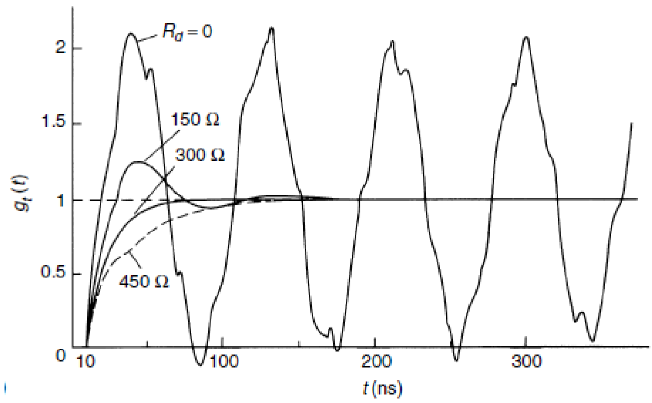
With g(t) as the voltage waveform of the step response as a function of time. This is illustrated in Fig. 3(a), where the response time $T = T_1 - T_2 + T_3 - T_4 + T_5$.

The principle unit step response of the system shown in Fig. 2 with different values of R_d is shown in Fig. 3 (b).

Oscillations in s step response normally originate from reflections on the supply conductor, because of the impedance mismatch between the characteristic impedance of the conductor and the high (in comparison to the conductor) impedance of the voltage divider and at the other end of the conductor – to HV generator mismatch.



(a)



(b)

Fig. 3 Unit step response of a measuring system

The impedance of a practical impulse measuring application would not be zero, but in the range of the characteristic impedance of the supply conductor. This explains the use of the resistor R_d ≈(characteristic impedance of supply conductor) in Fig. 2. The principle response of a practical measuring system would be more like curves in Fig. 3(b) with $R_d = 300\Omega\ or\ 450\Omega$, and pronounced "infinite line response".

It can be shown that the measuring system would react linearly to varying input voltages beyond the time, where the "infinite line" response has reached its final value.

A mathematical approximation of the infinite-line response would be a double-exponential function, which for practical applications would have reached the final value after 4-5 times the response time of the "infinite lime" response (pronounced T_∞ and defined according to the hatched area of Fig 3 (b)).

Practical measuring systems normally react in a way, which will justify the use of the infinite-line response time T_∞ as a guideline to the performance of a measuring system in connection with measuring fast rising voltages.

I t can also be shown that the peak voltage measuring error $\Delta V[kV]$ for linearly rising voltages can be calculated as the product of the response time $T[s]$ and the steepness $S\ [kV/s]$ of the rising voltage according to Fig. 4.

$$\Delta V = S \cdot T$$

International standards for impulse measuring systems are given in IEC 60-1 to 60-4 “High Voltage test techniques”.

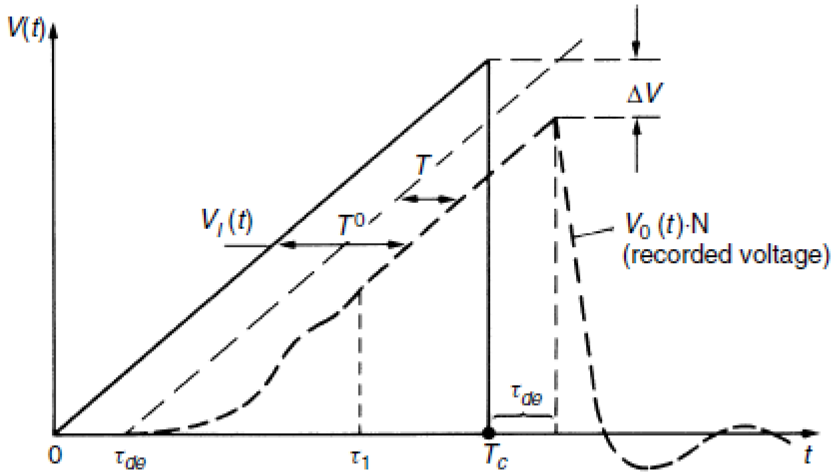


Fig.4 Peak voltage measuring error

4.3 Laboratory tasks

The main task is to use the principles outlined above by testing one of the capacitive impulse measuring systems of the high voltage laboratory.

4.3.1 Calculations

The students should take a picture of the USR test circuit and explain the components and how they work.

Please explain components in the circuit and how they work.

First there is a DC source use to generate a voltage step of 5V through a charging resistor of value 1.5MΩ. The step signal is a reverse step to avoid a short-circuit in the system.

Between the charging resistor and the voltage divider there is a damping resistor Rd used to prevent overshoot in the voltage measurement. According to the theory if the value of Rd is similar to the value of the impedance of the lead it is possible to avoid a non-desired time response.

The capacitive voltage divider is formed by C1= 600 pF and C2= 119.5 nF. C2>>C1 to have a voltage lower at the output.

After the voltage divider again is necessary to use another damping resistor in order to measure the real value of the voltage. The value of this damping resistor is R=Zk (impedance conductor).

The conductor is connected to an oscilloscope to measure the output voltage and compare it with the input voltage.

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Horizontal supply conductor is a 10m long wire with a diameter of 2mm. It has an average height of 1.6m over the ground plane. Based on arrangements and dimensions of circuit, the students need to conduct following calculations:

- Calculate the impedance of horizontal supply conductor Z_{hor};
- Calculate the capacitance C and inductance $L$of the supply conductor;
- Calculate the wave propagation velocity$v$ in the lead;
- Calculate the transfer ratio n based on values of the capacitors.

4.3.2 Unit step response test

The students need do following tasks:

- Conduct the unit step response test according the circuit constructed in section 4.3.1.
- Measure $u_1(t)$ and $u_2(t)$ with an oscilloscope, and comment the appearance of the curves. Then import the date files to eg. MATLAB to calculate the response time T.
- Short circuit R_d and measure $u_1(t)$ and $u_2(t)$ again. Calculate the response time T in this case.
- Calculate the impulse voltage peak measuring error ΔV for the linearly rising impulse voltages with different front steepness $S = 2MV/\mu s,\ 200kV/\mu s$ and $20kV/\mu s$.

Horizontal supply conductor is a 10m long wire with a diameter of 2mm. It has an average height of 1.6m over the ground plane. Based on arrangements and dimensions of circuit, the students need to conduct following calculations:

− Calculate the impedance of horizontal supply conductor;

$$(Z_L)_{\mathrm{hor}} = A\frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}} = 60 \times A(l, d, H) \quad [\Omega]$$

$$A = \ln\left[\frac{2l}{d}\sqrt{\frac{\sqrt{\{1+(2H/l)^2\}}-1}{\sqrt{\{1+(2H/l)^2\}}+1}}\right]$$
$$= \ln\left(\frac{4H}{d}\right) - \ln\frac{1}{2}(1+\sqrt{1+2(H/l)^2})$$

A = 8.3045 Ω

$$(\boldsymbol{Z_L})_{\boldsymbol{hor}} = \mathbf{60} * \boldsymbol{A} = \mathbf{498.27}\, \boldsymbol{\Omega} \sim \mathbf{500}\, \boldsymbol{\Omega}$$

− Calculate the capacitance C_L and inductance $L_L$of the supply conductor;

$$C_L = \frac{2\pi\varepsilon_0 l}{A};$$

ε_0 = 8.85 ×10^{-12} F·m^{-1}

$$\boldsymbol{C_L} = \mathbf{66.95}\, \boldsymbol{pF} \sim \mathbf{67}\, \boldsymbol{pF}$$

$$Z_L = \sqrt{\frac{L_L}{C_L}},$$

$$\boldsymbol{L_L} = \mathbf{12.85}\, \boldsymbol{\mu H} \sim \mathbf{13}\, \boldsymbol{\mu H}$$

− Calculate the wave propagation velocity v in the lead;

$$v = \sqrt{1/LC}$$

$$\boldsymbol{v} = \mathbf{33.88} \times \frac{\mathbf{10^6 m}}{\mathbf{s}} \sim \mathbf{3.38 cm/ns}$$

– Calculate the transfer ratio n based on values of the capacitors.

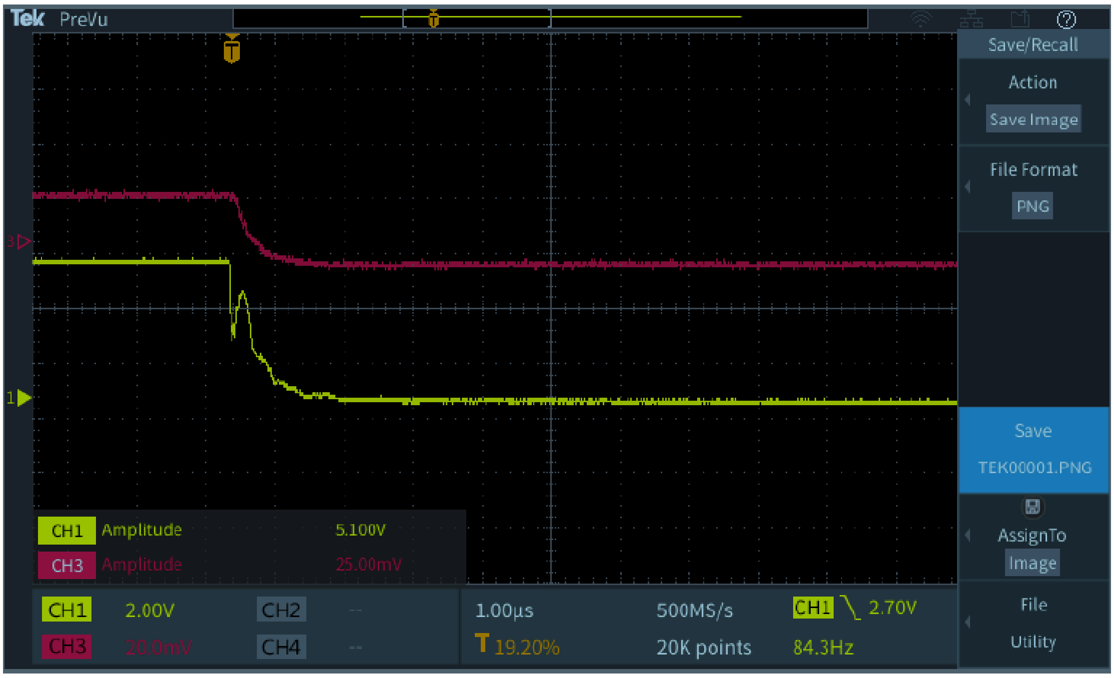
$$n = (Z_1 + Z_2)/Z_2$$

$$n = \frac{C_1 + C_2}{C_1}$$

$C_1 = 600\ pF$; $C_2 = 119.5\ nF$

$$\boldsymbol{n = 200.166 \sim 200}$$

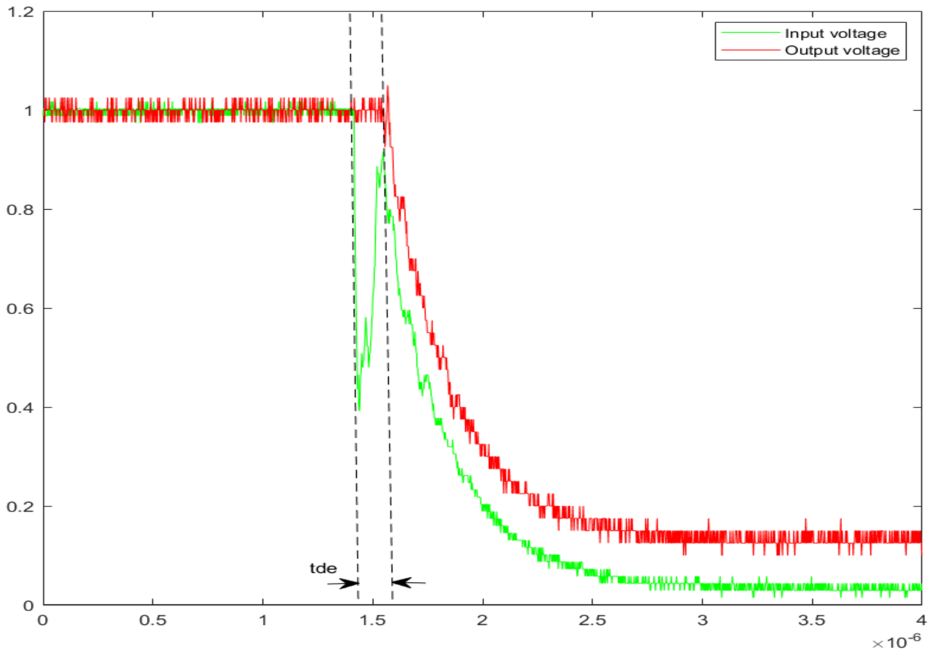
– Measure $u1(t)$ and $u2(t)$ with an oscilloscope, and comment the appearance of the curves. Then import the date files to eg. MATLAB to calculate the response time T.



From the scope the input voltage (5V amplitude) is the yellow curve and the voltage after the capacitive voltage divider is the red curve (25mV amplitude). If we compare both curves it can be validated the transfer ratio found previously:

5V /25mV = 200 = n

Moreover, the output voltage does not reach the final value of the input step voltage because of the capacitors of the voltage divider. In this case the value of Rd = 470 Ω which allows to damp the input voltage and that is why in the output voltage there is no overshoot.



The response time is calculated as stated in the following equations:

$$T^0 = \int_0^\infty [1 - g(\tau)]d\tau$$

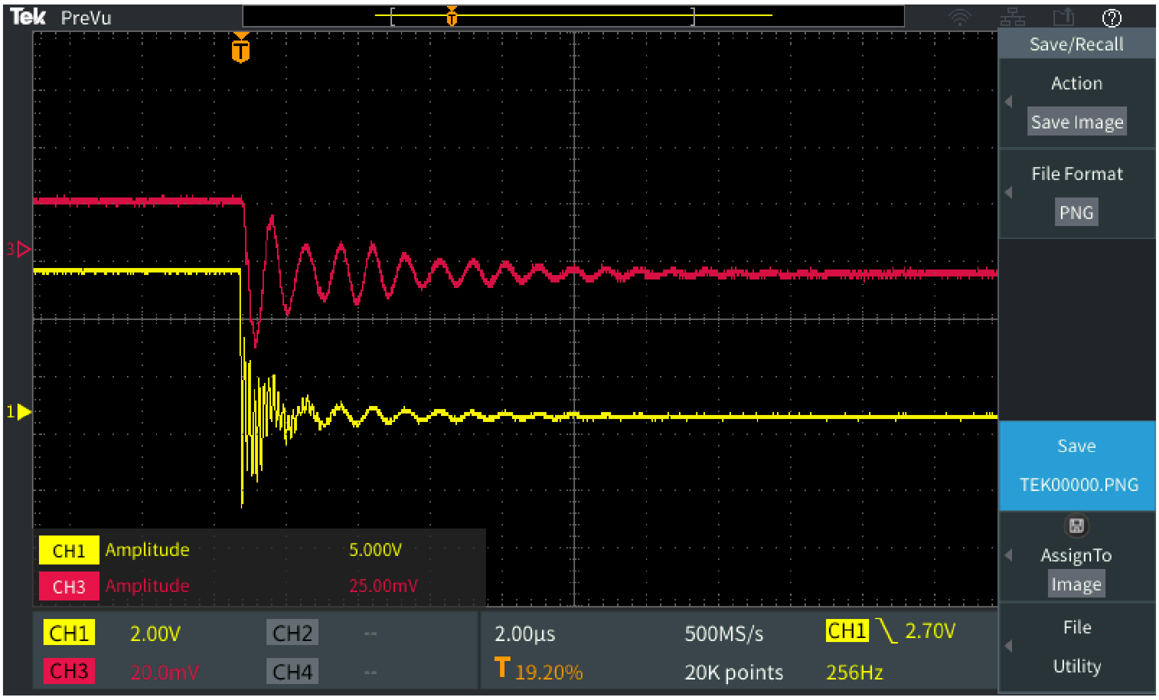
$$T = T^0 - \tau_{de} = \int_{\tau_{de}}^\infty [1 - g(\tau)]d\tau$$

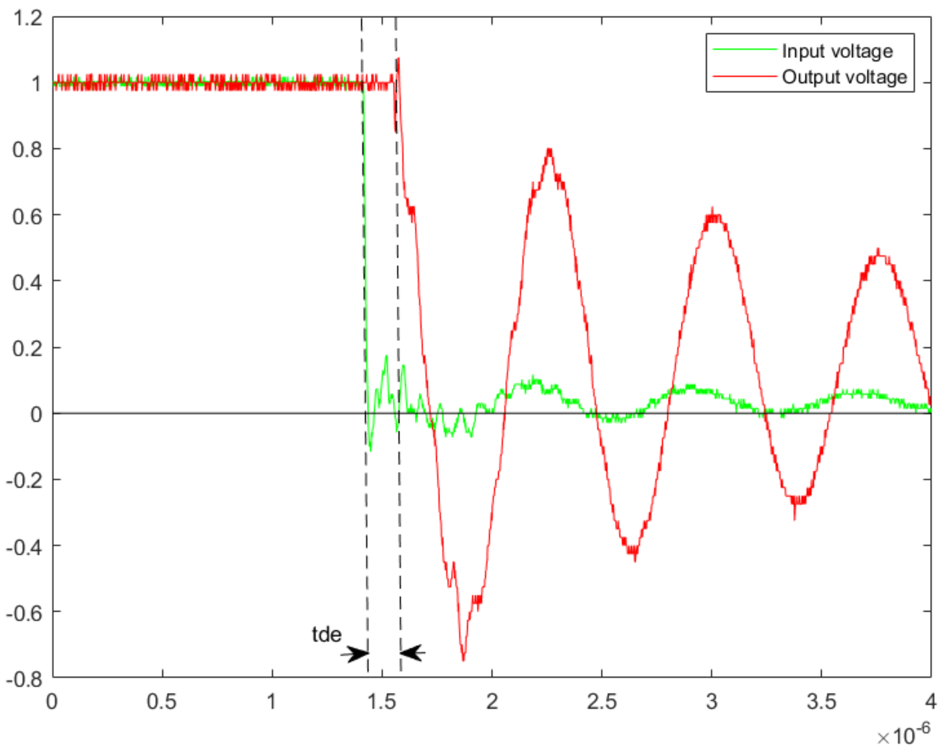
T = $\boldsymbol{T^0}$ – tde = 211.13 $\boldsymbol{ns}$

Where tde is the is the time delay at which the output voltage starts falling from 1 to 0.

– Short circuit R_d and measure $u_1(t)$ and $u_2(t)$ again. Calculate the response time T in this case.

If the value of Rd is 0 then the system will be undamped and therefore more oscillations will appear in the time response. The next figure reflects these oscillations and even though it seems that the response time in this case is higher than the damped system it is not. This is because when the output voltage gets lower than 0 it is necessary to subtract this time periods as: $T = T_1 - T_2 + T_3 - T_4 + T_5$ - ……





The response time is:

$$T = T1 - T2 + T3 - T4 + T5 - T6 + T7 - tde = 482.9\ ns$$

– Calculate the impulse voltage peak measuring error ΔV for the linearly rising impulse voltages with different front steepness S=2MV/μs, 200 kV/μs and 20 kV/μs.

$$\Delta V = S \cdot T$$

S = 2MV/μs:

T = 211.13 ns → ΔV = 422.7 kV

T = 482.9 ns → ΔV = 965.8 kV

S= 200 kV/μs

T = 211.13 ns → ΔV = 42.27 kV

T = 482.9 ns → ΔV = 96.58 kV

S= 20 kV/μs

T = 211.13 ns → ΔV = 4.226 kV

T = 482.9 ns → ΔV = 9.658 kV