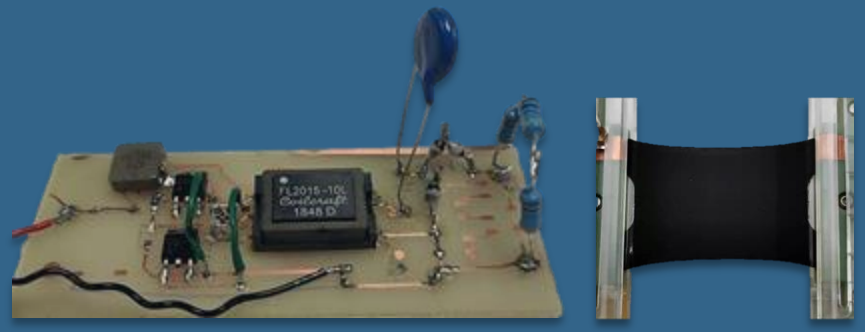
INTELLIGENT MATERIAL SYSTEMS LAB

ZeMA

UNIVERSITÄT DES SAARLANDES



Modelling and Control of an High Voltage Driving Circuit for Dielectric Elastomer Actuators

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Intelligent Material Systems Lab (iMSL)
Saarland University, Saarbrücken, Germany

Department of Electrical and Information Engineering (DEI)

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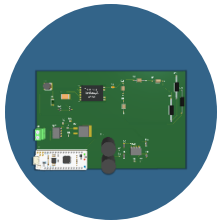
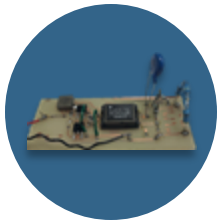
Tutors
David Naso
Gianluca Rizzello

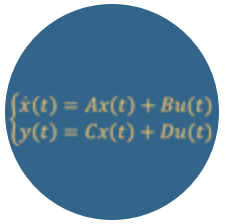
Politecnico di Bari

Outline

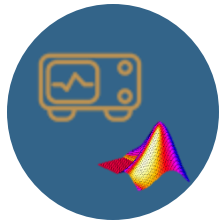

Introduction on Dielectric Elastomer (DE)


Motivation of the Ph.D work

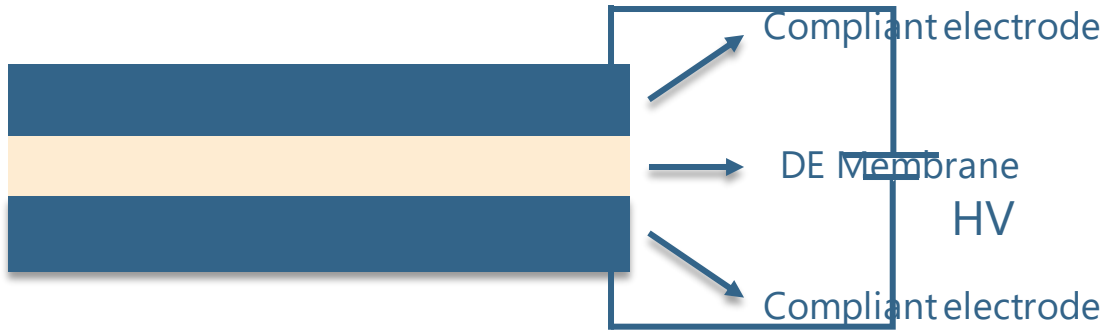

High Voltage (HV) circuit study



Mathematical model


Experimental validation

- DE: Dielectric Elastomer Membrane + compliant electrode
- High voltage needed

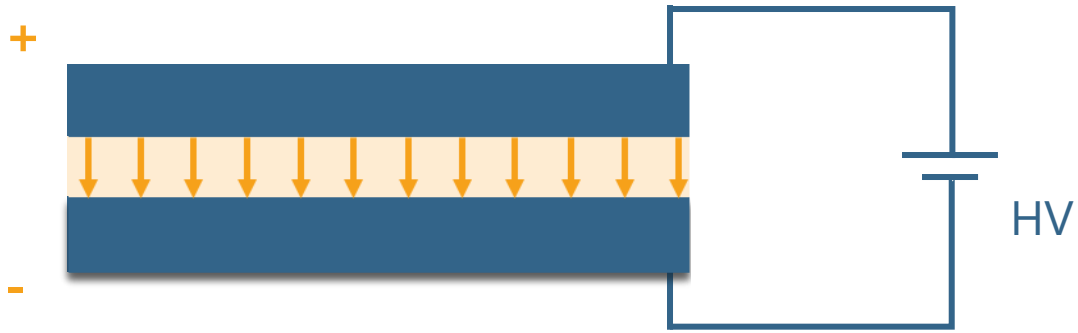


Dielectric Elastomer (DE)

- DE: Dielectric Elastomer Membrane + compliant electrode

- High voltage needed
  - Electric field
  - Maxwell stress
  - Expansion in area and reduction in thickness
  - Variable capacitance

Energy conversion:
From electrical energy to mechanical energy

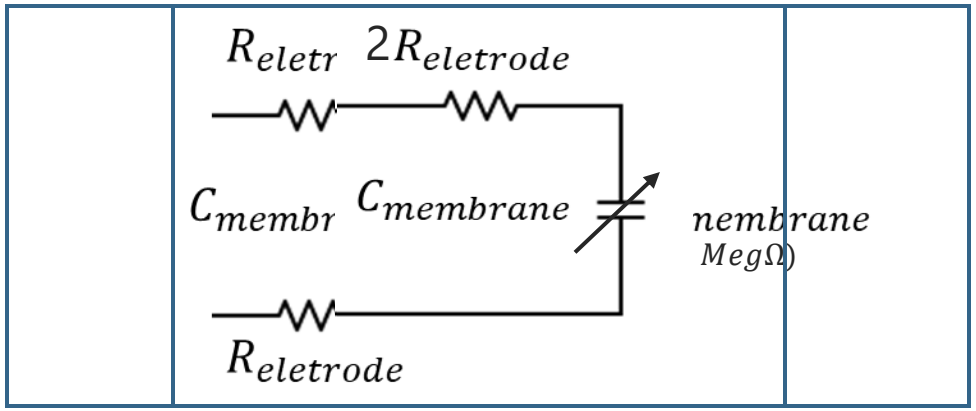


Dielectric Elastomer (DE)

- DE: Dielectric Elastomer Membrane + compliant electrode

- High voltage needed
  - Electric field
  - Maxwell stress
  - Expansion in area and reduction in thickness
  - Variable capacitance

DE's electrical model



Light weight

High flexibility

High frequencies

Low energy consumption

High force

Low acustic noise

Dielectric Elastomer (DE)

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- High voltage needed
  - Electric field
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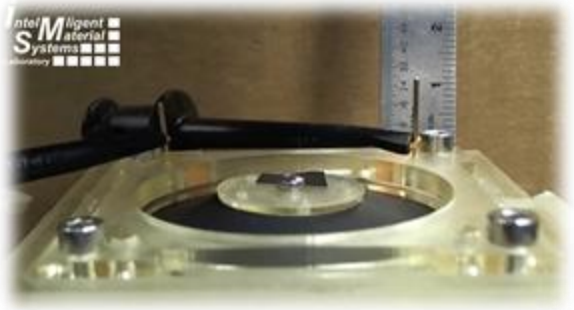
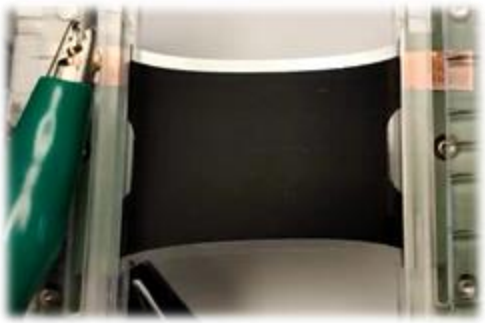




Light weight

Low energy consumption

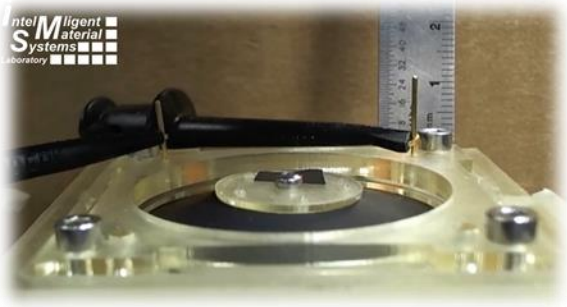
Hig

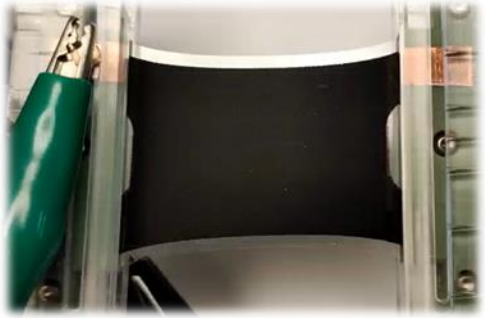
High force

High frequencies

Low acustic noise

Motivation of the Ph.D. work

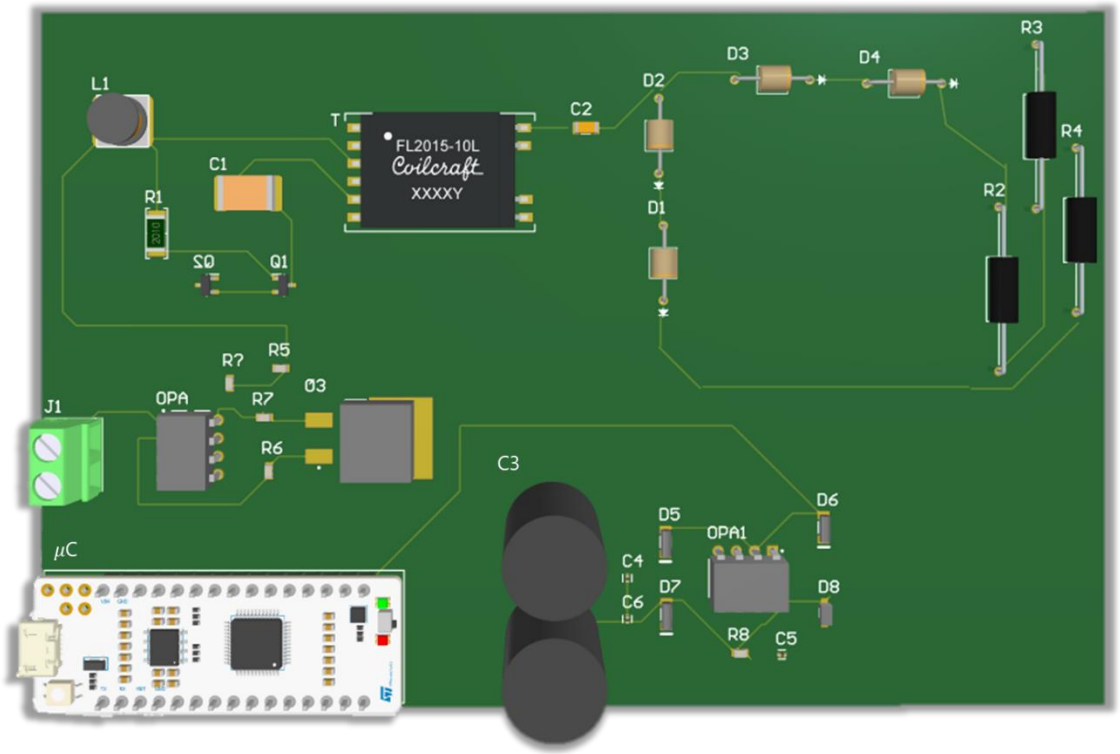




High Voltage Amplifiers

Motivation of the Ph.D. work

Development of a controlled High Voltage source for Dielectric Elastomer Actuators (DEAs) embeddable in different systems

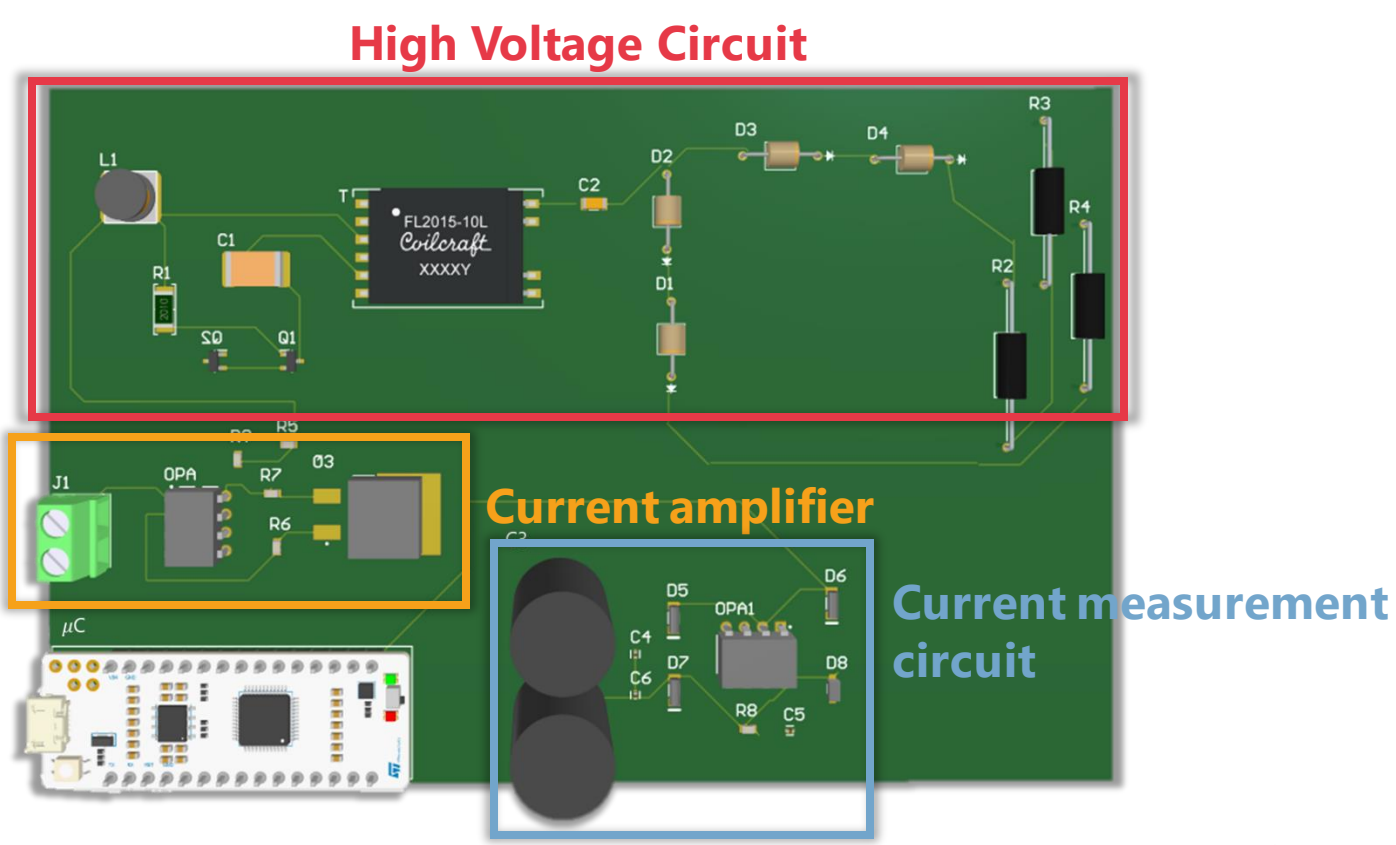


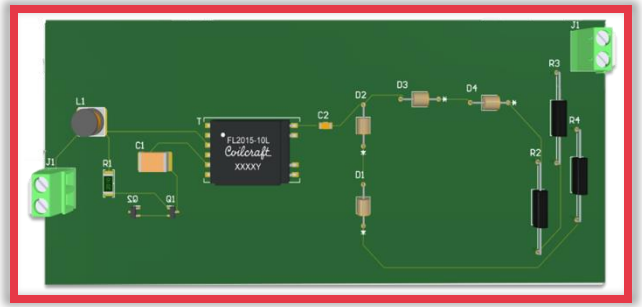
Properties

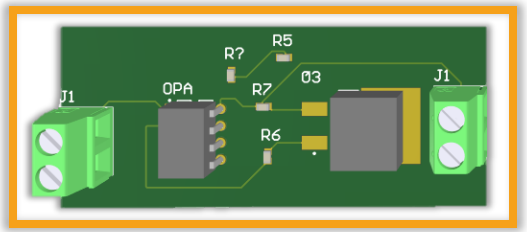
- Controlled HV source for capacitive loads
- Compact, small, lightweight circuit
- Suitable for different input signals (Step, sine, etc.)
- Increased energy efficiency through control
- Demonstrators & Systems integration

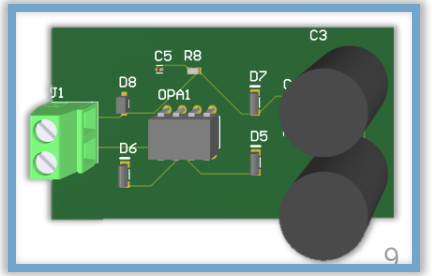
Motivation of the Ph.D. work

Development of a controlled High Voltage source for Dielectric Elastomer Actuators (DEAs) embeddable in different systems



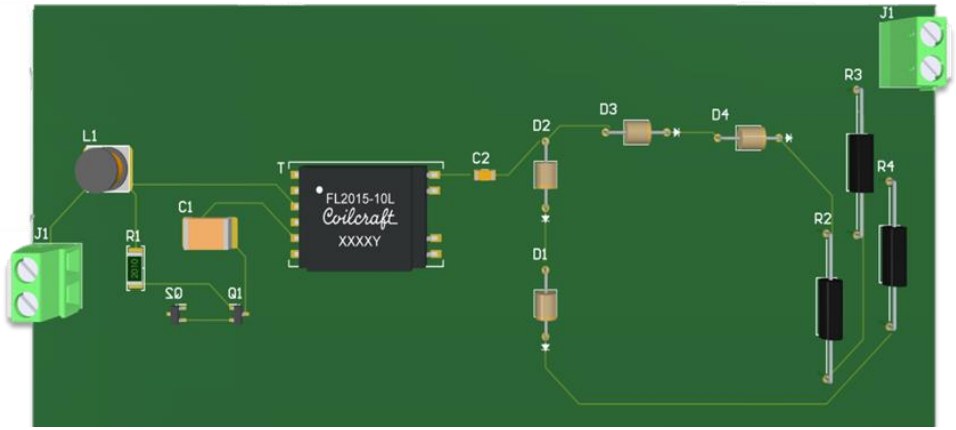


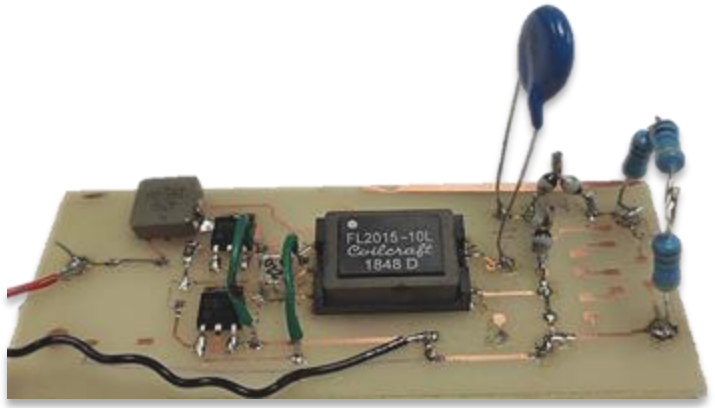




Motivation of the Ph.D. work

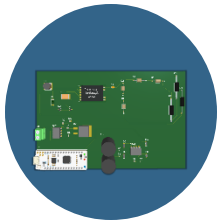
High Voltage Circuit





Outline

Introduction on Dielectric Elastomer (DE)



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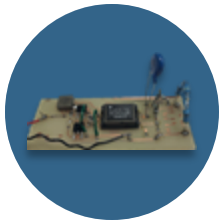
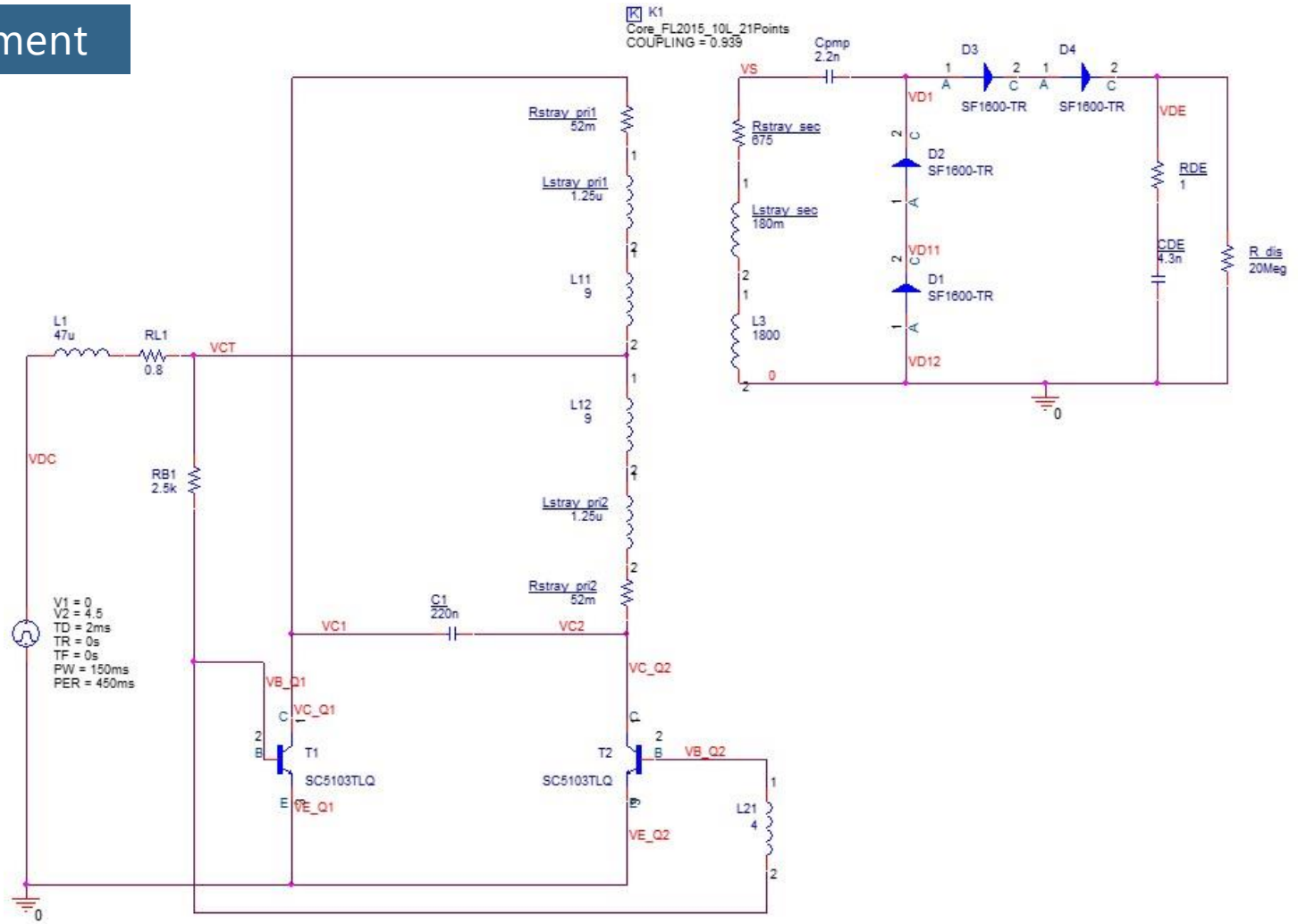


High Voltage (HV) circuit study

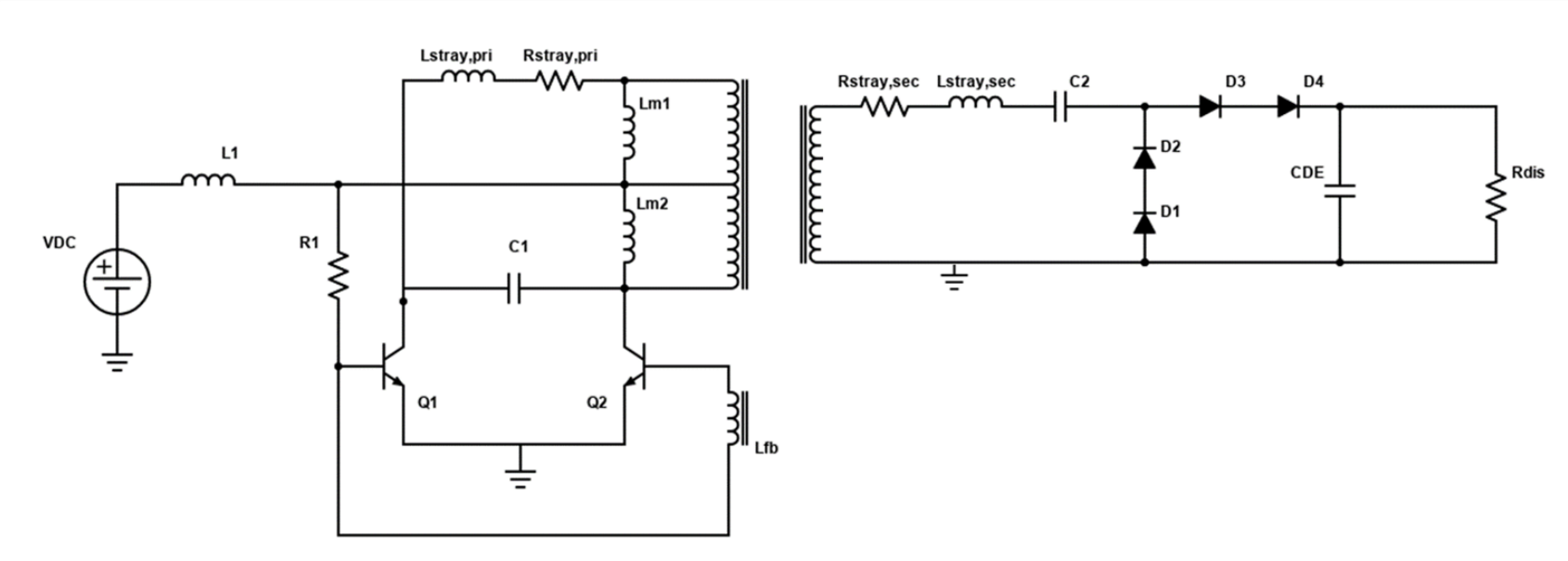
Mathematical model

Experimental validation

OrCAD - PSpice simulation environment



High Voltage circuit study



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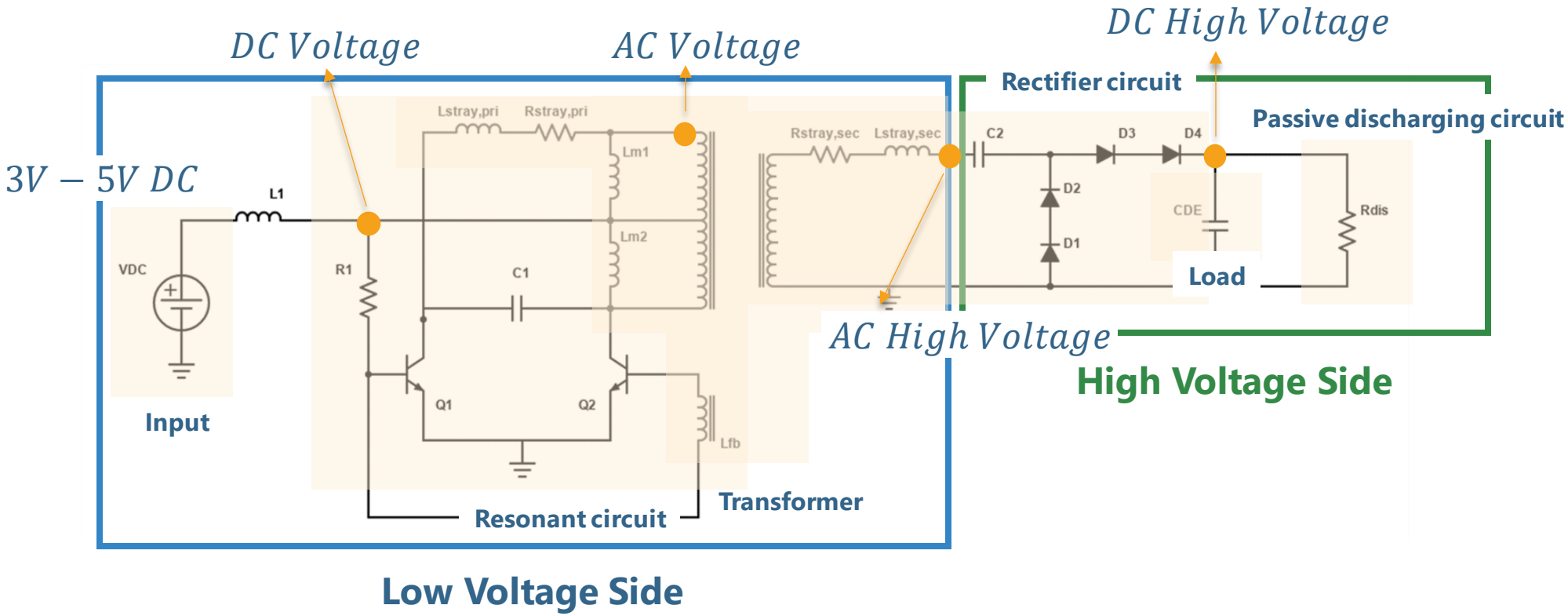
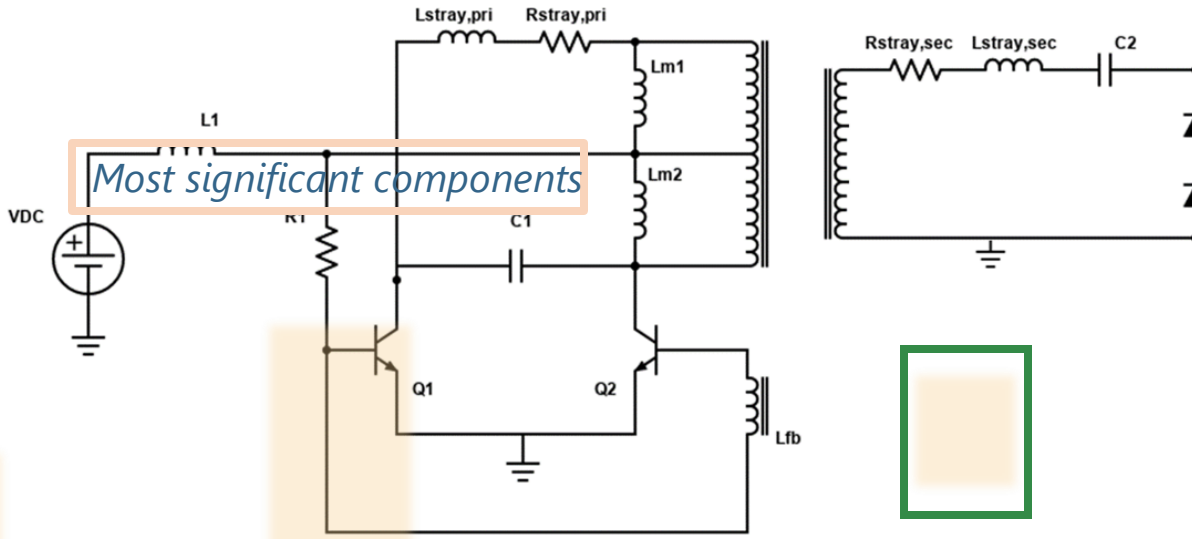


High Voltage circuit study

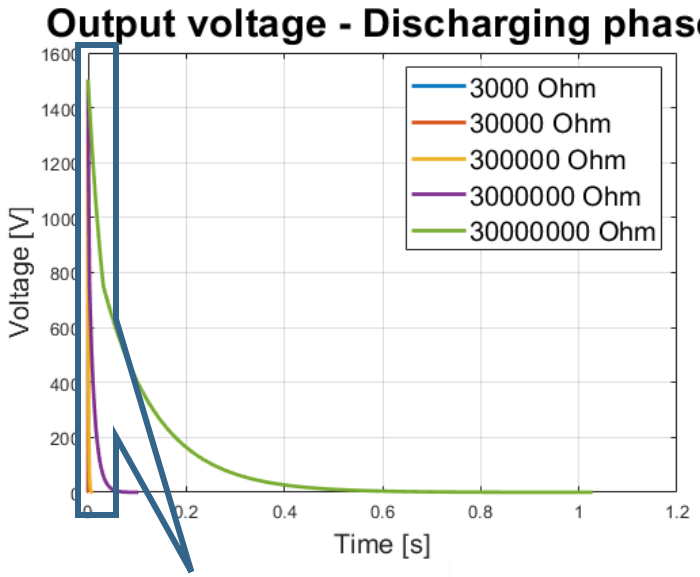
Parameters analysis criteria

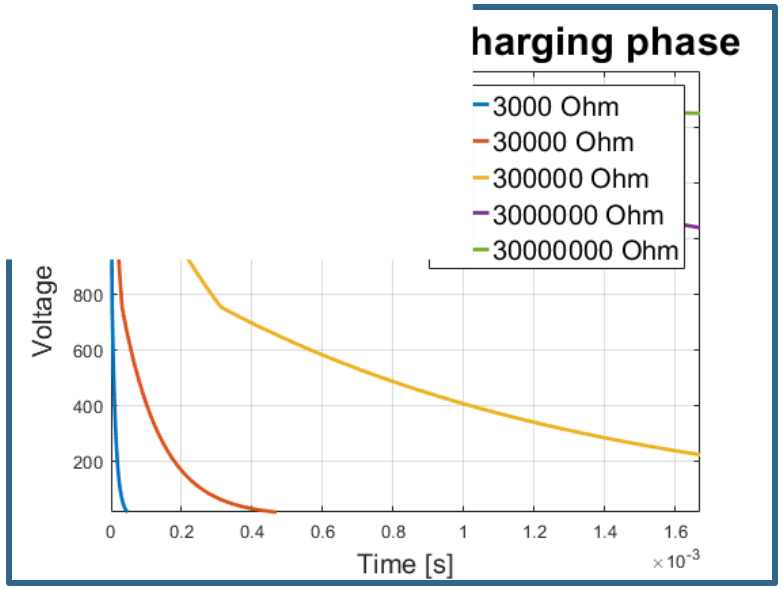
- Output voltage amplitude
- Time constant



Most significant components

For example..





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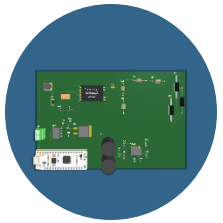

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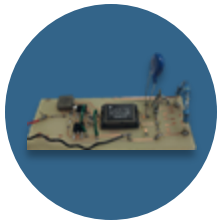

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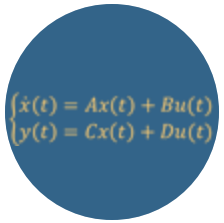
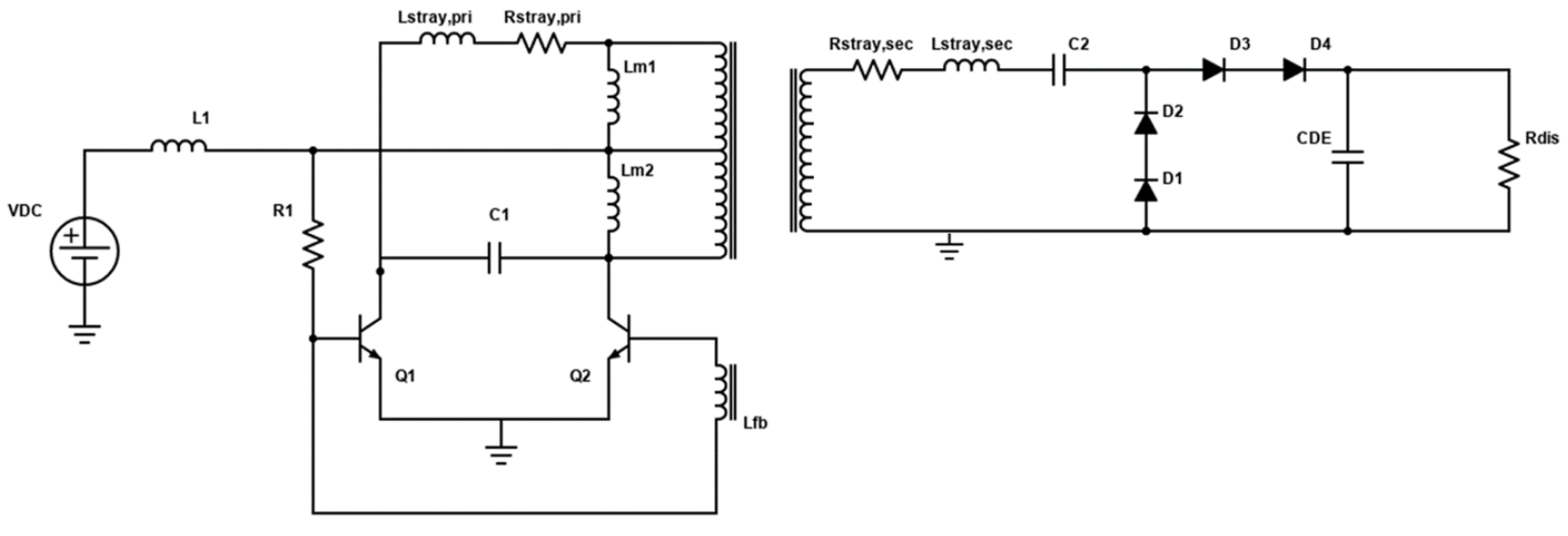
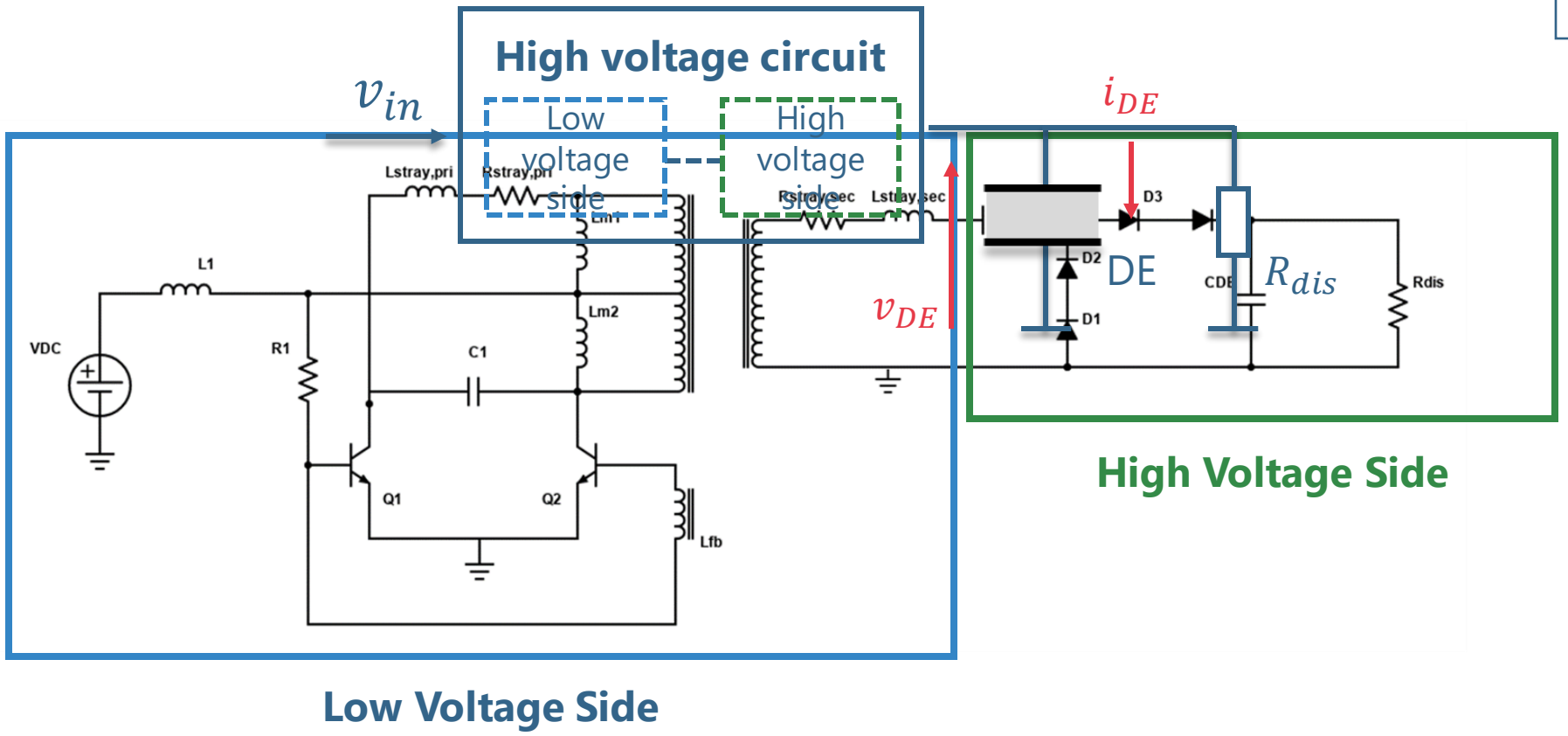


Mathematical model

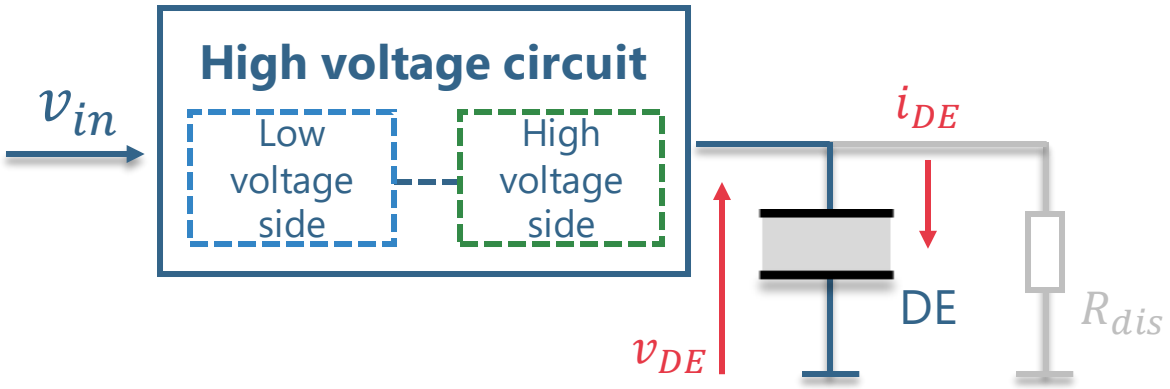
Experimental validation


Lstray,pri
Rstray,pri
Lm1
L1
Lm2
VDC
R1
C1
Q1
Q2
Lfb
Rstray,sec
Lstray,sec
C2
D3
D4
D2
CDE
Rdis
D1

Mathematical model



Mathematical model

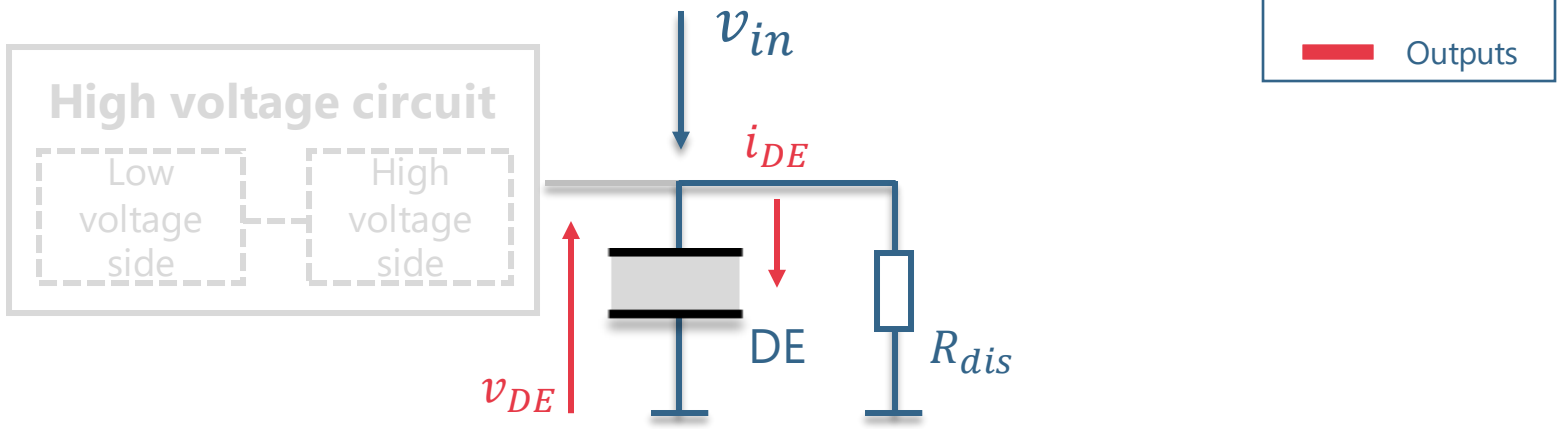


Charging phase

$$\begin{cases} \dot{x}(t) = A_{cha}x(t) + Bv_{in}(t) \\ y(t) = C_{cha}x(t) + Dv_{in}(t) \end{cases}$$

- $Input: v_{in}$
- $Outputs: v_{DE}, i_{DE}$
- **Average model:** Switching behaviour between resonant circuit and rectifier circuit
- Discharging phase OFF

Mathematical model



Charging phase

$$\begin{cases} \dot{x}(t) = A_{cha}x(t) + Bv_{in}(t) \\ y(t) = C_{cha}x(t) + Dv_{in}(t) \end{cases}$$

- $Input: v_{in}$
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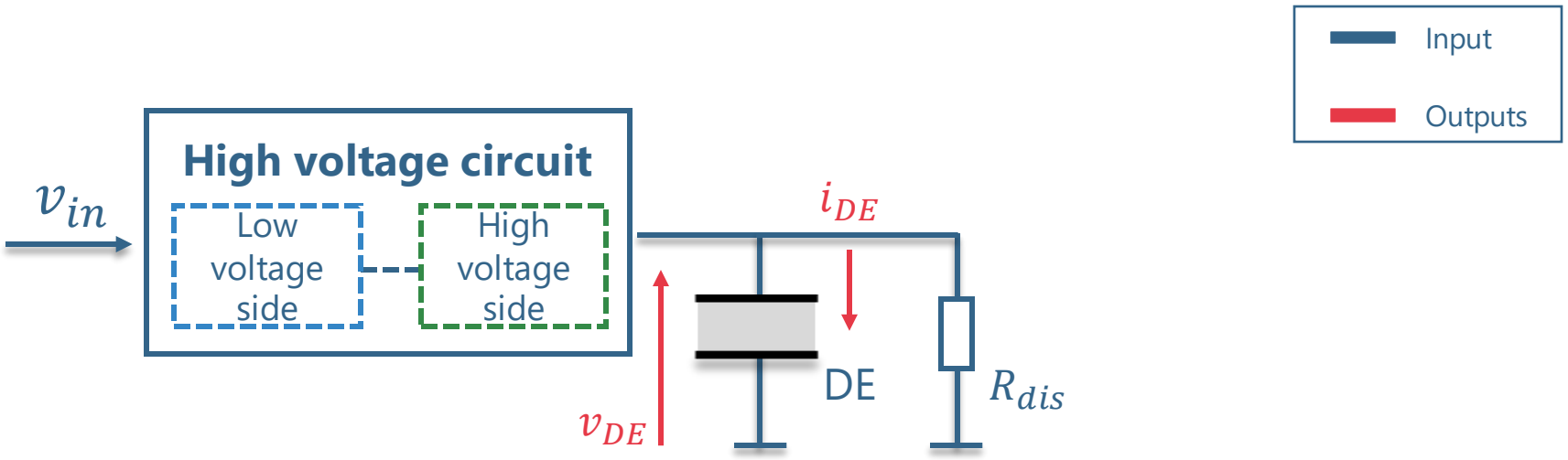
- **Average model:** Switching behaviour between resonant circuit and rectifier circuit
- Discharging phase OFF

Discharging phase

$$\begin{cases} \dot{x}(t) = A_{dis}x(t) + Bv_{in}(t) \\ y(t) = C_{dis}x(t) + Dv_{in}(t) \end{cases}$$

- $Input: v_{in}$
- $Outputs: v_{DE}, i_{DE}$
- Charging phase OFF
- Discharging behaviour as a capacitor

Mathematical model



Charging phase

$$\begin{cases} \dot{x}(t) = A_{cha}x(t) + Bv_{in}(t) \\ y(t) = C_{cha}x(t) + Dv_{in}(t) \end{cases}$$

- $Input: v_{in}$
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- Discharging phase OFF

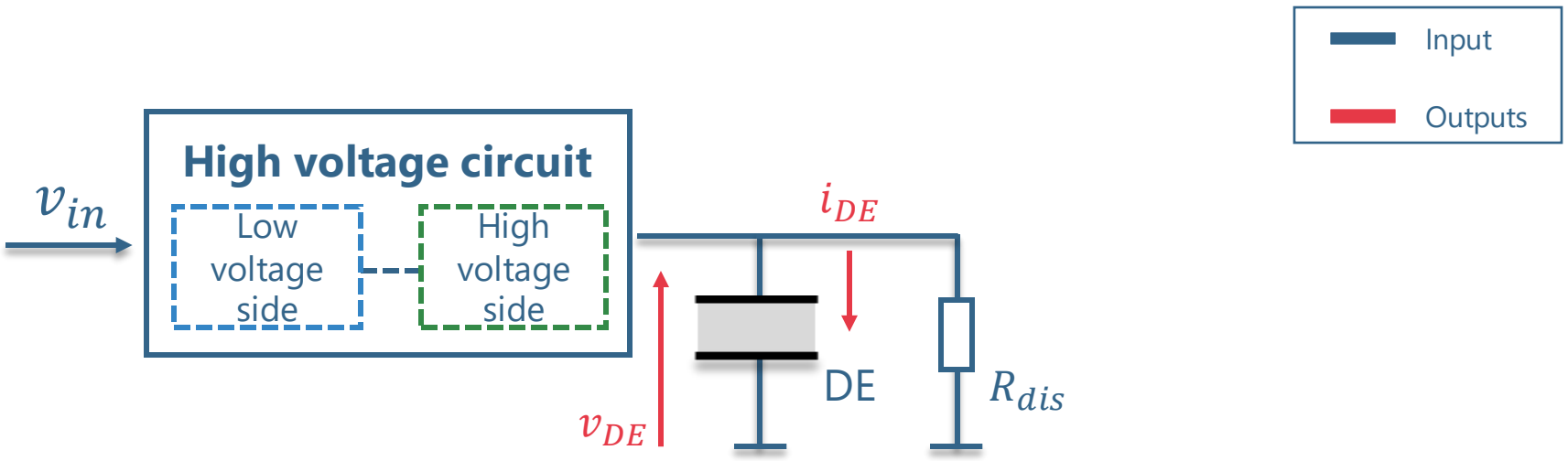
$v_{in} \lessgtr K$

Discharging phase

$$\begin{cases} \dot{x}(t) = A_{dis}x(t) + Bv_{in}(t) \\ y(t) = C_{dis}x(t) + Dv_{in}(t) \end{cases}$$

- $Input: v_{in}$
- $Outputs: v_{DE}, i_{DE}$
- Charging phase OFF
- Discharging behaviour as a capacitor

Mathematical model



Charging phase

- [illegible]
- [illegible]
- [illegible] between resonant circuit and rectifier circuit
- Discharging phase OFF

Discharging phase

- [illegible]
- Discharging behaviour as a capacitor

$$\begin{cases} \dot{x}(t) = \left(A_{cha}d - A_{dis}(d-1)\right)x(t) + \left(B_{cha}d - B_{dis}(d-1)\right)v_{in}(t) \\ y(t) = \left(C_{cha}d - C_{dis}(d-1)\right)x(t) + \left(D_{cha}d - D_{dis}(d-1)\right)v_{in}(t) \end{cases}$$

Mathematical model

$$i(t) = C\frac{dV}{dt} + V\frac{dC}{dt}$$

Mathematical model: 1st version

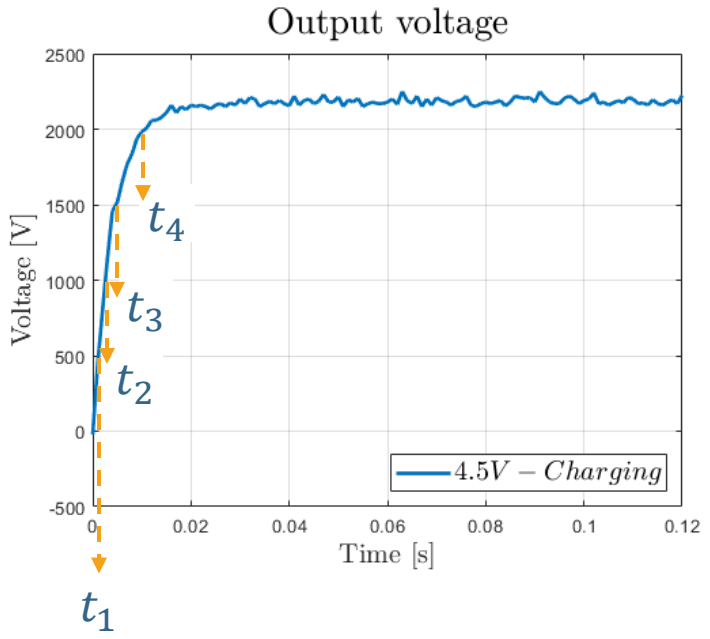
Static capacitance

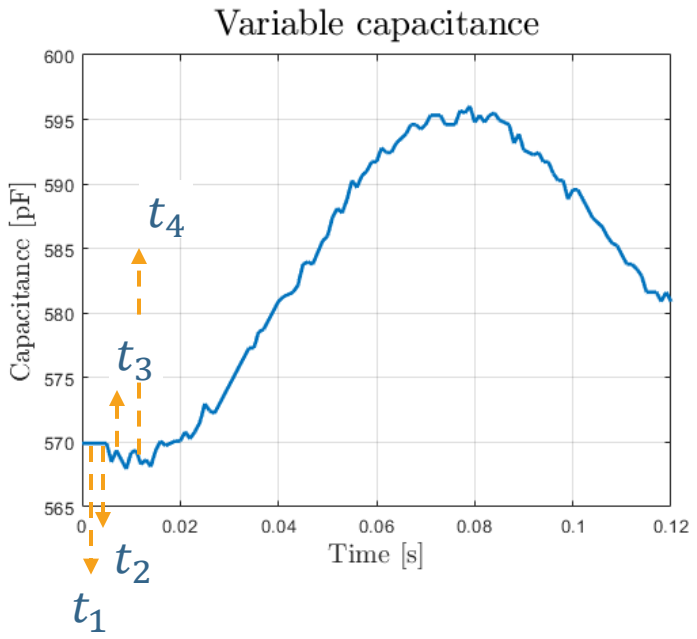
$$i(t) = C\frac{dV}{dt}$$

$$\frac{dV}{dt}\% \gg \frac{dC}{dt}\%$$

Real capacitors

State variables: $\boldsymbol{x}(t) = \boldsymbol{v_C}(t)$





Mathematical model

$$i(t) = C\frac{dV}{dt} + V\frac{dC}{dt}$$

Mathematical model: 1st version

Static capacitance

$$i(t) = C\frac{dV}{dt}$$

$$\frac{dV}{dt}\% \gg \frac{dC}{dt}\%$$

Real capacitors

State variables: $\boldsymbol{x}(t) = \boldsymbol{v_C}(t)$

Mathematical model: 2nd version

Variable capacitance

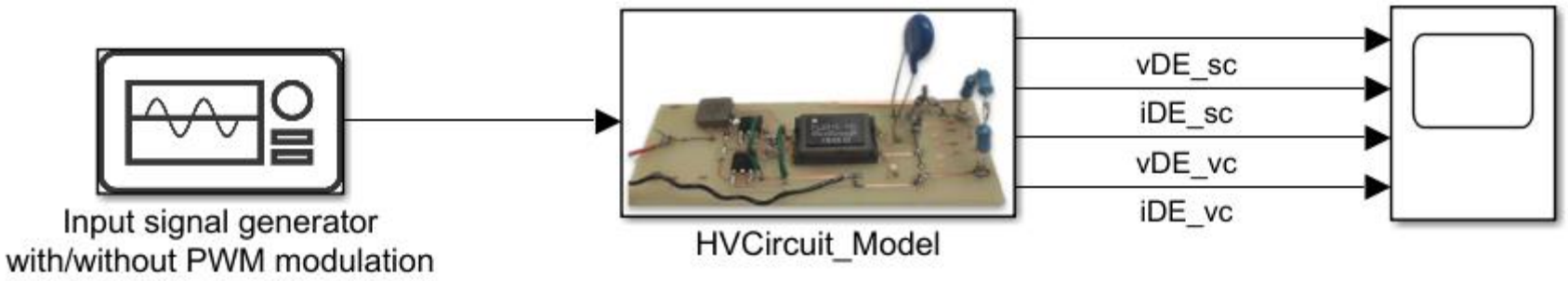
$$i(t) = C\frac{dV}{dt} + V\frac{dC}{dt}$$

Change of state variables

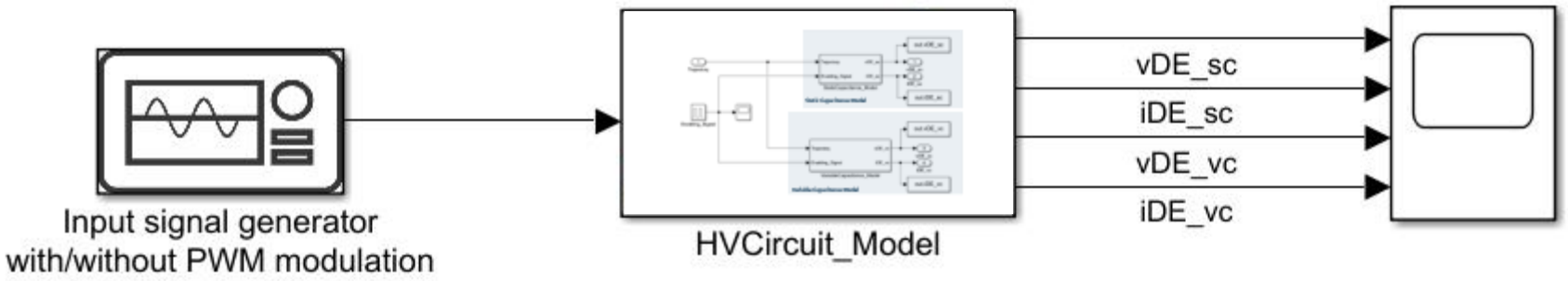
$$i(t) = \frac{d}{dt}q_C(t)$$

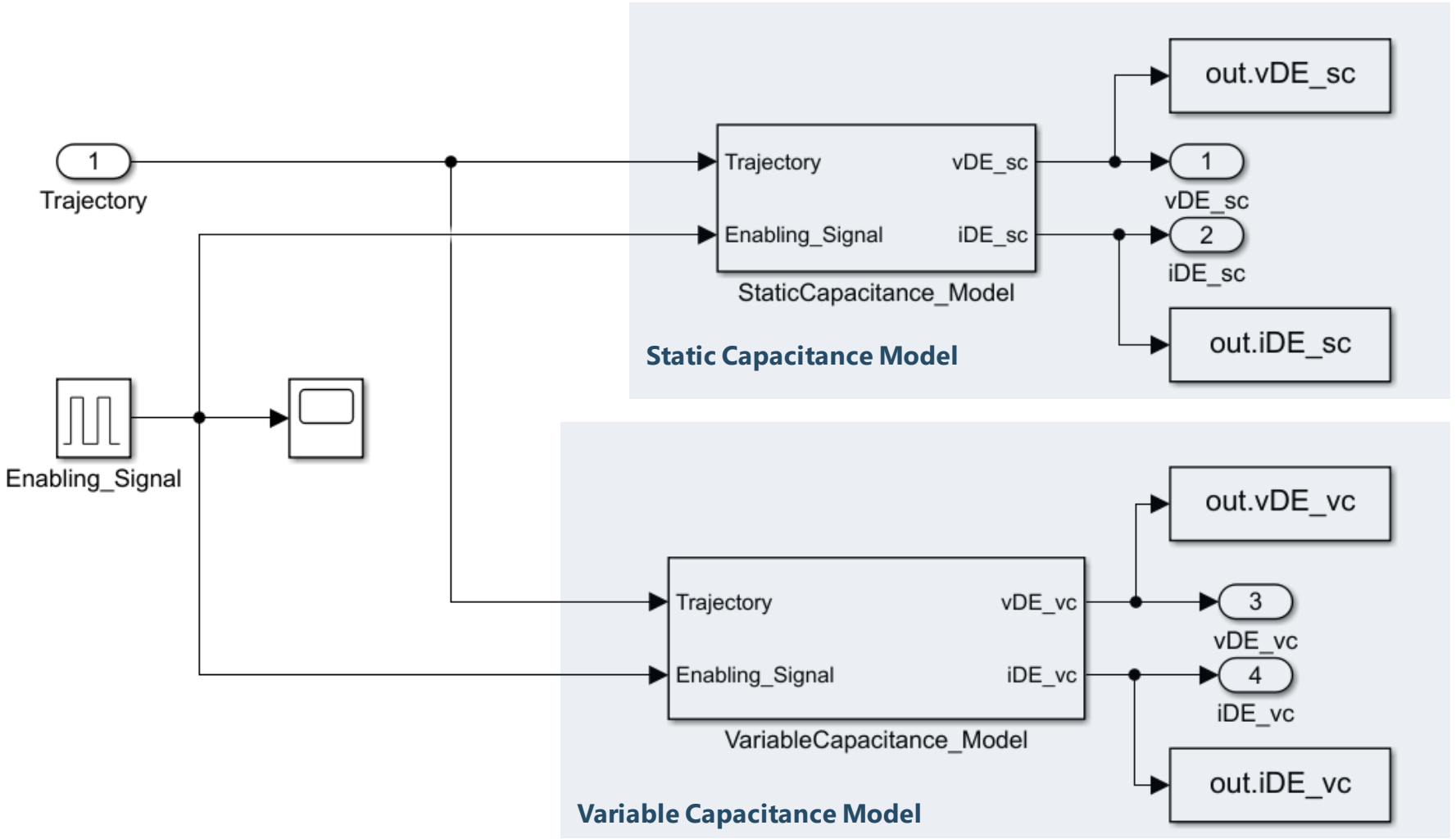
State variables: $\boldsymbol{x}(t) = \boldsymbol{q_C}(t)$

Mathematical model



Mathematical model




1
Trajectory
Enabling_Signal
Trajectory
vDE_sc
Enabling_Signal
iDE_sc
StaticCapacitance_Model
out.vDE_sc
1
vDE_sc
2
iDE_sc
out.iDE_sc
Static Capacitance Model
Trajectory
vDE_vc
Enabling_Signal
iDE_vc
VariableCapacitance_Model
out.vDE_vc
3
vDE_vc
4
iDE_vc
out.iDE_vc
Variable Capacitance Model

Outline

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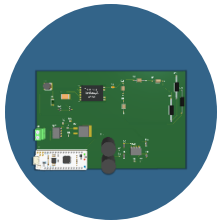
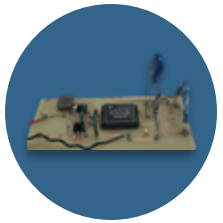
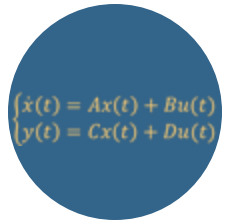


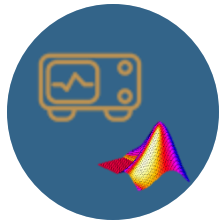
Motivation of the Ph.D work



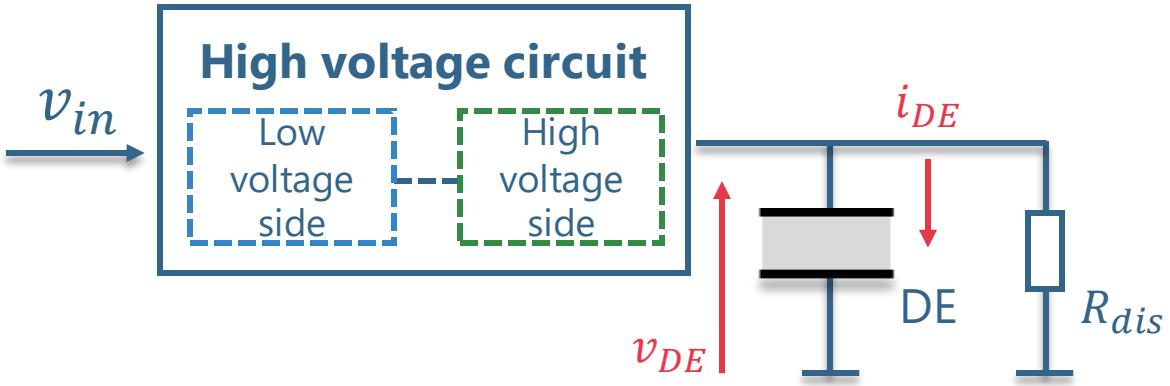
High Voltage (HV) circuit study



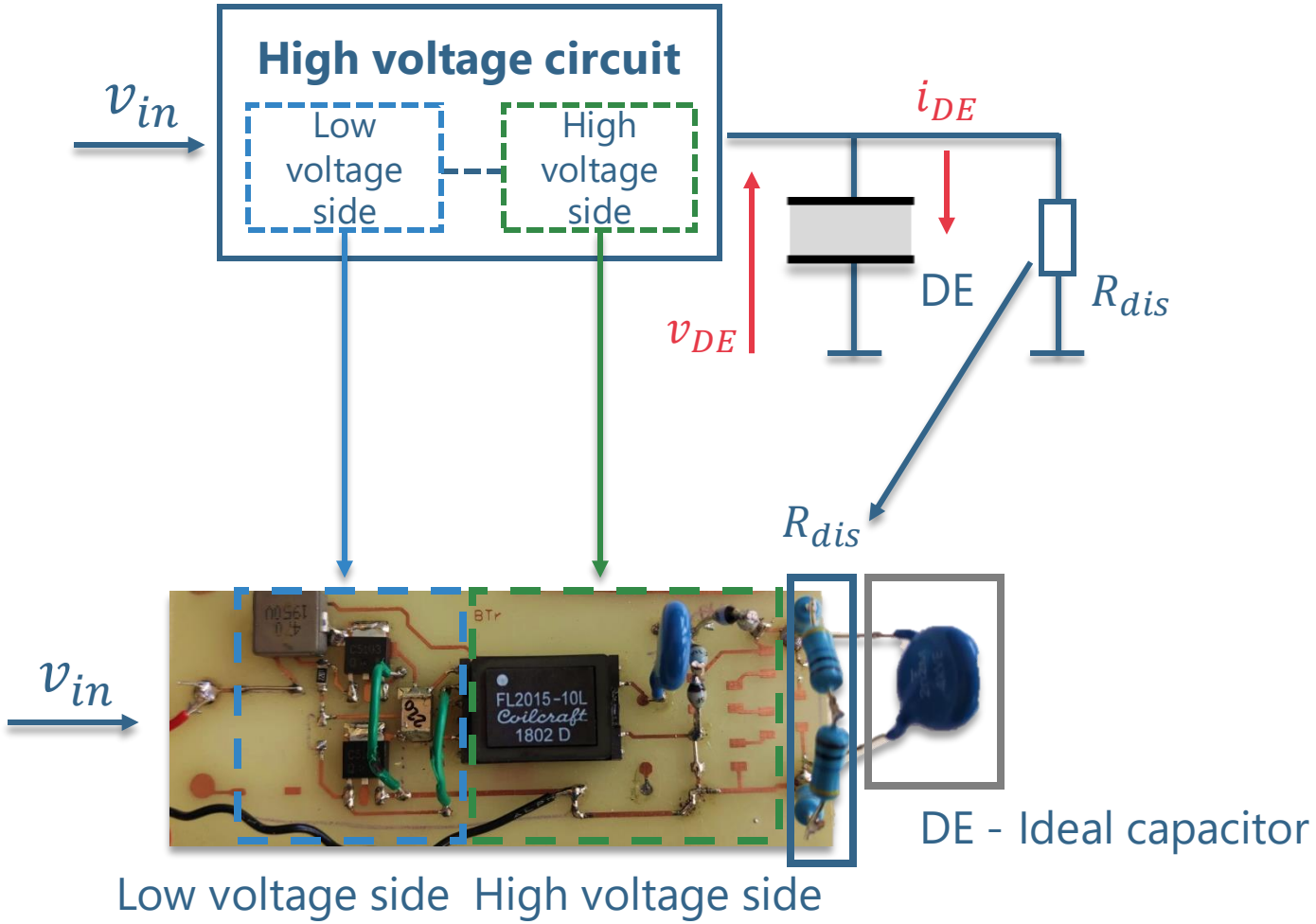
Mathematical model



Experimental validation

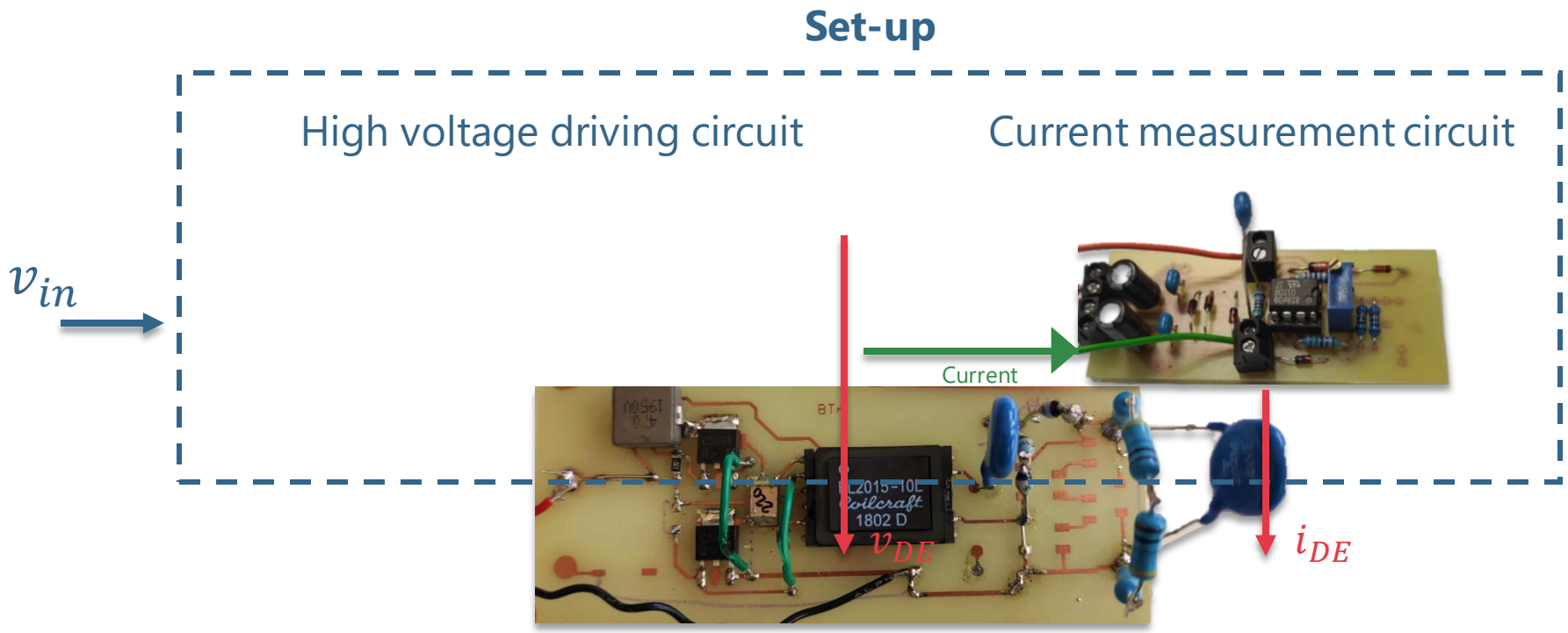

v_{in}
High voltage circuit
Low voltage side
High voltage side
i_{DE}
v_{DE}
DE
R_{dis}

Experimental validation



Experimental validation

EXPERIMENTS: Ideal capacitor as load

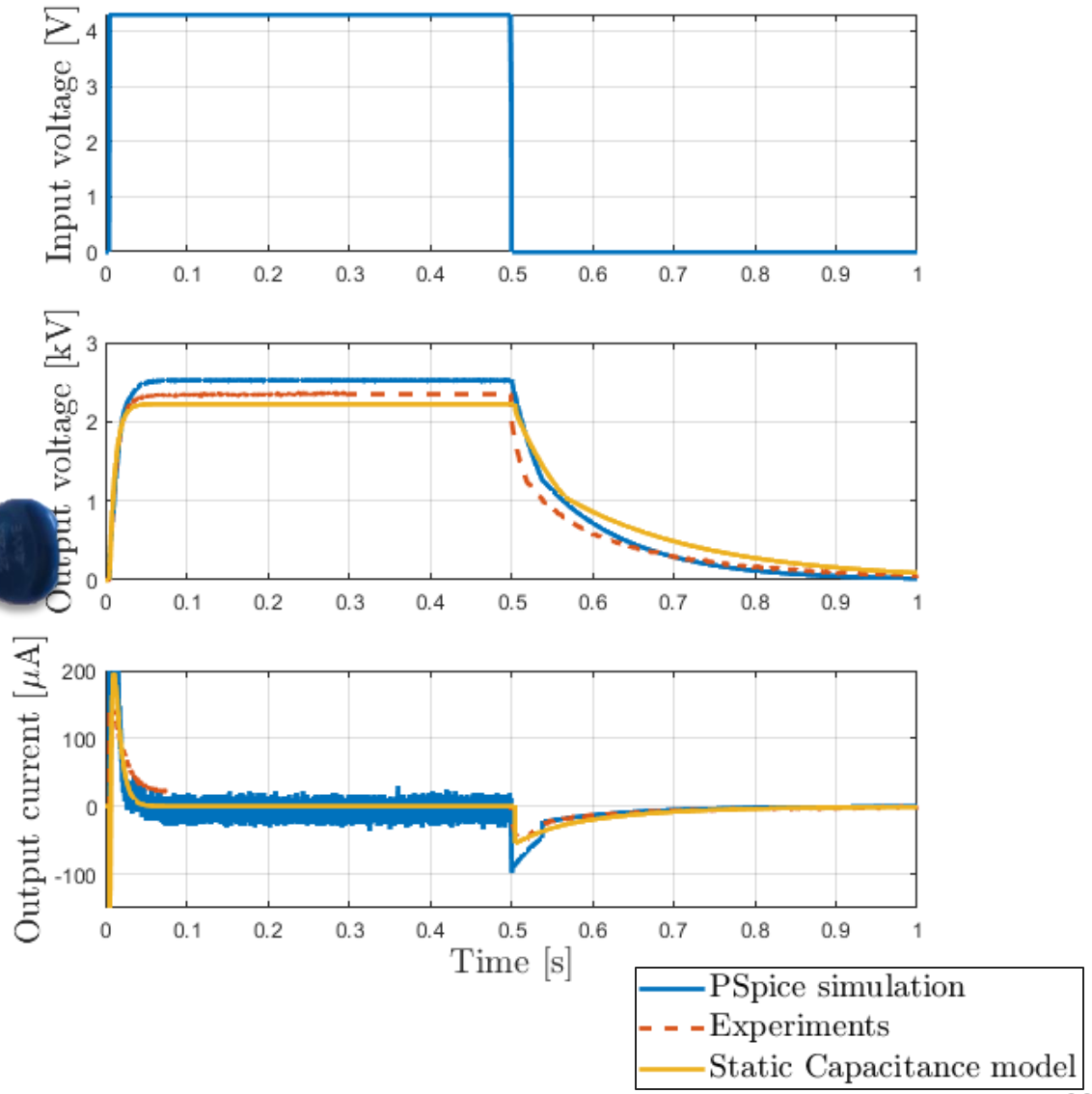


Experimental validation

EXPERIMENTS: Ideal capacitor as load

Case of study

Input: Step – $4.3V$
Load: $2.2nF$
$R_{dis} = 40Meg\Omega$

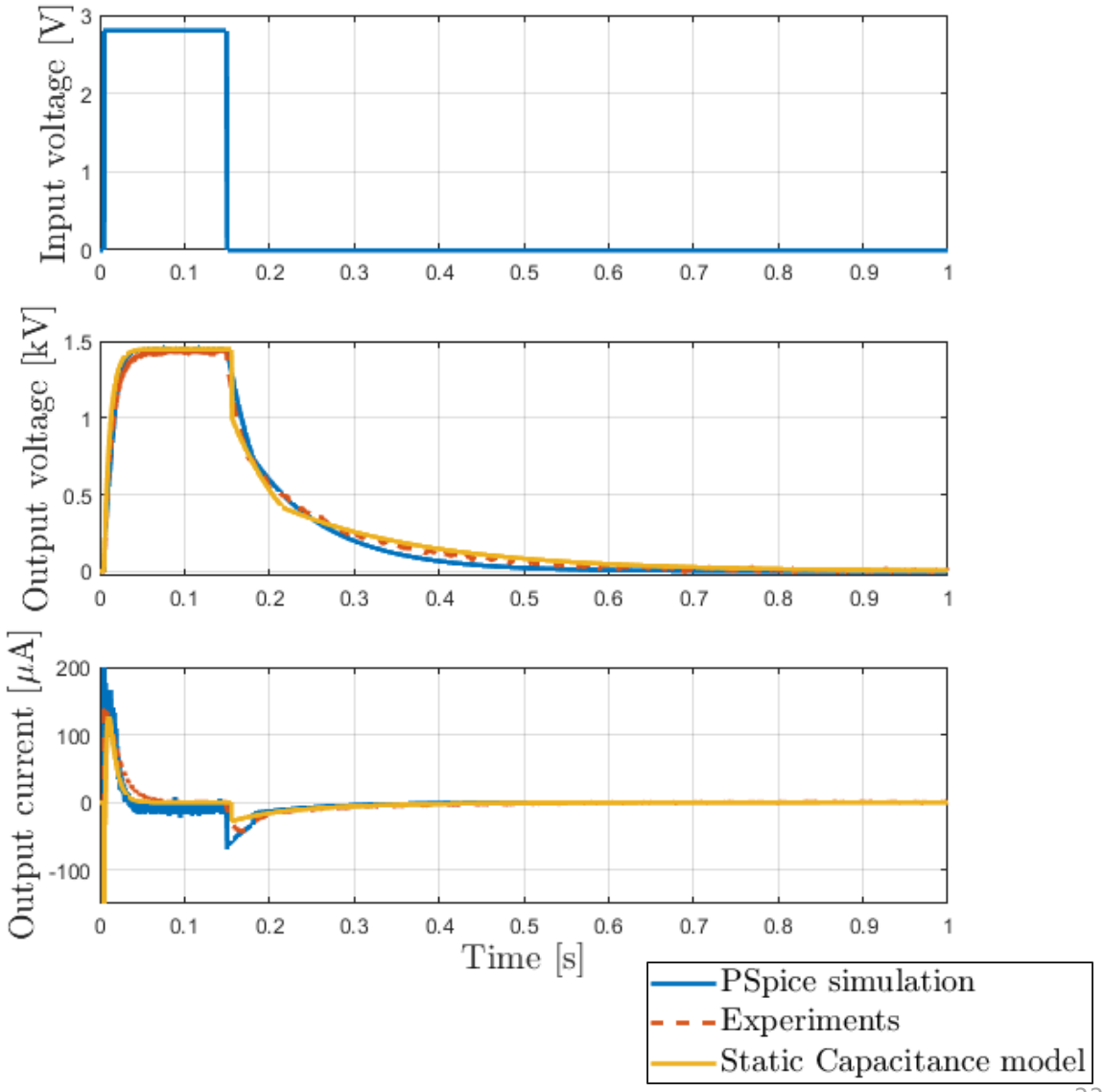


Experimental validation

EXPERIMENTS: Ideal capacitor as load

Case of study

Input: Step – ~~4~~ $8V$ ← Input change
Load: $2.2nF$
$R_{dis} = 40Meg\Omega$

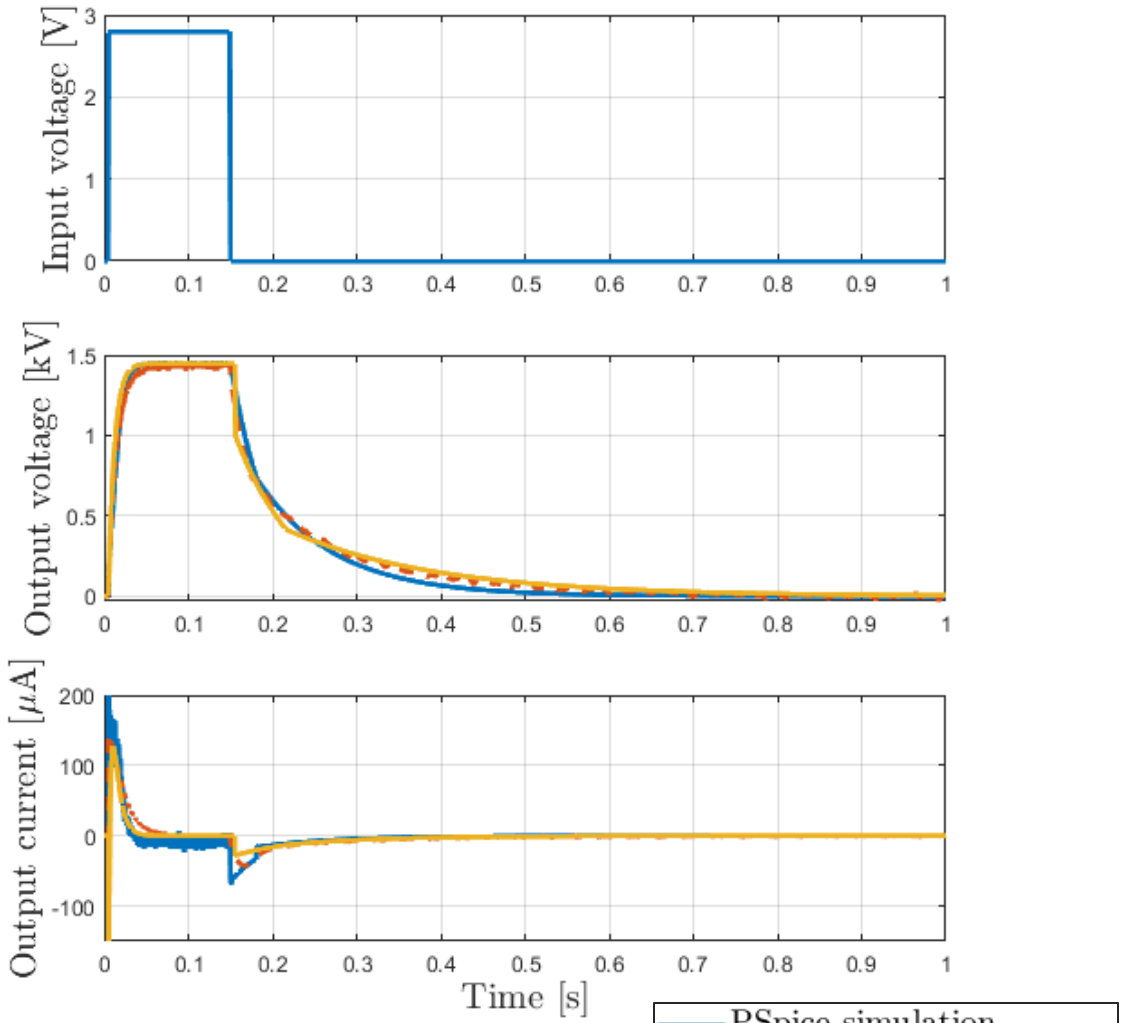


Experimental validation

EXPERIMENTS: Ideal capacitor as load

Case of study

Input: Step – $2.8V$
Load: $2.2nF$
$R_{dis} = 30Meg\Omega$ ← R_{dis} change

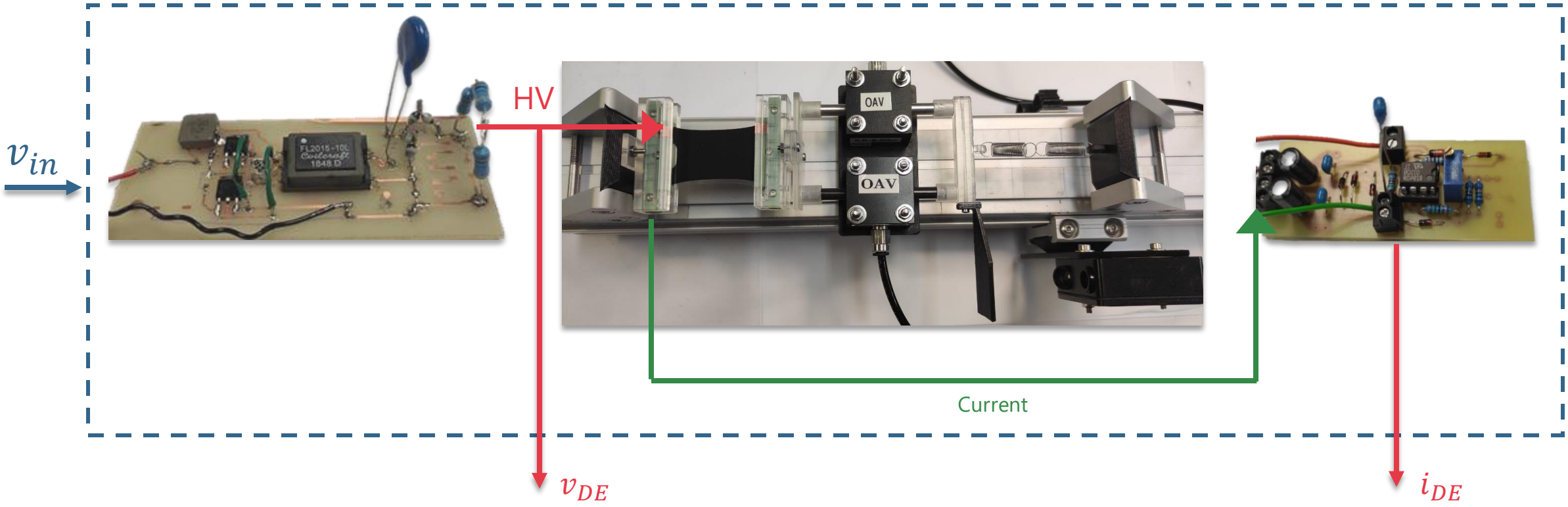


Perri, Carmen, et al. "Modelling and Validation of a High Voltage Driving Circuit for Dielectric Elastomer Actuators." *2021 IEEE 30th International Symposium on Industrial Electronics (ISIE)*. IEEE, 2021.

Experimental validation

EXPERIMENTS: Real DE

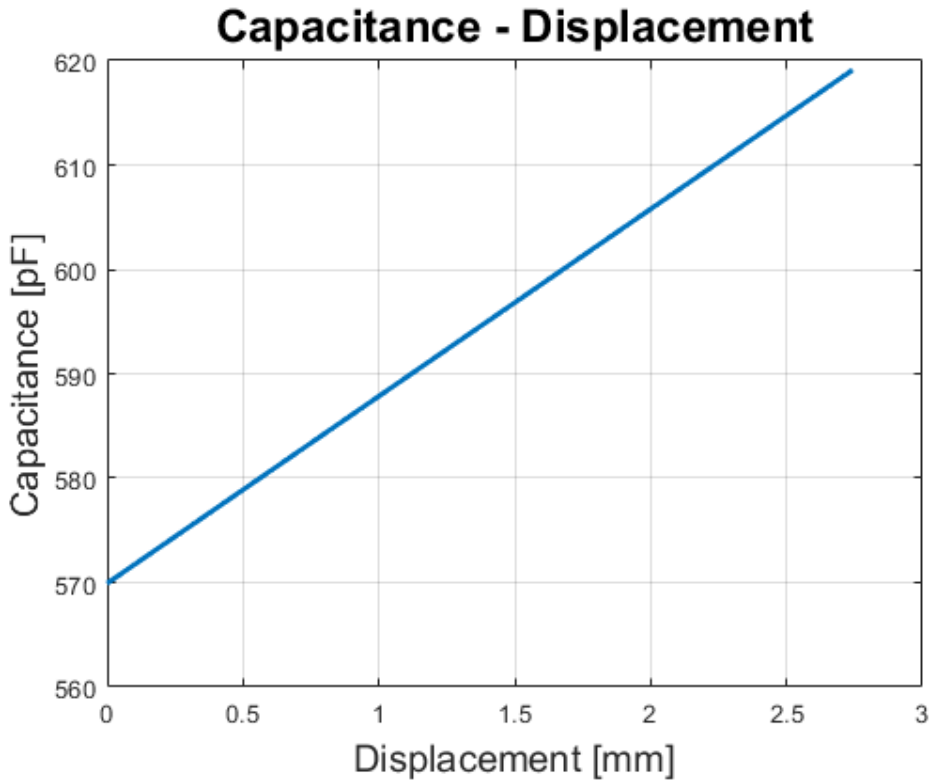
Set-up



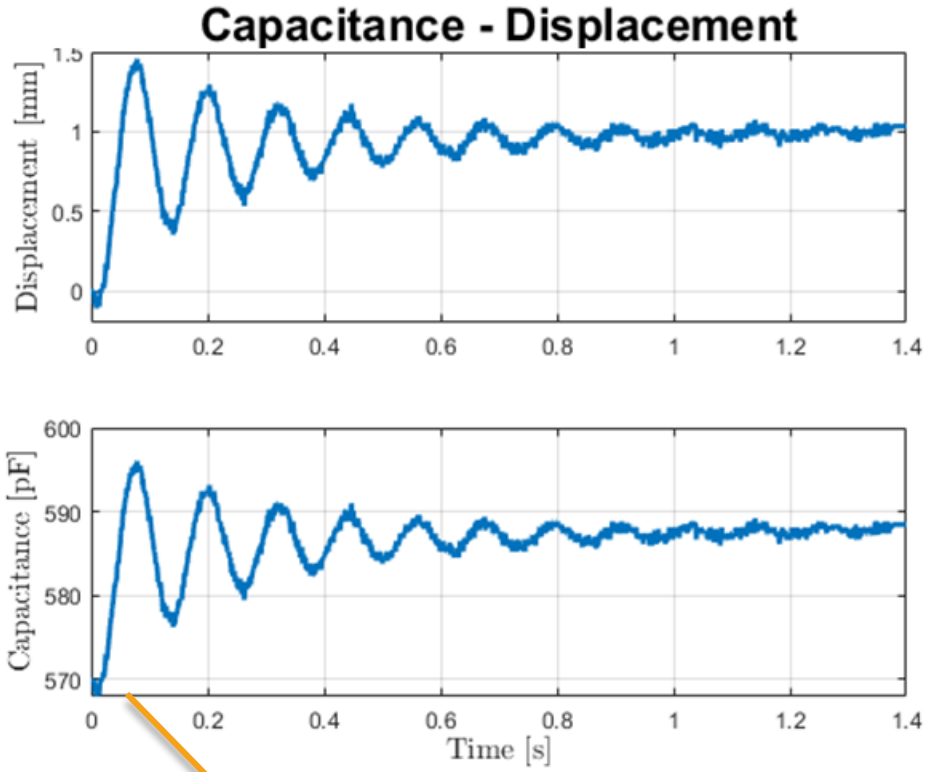
Experimental validation

EXPERIMENTS: Real DE

DE characterization



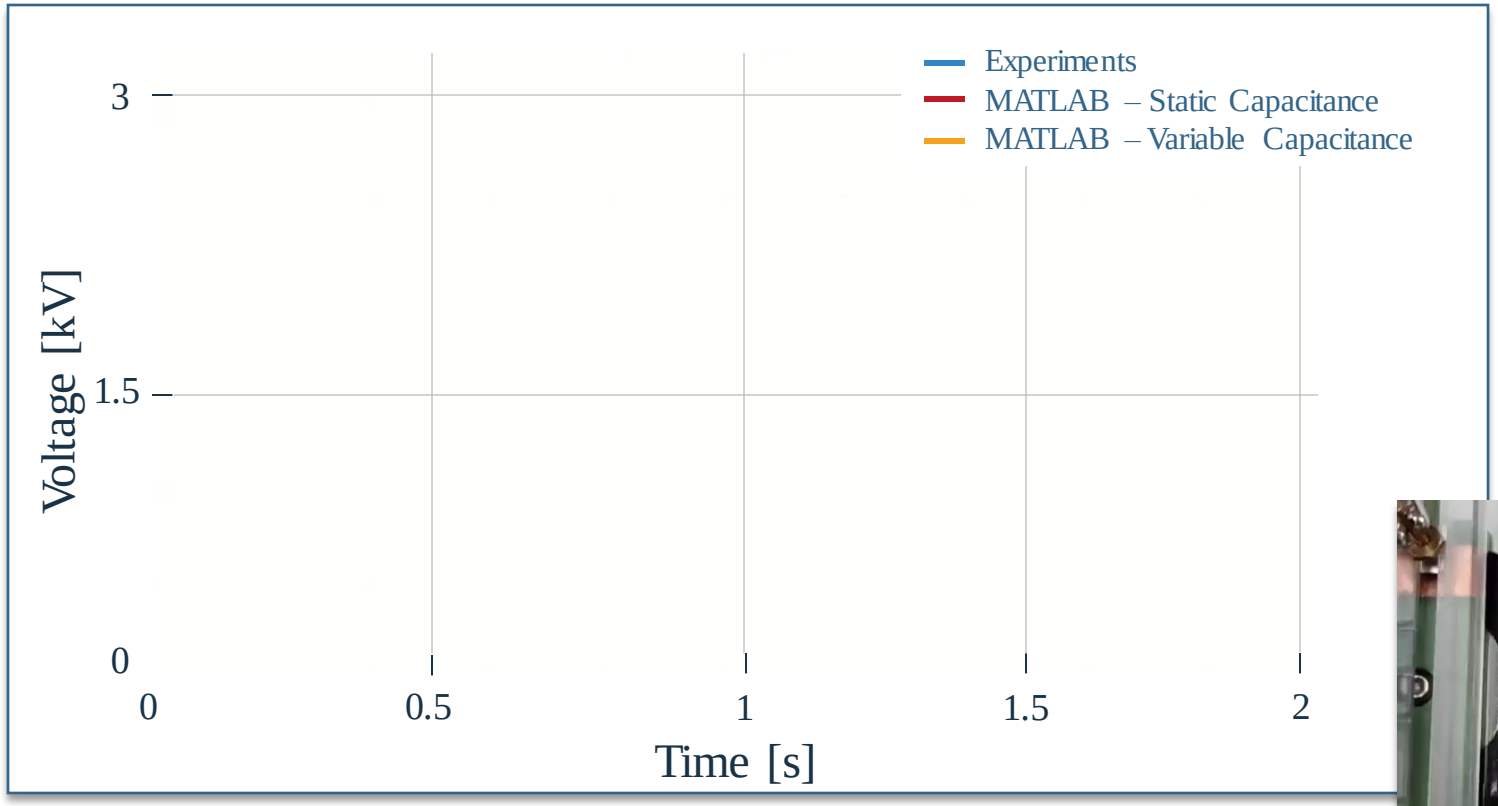
$$C(x) = p_1 x + p_2$$



Variable capacitance

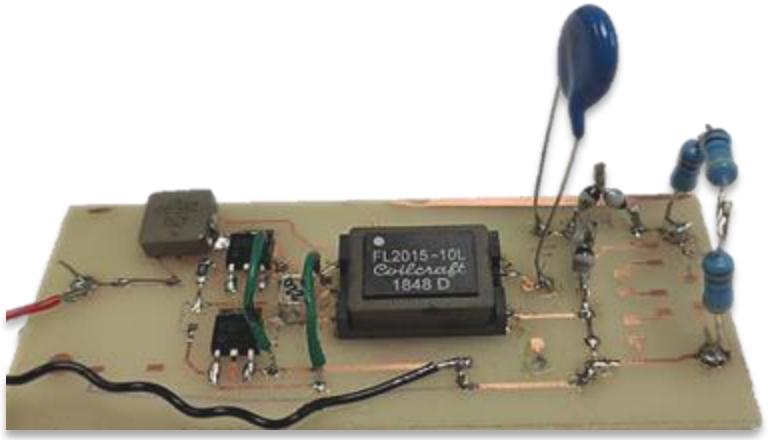
Experimental validation

EXPERIMENTS: Real DE



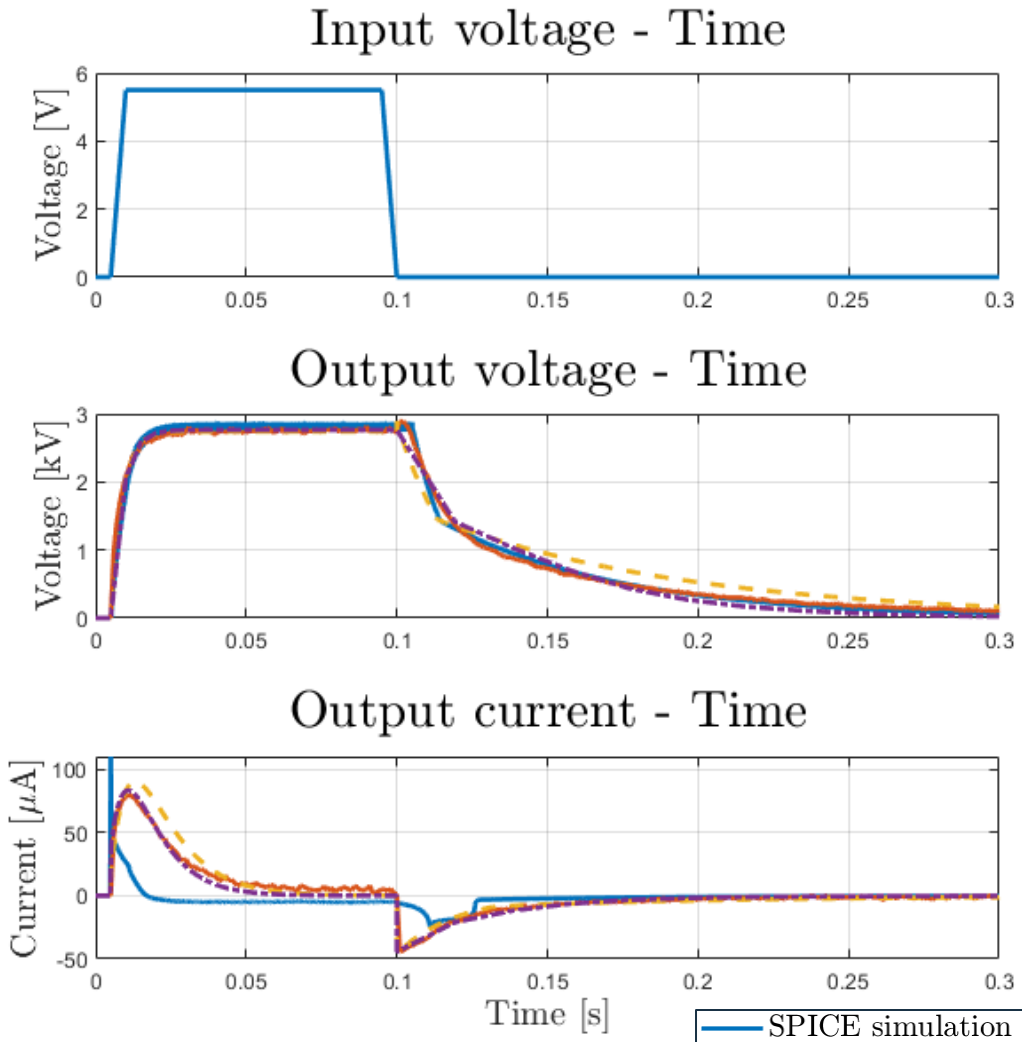
Experimental validation

EXPERIMENTS: Real DE



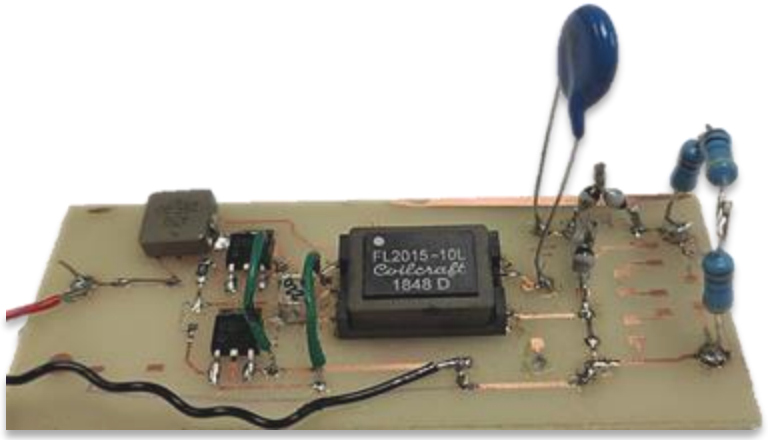
Case of study

Input: Step – 5.5V
Load: DE
$R_{dis} = 30Meg\Omega$



Experimental validation

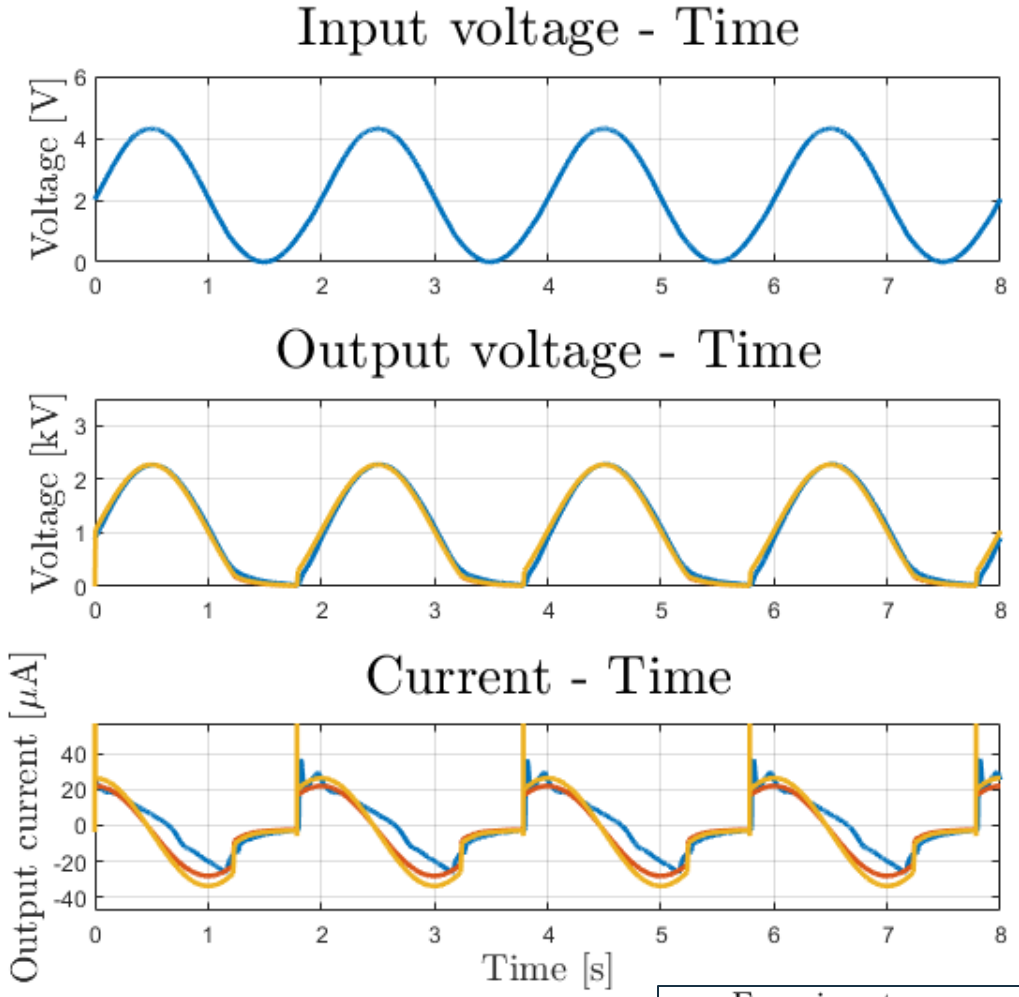
EXPERIMENTS: Real DE



Case of study

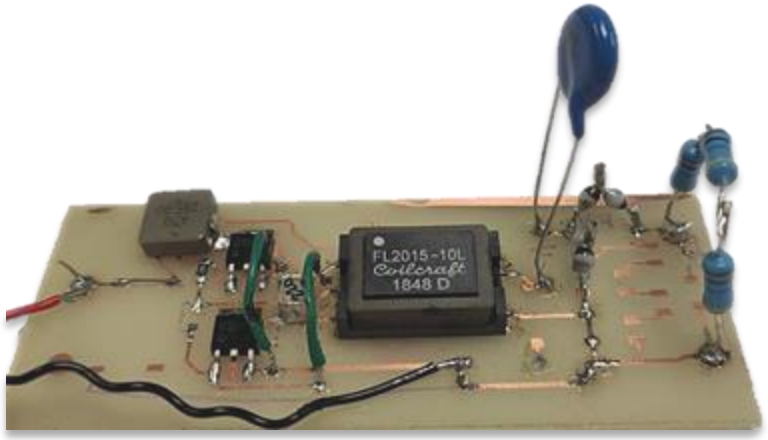
Input signal change

Input: Step – $5V_{pp}, f = 0.5Hz$
Load: DE
$R_{dis} = 30Meg\Omega$



Experimental validation

EXPERIMENTS: Real DE



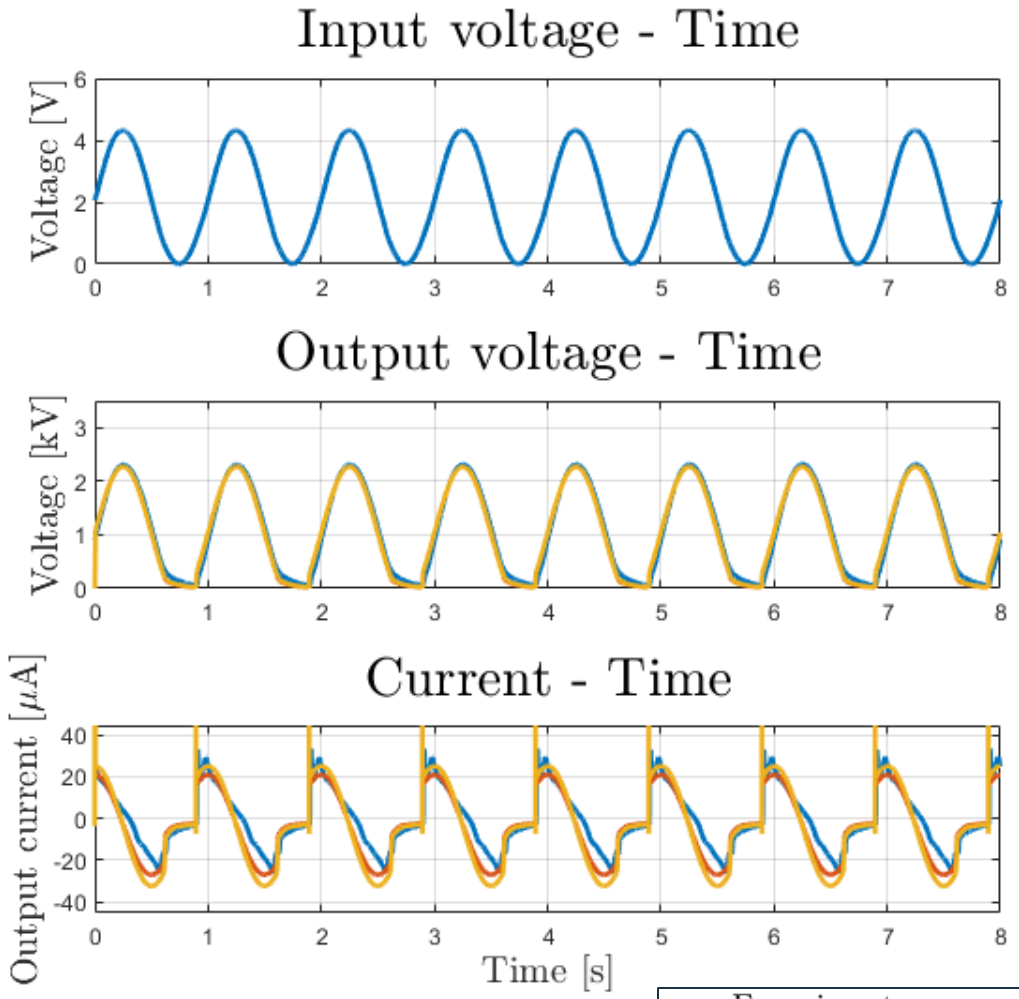
Case of study

Frequency change

Input: Sine – $4V_{pp}, f = 0.5Hz$

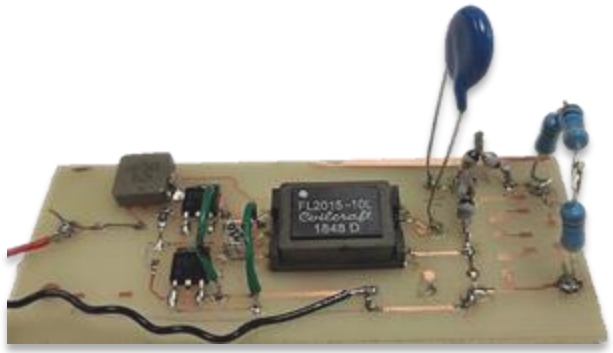
Load: DE

$R_{dis} = 30Meg\Omega$



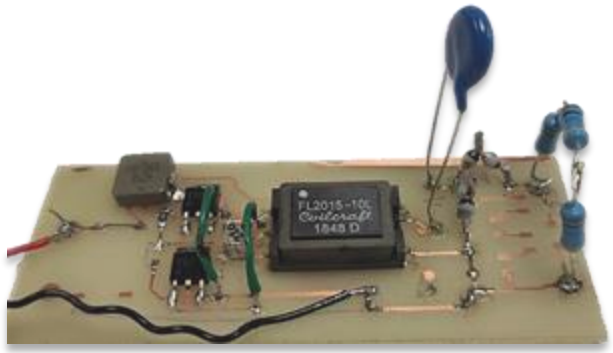
Conclusions

- ✓ High voltage circuit analysis carried out in OrCAD - PSpice → DC-DC converter in high voltage
- ✓ Mathematical model developed → Average model
- ✓ Implementation in MATLAB & Simulink
- ✓ Experimental validation for different input signals



Next steps

- Circuit optimization
  → Active discharging phase: Fast discharging time, controllable discharging behaviour
- Control algorithm develop
- Implementation on $\mu - Controller$ (Nucleo board stm32)
- Experimental validation



INTELLIGENT MATERIAL SYSTEMS LAB

ZeMA

UNIVERSITÄT DES SAARLANDES

What questions can I still answer?

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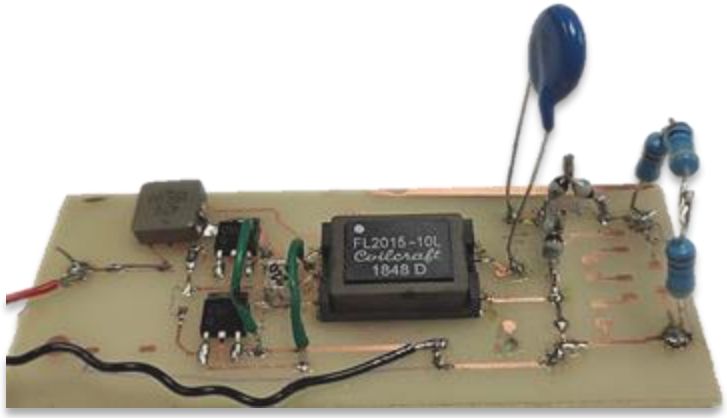

Modelling and Control of an High Voltage Driving Circuit for DEAs

Department of Electrical and Information Engineering (DEI)

Polytechnic of Bari, Bari, Italy

Tutors
David Naso
Gianluca Rizzello

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