ENERGY CONVERSION SYSTEM FOR AN ELECTRIC CITY BUS/MICROBUS, WITH SUPERCAPACITOR ENERGY STORAGE AND SUPERHIGH POWER DENSITY DRIVE (ECON-BUS)

PN-III-P2-2.1-PED-2019-5230

INTELLIGENT CONTROL OF ENERGY CONVERSION AND STORAGE

Universitatea Politehnica Timișoara

The project consortium:

Romanian Academy,
Timisoara Branch

University POLITEHNICA
Timisoara

INTELLIGENT CONTROL OF ENERGY CONVERSION AND STORAGE

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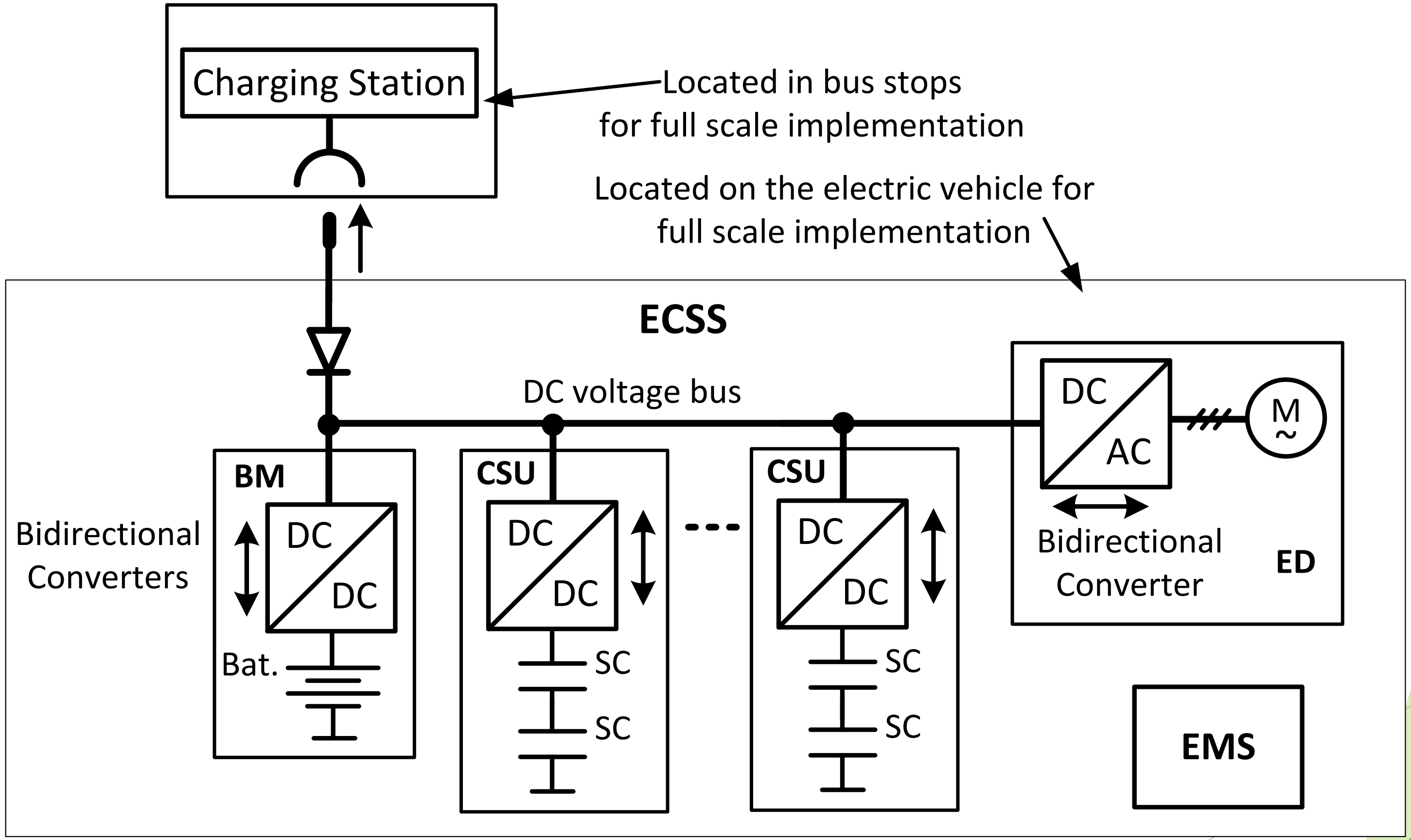
The project objectives were:

-the investigation/preliminary design of a full scale drive (100kW) with a super-high torque/power density permanent magnet synchronous motor, for an *urban electric transportation energy conversion system*;
-the development of a small scale (5kW) laboratory demonstration model, including the power electronics converters, and
- using supercapacitors (SC) as main energy storage devices.

The block diagram of the conversion and storage system:



The next presentations content:

- The super-high torque/power density permanent magnet synchronous motor, analysis, design, experimental model;
- Power converters analysis, design and small scale experimental results;
- Drive analysis, simulations and small scale experiments.

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THE SUPER-HIGH TORQUE/POWER DENSITY PERMANENT MAGNET SYNCHRONOUS MOTOR, ANALYSIS, DESIGN, EXPERIMENTAL MODEL

Speaker: Lucian TUTELEA

Overview

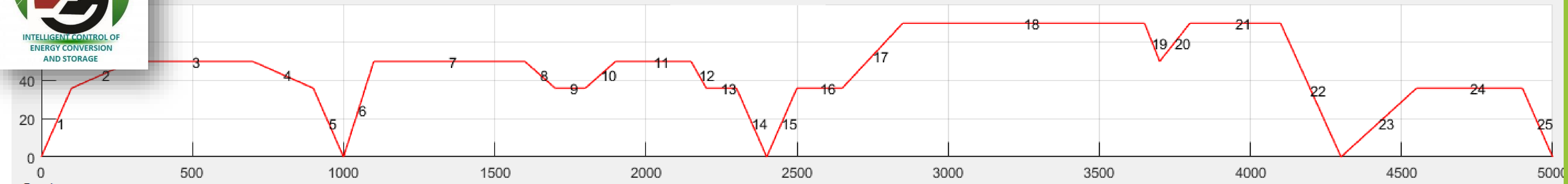
- Estimated total required power
- 100kW IPMSM preliminary design
- 5kW IPMSM preliminary design
- 5kW IPMSM stator and rotor laminations

Estimated total required power/energy

- Preliminary considerations:
  - Total weight: 7t
  - Frontal area $4m^2$
  - Aerodynamic friction coefficient: 0.9
  - Rolling friction coefficient: 0.01
  - Maximum travel distance: 5000m
  - Maximum slope length: 200m
  - Maximum ramp at constant base speed: 0.1%
  - Maximum frontal wind: 17.1m/s
  - Auxiliary system power consumption: 5%Pn
  - Supercapacitor efficiency:0.95
  - Power converter efficiency:0.95
  - Electrical machine efficiency:0.9
  - Mechanical transmission efficiency:0.95

Estimated total required power/energy

Ebus data interface



Panel

	Sct. 1	Sct. 2	Sct. 3	Sct. 4	Sct. 5	Sct. 6	Sct. 7	Sct. 8	Sct. 9	Sct.10	Sct.11	Sct.12	Sct.13	Sct.14	Sct.15	Sct.16	Sct.17	Sct.18	Sct.19	Sct.20	Sct.21	Sct.22	Sct.23	Sct.24	Sct.25
Distance [m]:	100	200	400	200	100	100	500	100	100	100	250	50	100	100	100	150	200	800	50	100	300	200	250	350	100
Speed [km/h]:	36	50	50	36	0	50	50	36	36	50	50	36	36	0	36	36	70	70	50	70	70	0	36	36	0

Initial speed profile

Plot speed profile

Total resulting distance: 5000 [m]

Remaining distance: 0 [m]

Panel

Input data

Total weight:	7000	kg
Frontal area:	4	m^2
Coeff. of aero. friction	0.8	-
Rolling friction coeff.:	0.01	-
Maximum distance:	5000	m
Max. slope length:	200	m
Max. ramp at const. base speed:	0.1	%
Max. frontal wind:	17.1	m/s
Mechanical transmision eff:	0.95	-
Electrical machine's eff:	0.9	-
Power converter eff:	0.95	-
Supercapacitor eff:	0.95	-
Gravitational acceleration:	9.80665	m/(s^2)
Auxiliary system power consumption:	0.05	of Pn

Panel

Output data

Rolling force:	686.466	N
Ramp climbing force:	6830.59	N
Aerodynamic force at smallets profile speed:	196	N
Aerodynamic force at base speed with wind:	1439.44	N
Total resisting force:	8956.5	N
Requested power for total resisting force:	94.0432	kW
Requested power for total resisting force with transmision efficiency:	98.9929	kW
Energy required for rolling friction:	0.953424	kWh
Energy required for ramp climbing:	0.379477	kWh
Energy required for aerodynamic force without wind for speed profile:	0.505222	kWh
Energy required for aerodynamic force with wind for speed profile:	2.49213	kWh
Kinetic energy based on speed profile:	0.819787	kWh
Total efficiency:	0.771637	-
Total energy losses due to all acc./dec. cycles:	0.331666	kWh
Total energy required in supercapacitors for:	4.1567	kWh
Average power:	38.5742	kW

Set initial values

Calculate

Exit

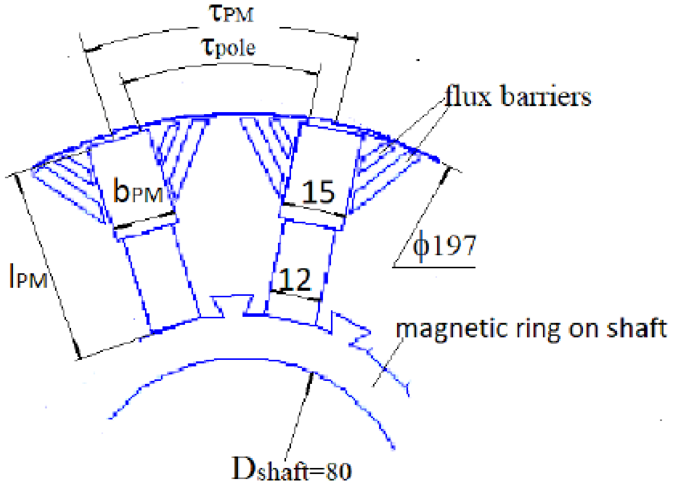
100 kW IPMSM preliminary design

- 100 kW IPMSM designed to meet the speed and torque conditions, considering:
  - 400Nm at 2400rpm, Id=0
  - 200Nm at 4800 rpm, Id<0
  - Outer stator diameter: OSD≤300mm
  - Inner stator diameter: ISD=200mm
  - Stack length: lstack<200mm
  - Air-gap g=1.5mm
  - Efficiency>0.93, cosφ>0.7

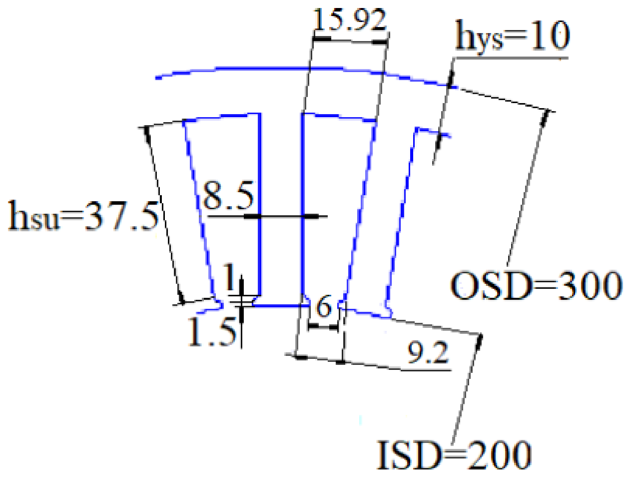
For 600V dc inverter voltage and a potential 7 tone urban electric minibus

100 kW IPMSM preliminary design

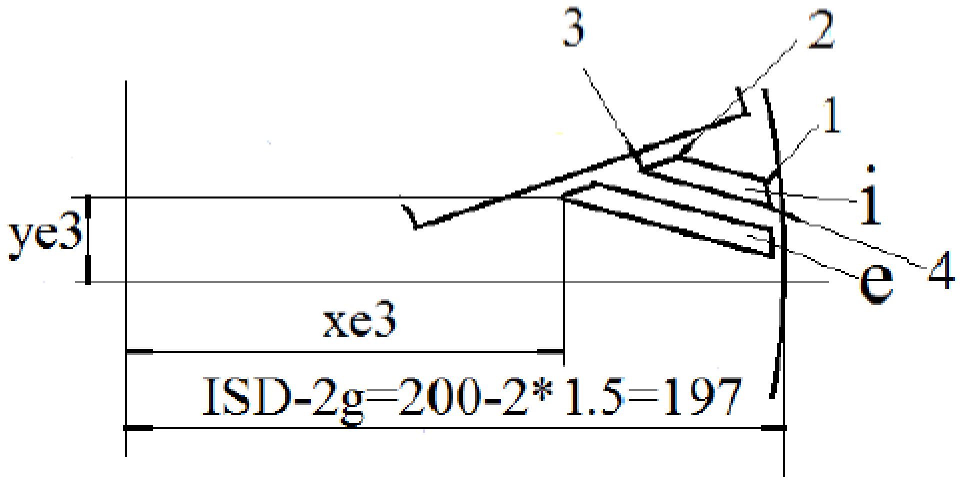
- Rotor cross section



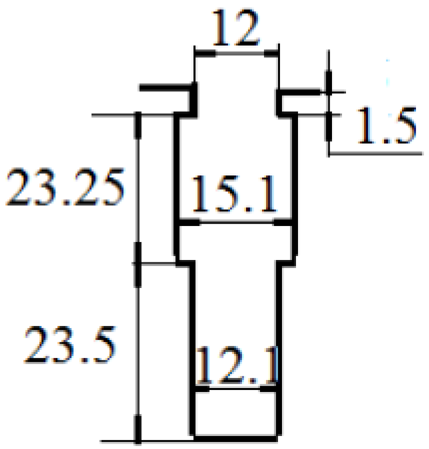
- Stator slot



- Flux barrier



- Rotor slot for PM



100 kW IPMSM preliminary design

General data

- The cooper losses at 400Nm: 1211.05W
- Core losses at rated voltage: 1446.09W
- Considering mechanical losses 2% of rated power, the efficiency:

$$\eta_{electric} = \frac{P_{elm}}{P_{elm} + p_{ironsb} + p_{cob} + p_{mec}} = $$

$$= \frac{100}{100.531 + 1.446 + 1.726 + 2} = 0.946$$

- With the assumption of **Kfill=0.4**, the current density for the maximum torque, is:

$$j_{cob} = \frac{n_s I_{1b}}{K_{fill} A_{slotu}} = \frac{1329.77}{0.45 \times 471} = 6.27 A/mm^2$$

- The total length of the magnets available l_{PM} is 56.5mm;
- The magnetic rotor pole span at lowest diameter:

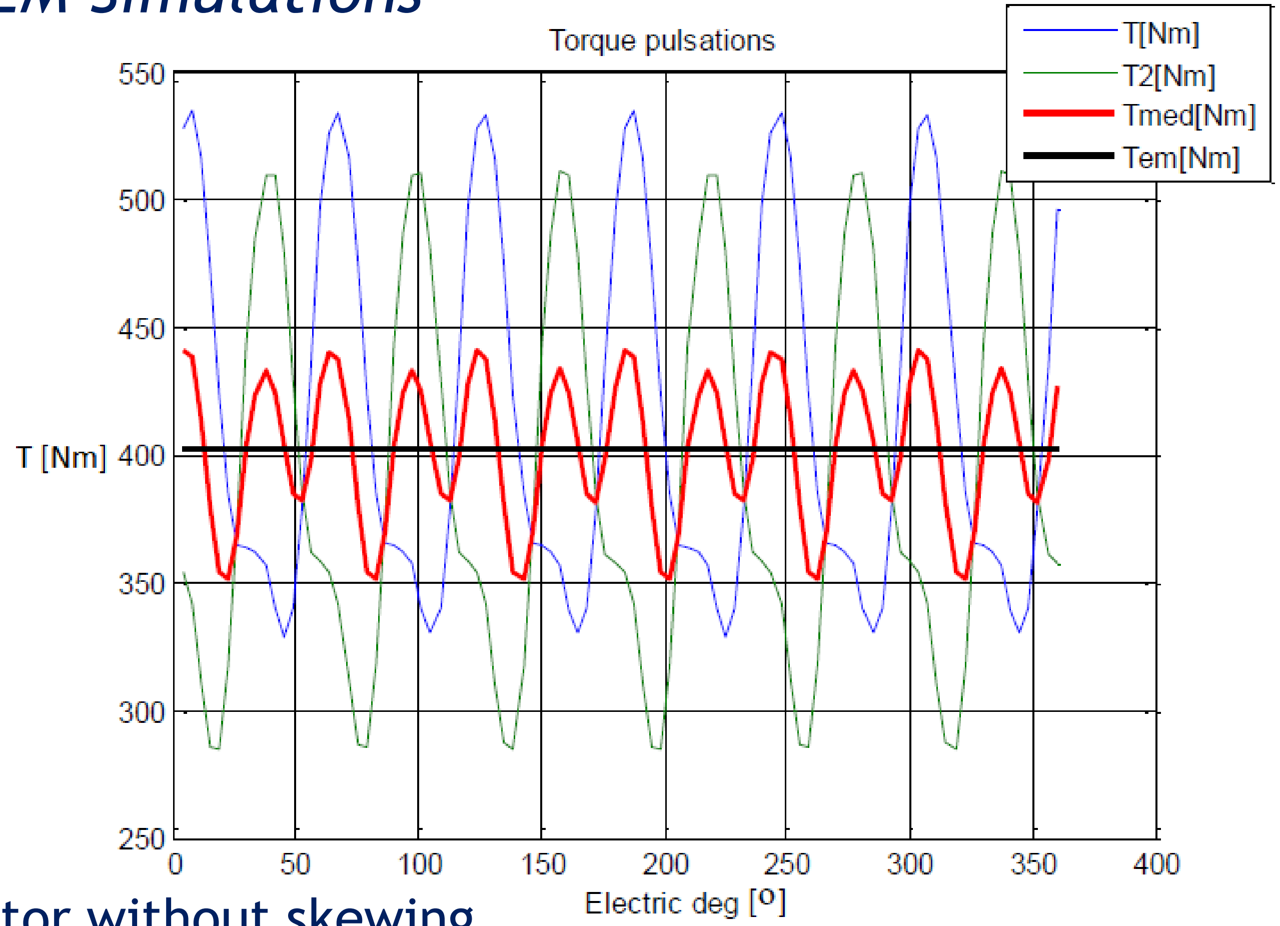
$$\tau_{min} = \frac{\pi D_{shaft}}{2p} - h_{PM} = \frac{\pi \times 80}{2 \times 6} - 12 \approx 9mm$$

- The slot mmf for maximum torque is:

$$n_{slot} I_{1b} = \frac{w_1 I_{1b}}{6} = \frac{7978}{6} = 1329.77 Aturns / slot$$

100 kW IPMSM preliminary design

2D FEM Simulations



- T, T2 -> rotor without skewing
- Tmed -> 5° radially segmented rotor (two segments)
- Tem -> mean value

5 kW IPMSM preliminary design

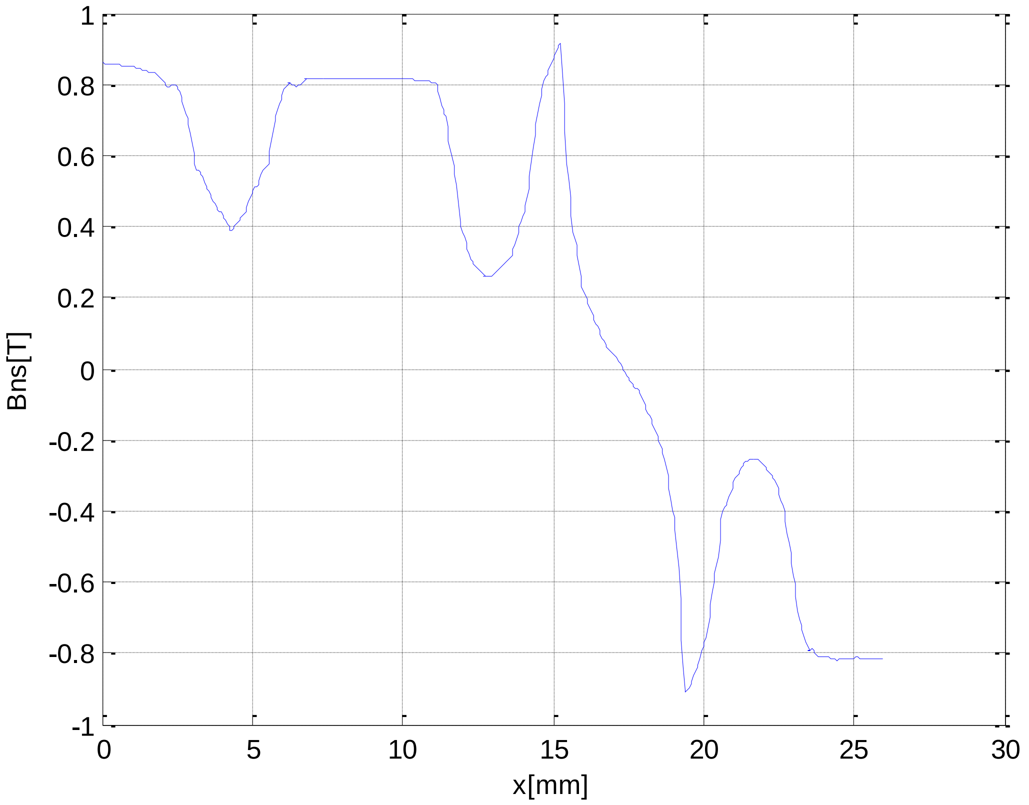
- 5 kW IPMSM designed to meet the speed and torque conditions considering:
  - 20Nm at 2400rpm, In=9.6A
  - 8-10Nm at 4800 rpm, Id<0
  - Outer stator diameter: OSD=160mm
  - Inner stator diameter: ISD=100mm
  - Stack length: lstack=75mm
  - Air-gap g=0.5mm

For 600V dc inverter voltage

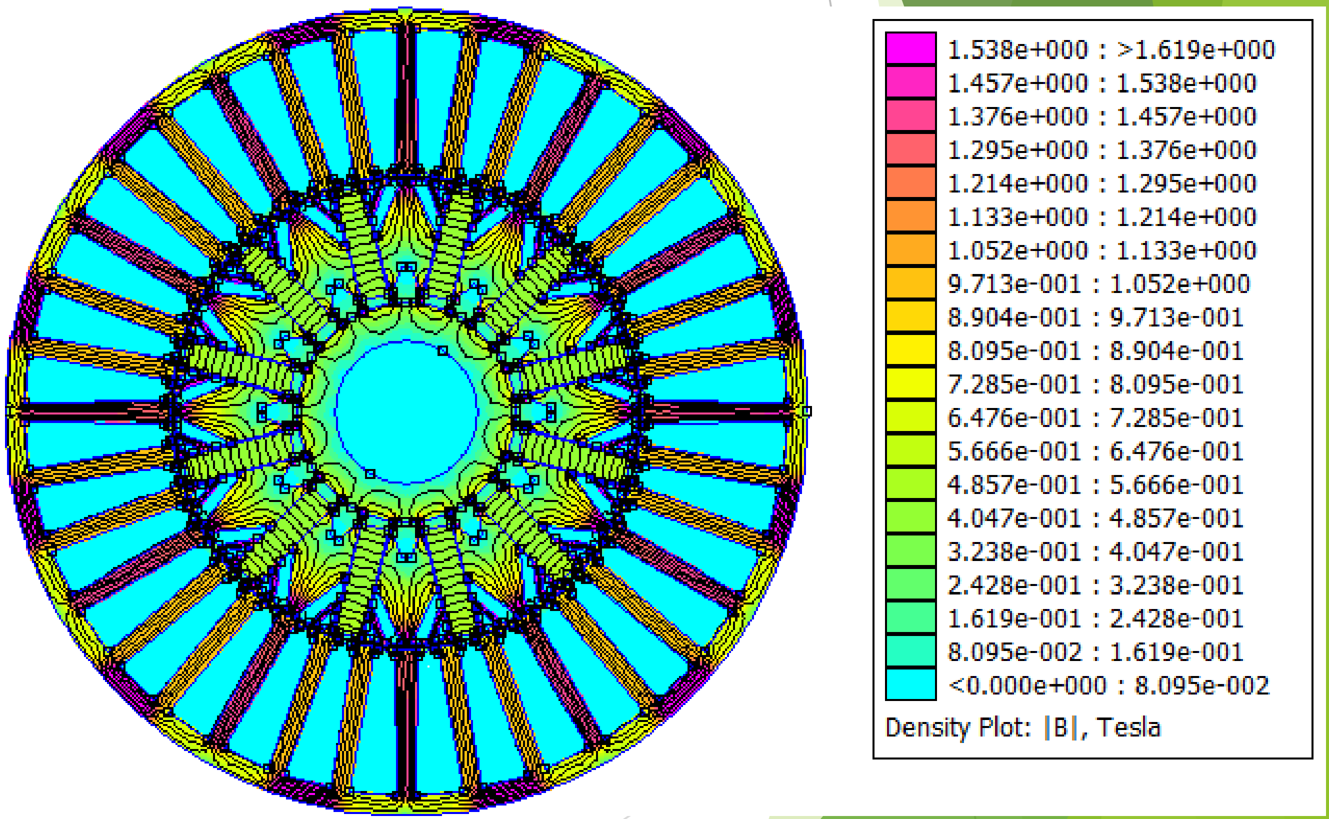
5 kW IPMSM preliminary design

2D FEM Simulations – no excitation current Is=0A

- Air gap magnetic flux density distribution



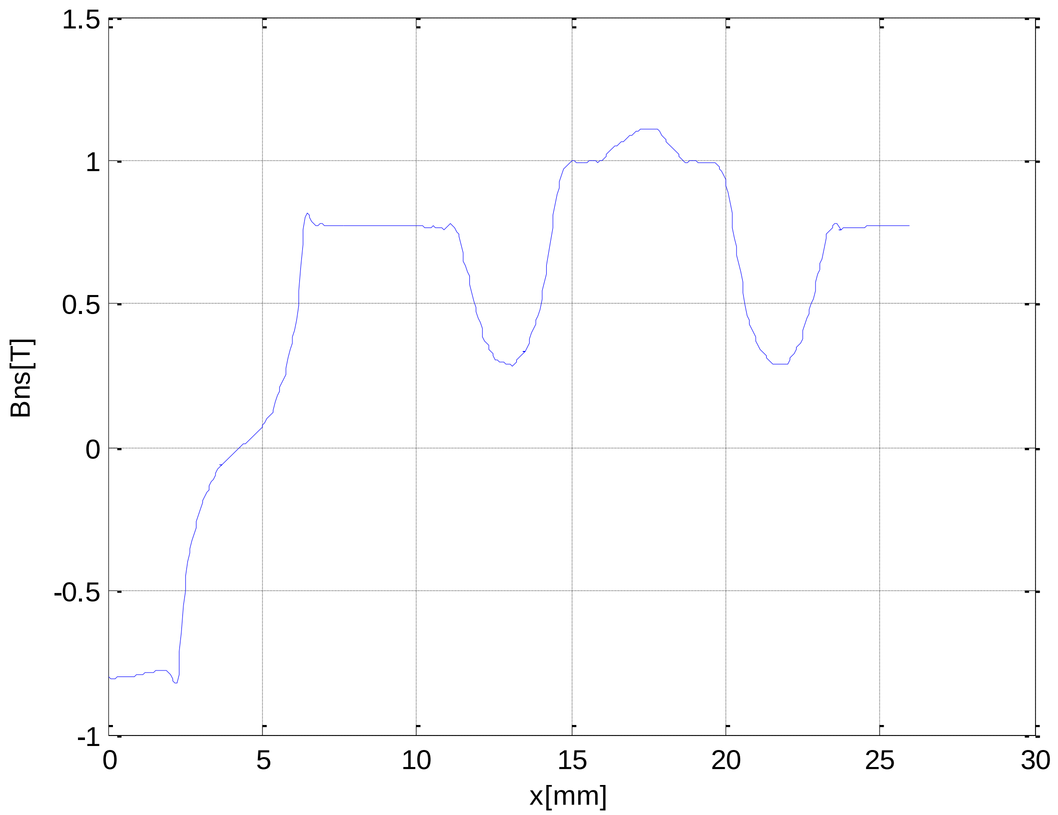
- Magnetic flux density distribution



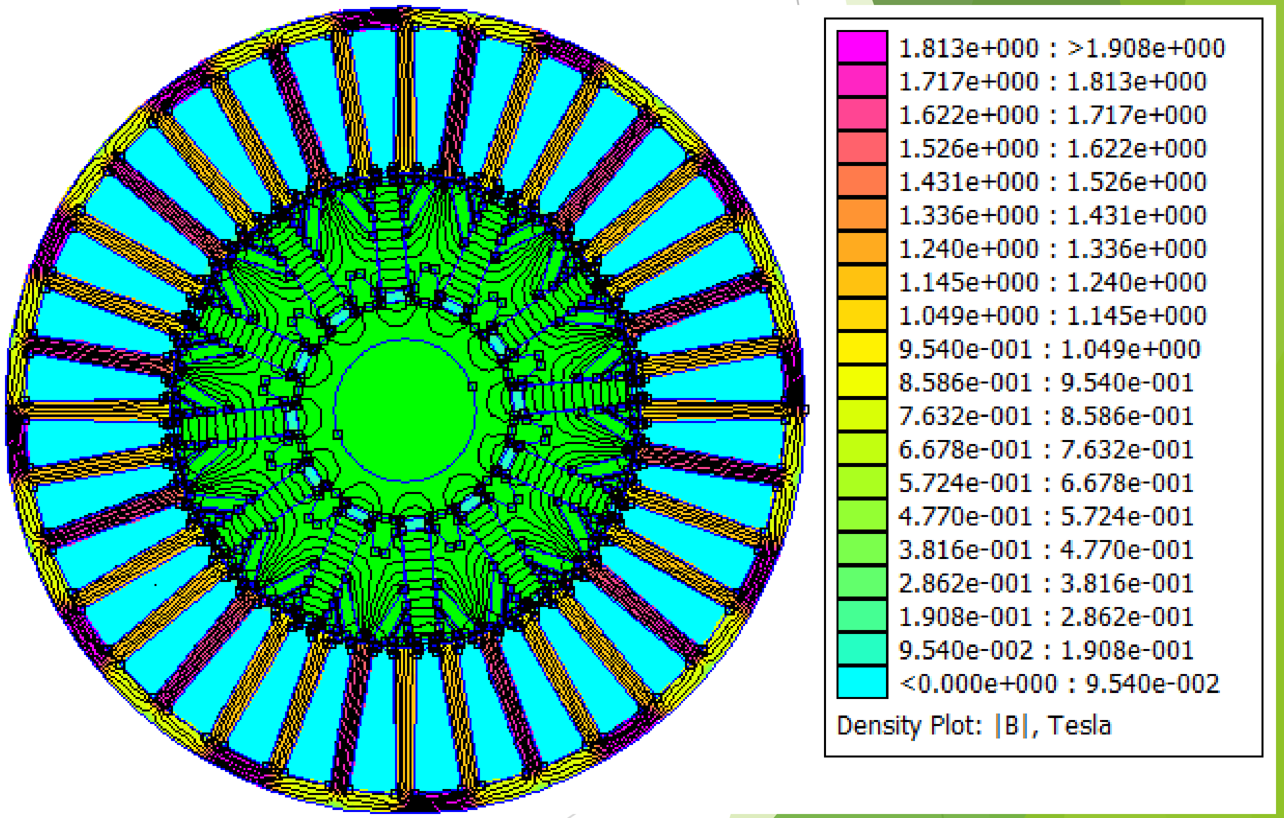
5 kW IPMSM preliminary design

2D FEM Simulations – rated excitation current Id=9.6A, Iq=0

- Air gap magnetic flux density distribution



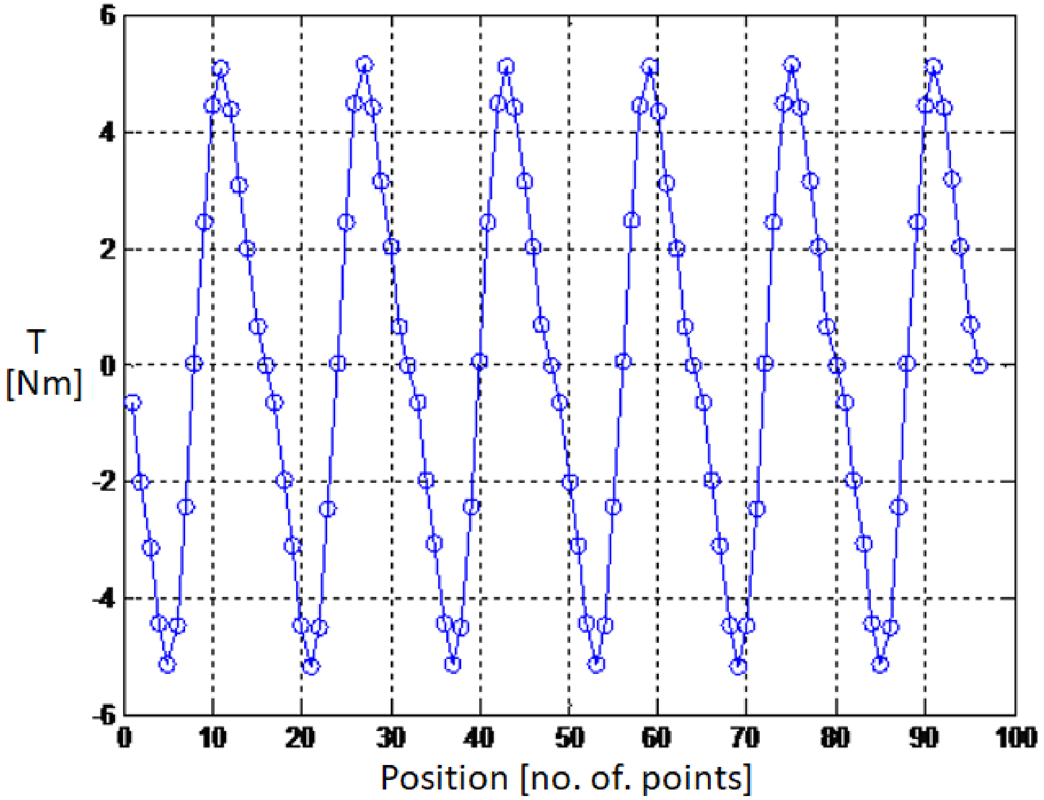
- Magnetic flux density distribution



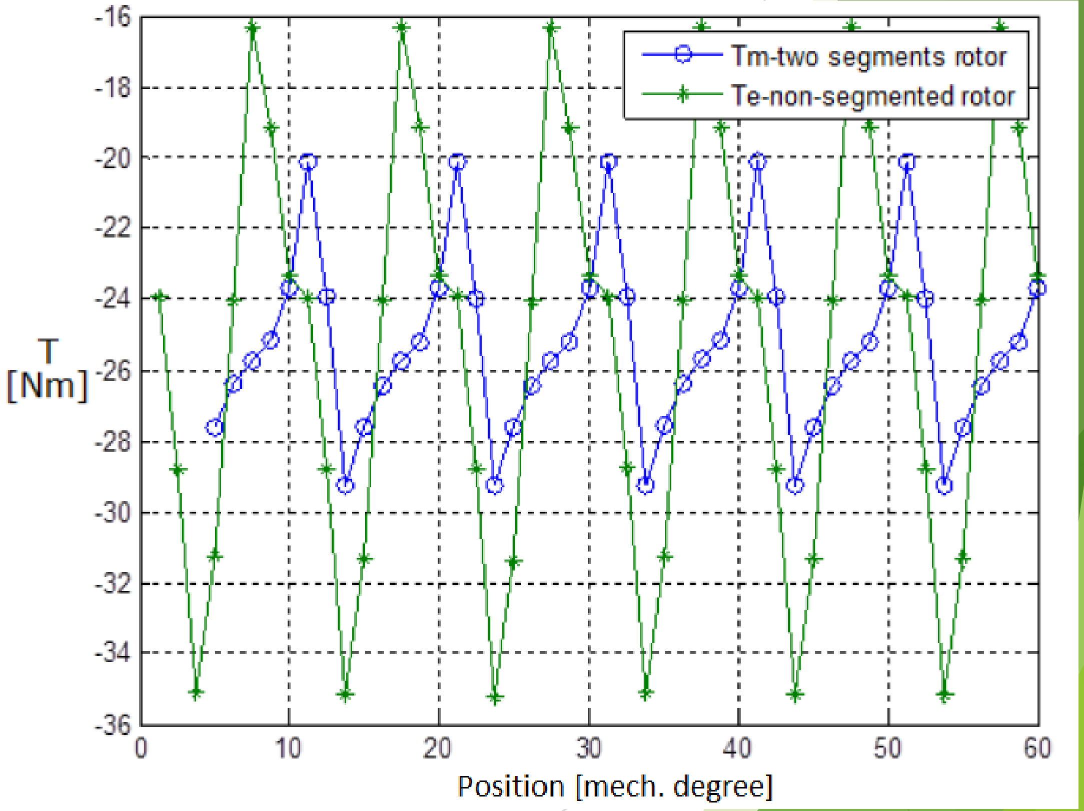
5 kW IPMSM preliminary design

2D FEM Simulations

- Cogging torque for Is=0A (no skew)



- Torque Id=0A, Iq=In=9.6A

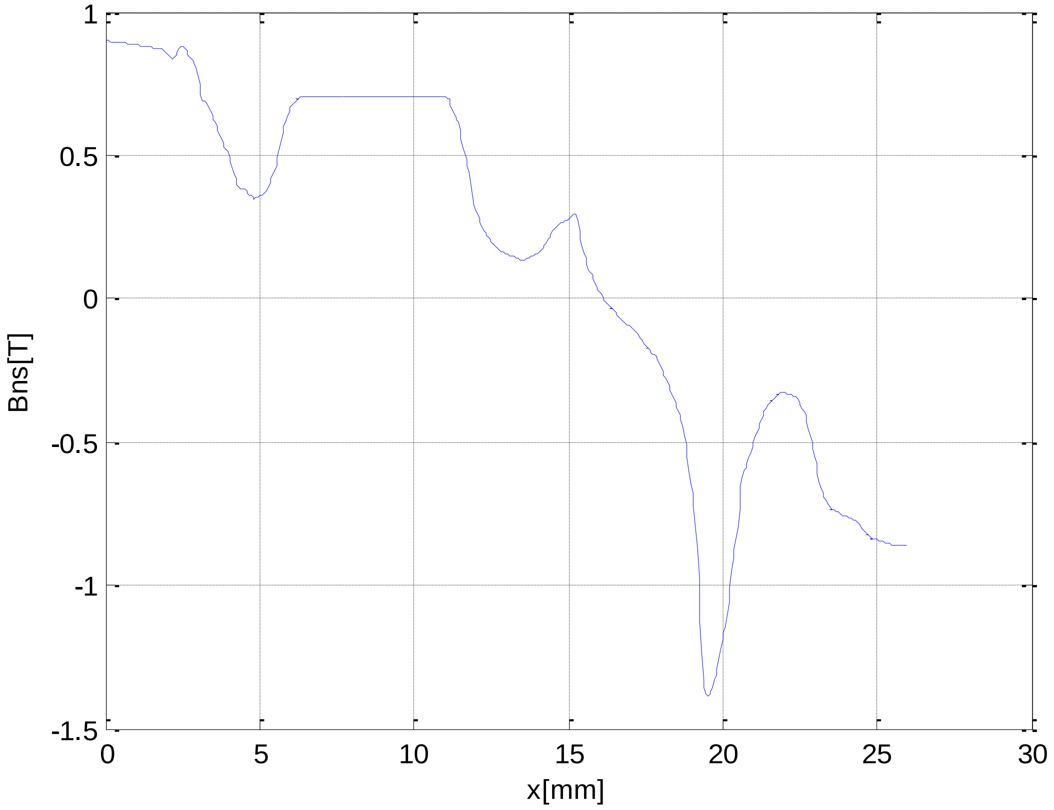


- Green – Non-segmented rotor
- Blue – Two-segmented rotor

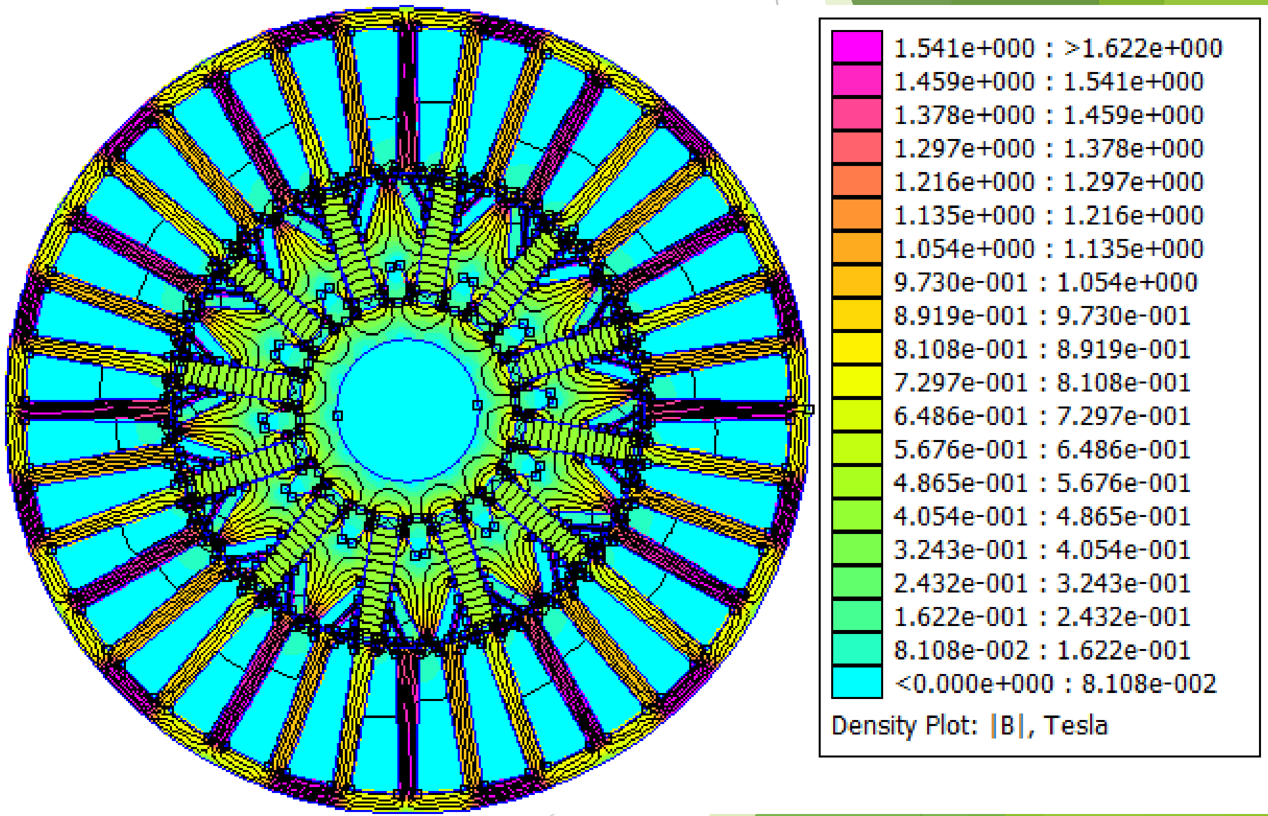
5 kW IPMSM preliminary design

2D FEM Simulations – no excitation current Id=0A, Iq=-9.6A

- Air gap magnetic flux density distribution



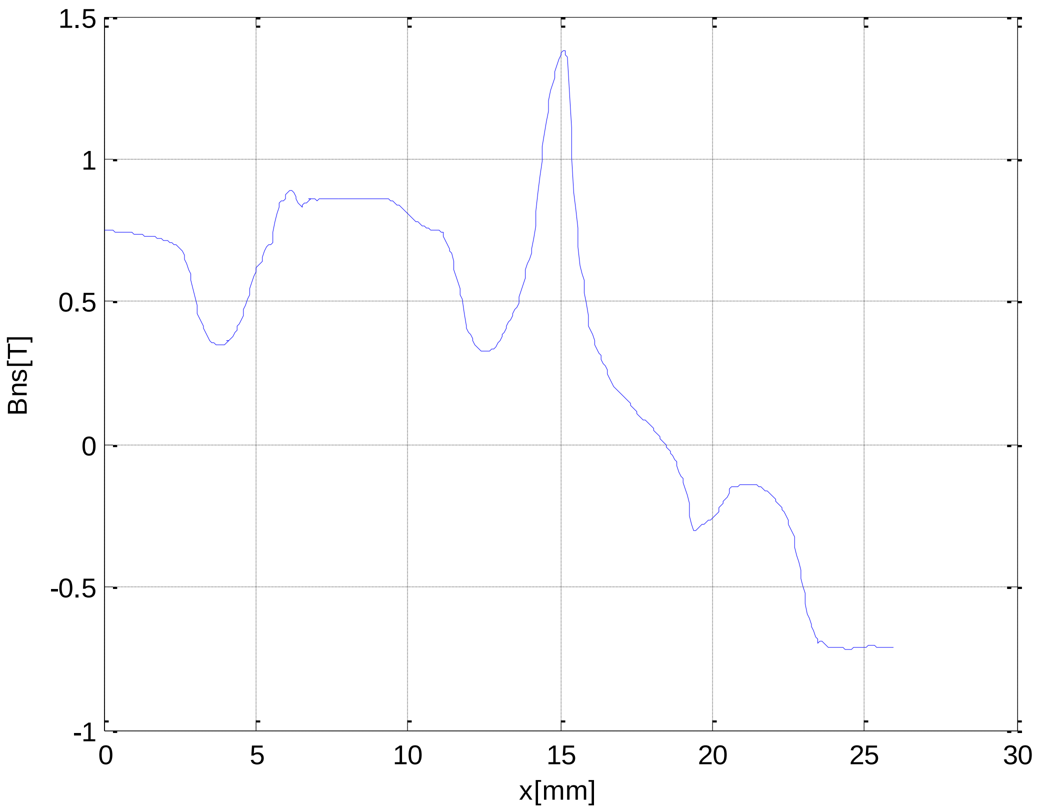
- Magnetic flux density distribution



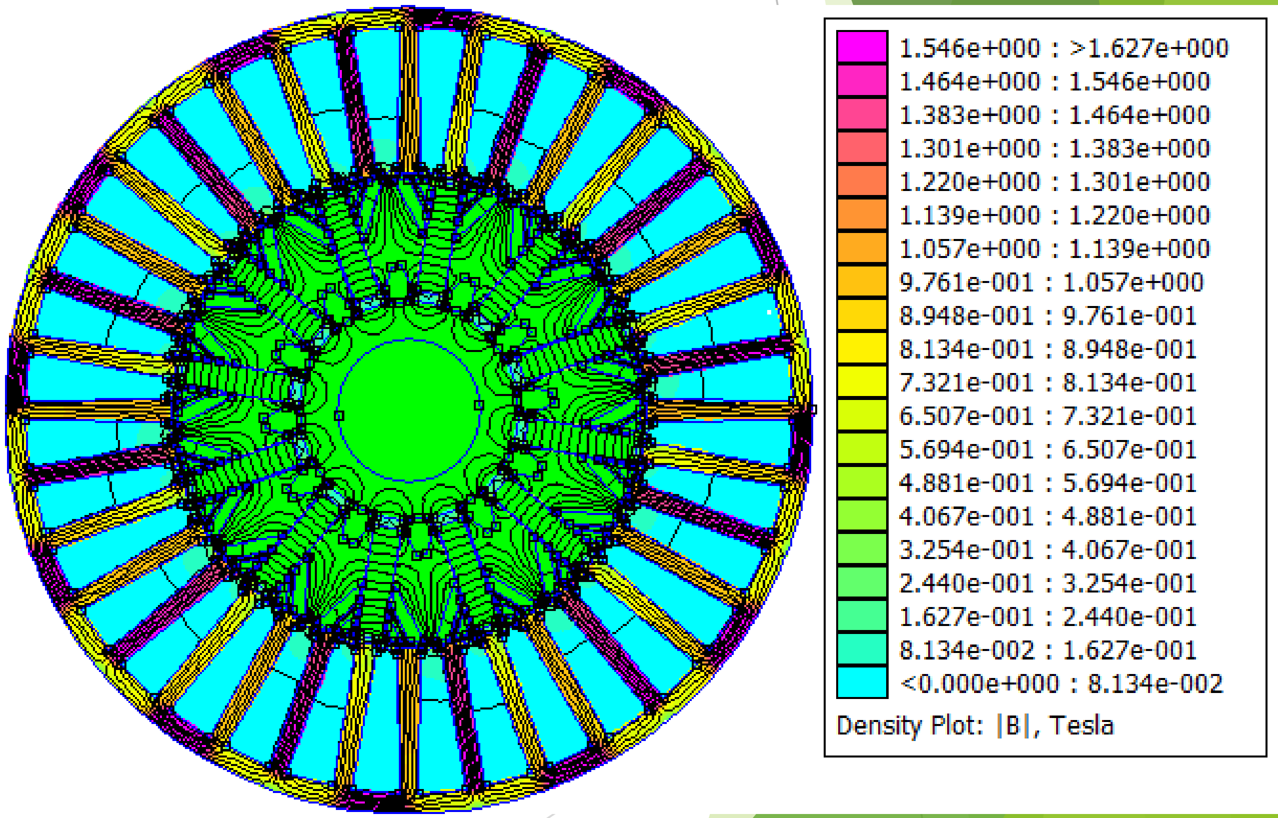
5 kW IPMSM preliminary design

*2D FEM Simulations – no excitation current Id=0A, Iq=*9.6A

- Air gap magnetic flux density distribution



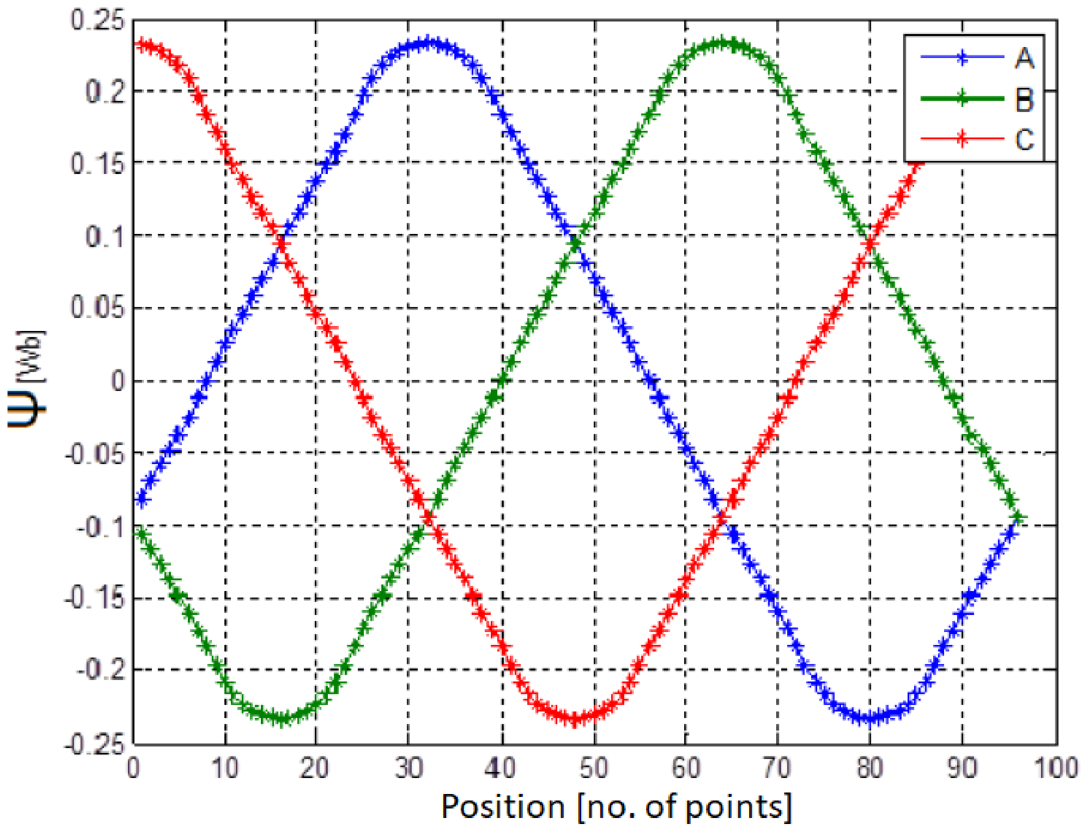
- Magnetic flux density distribution



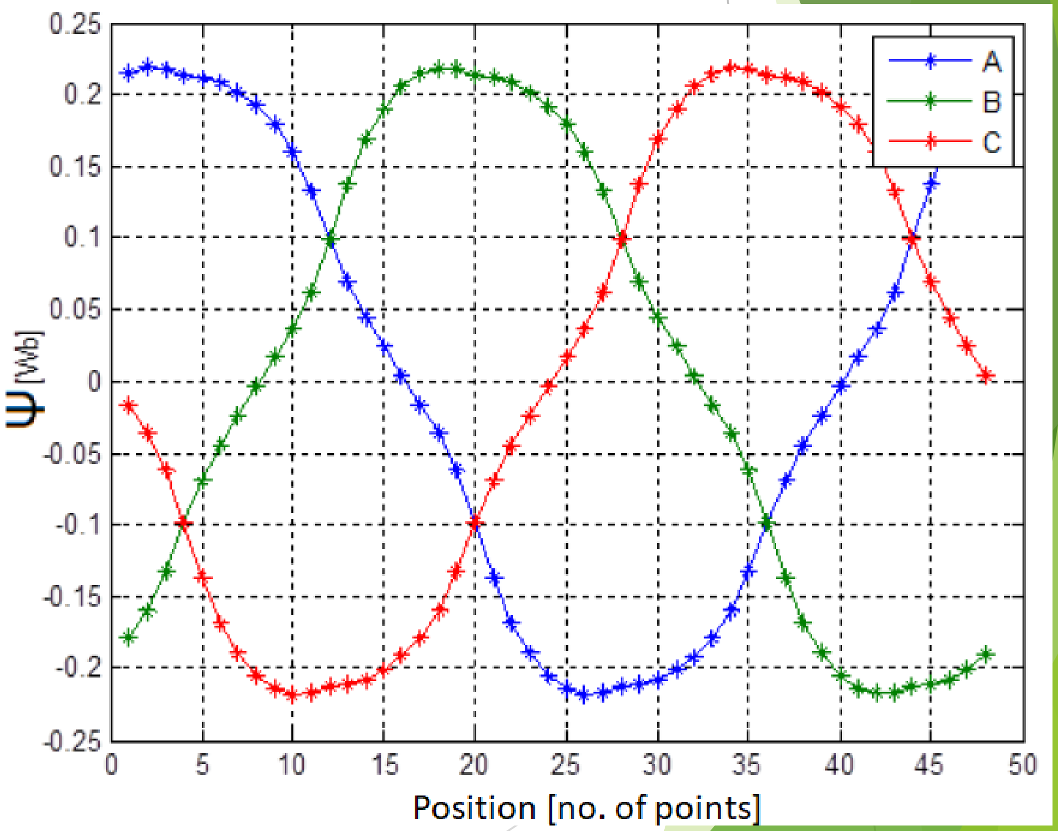
5 kW IPMSM preliminary design

2D FEM Simulations – magnetic flux

- PMs magnetic flux Is=0A



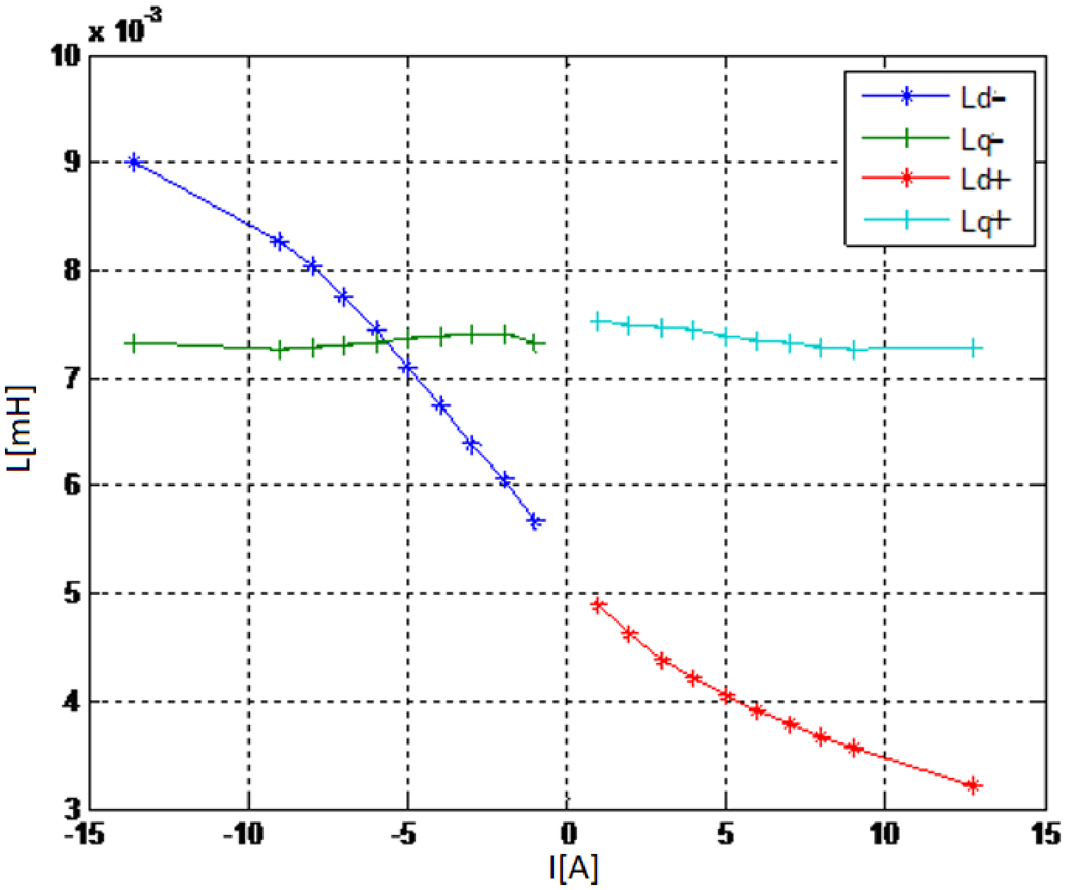
- PMs magnetic flux, Iq=In=9.6A



5 kW IPMSM preliminary design

2D FEM Simulations – magnetic flux

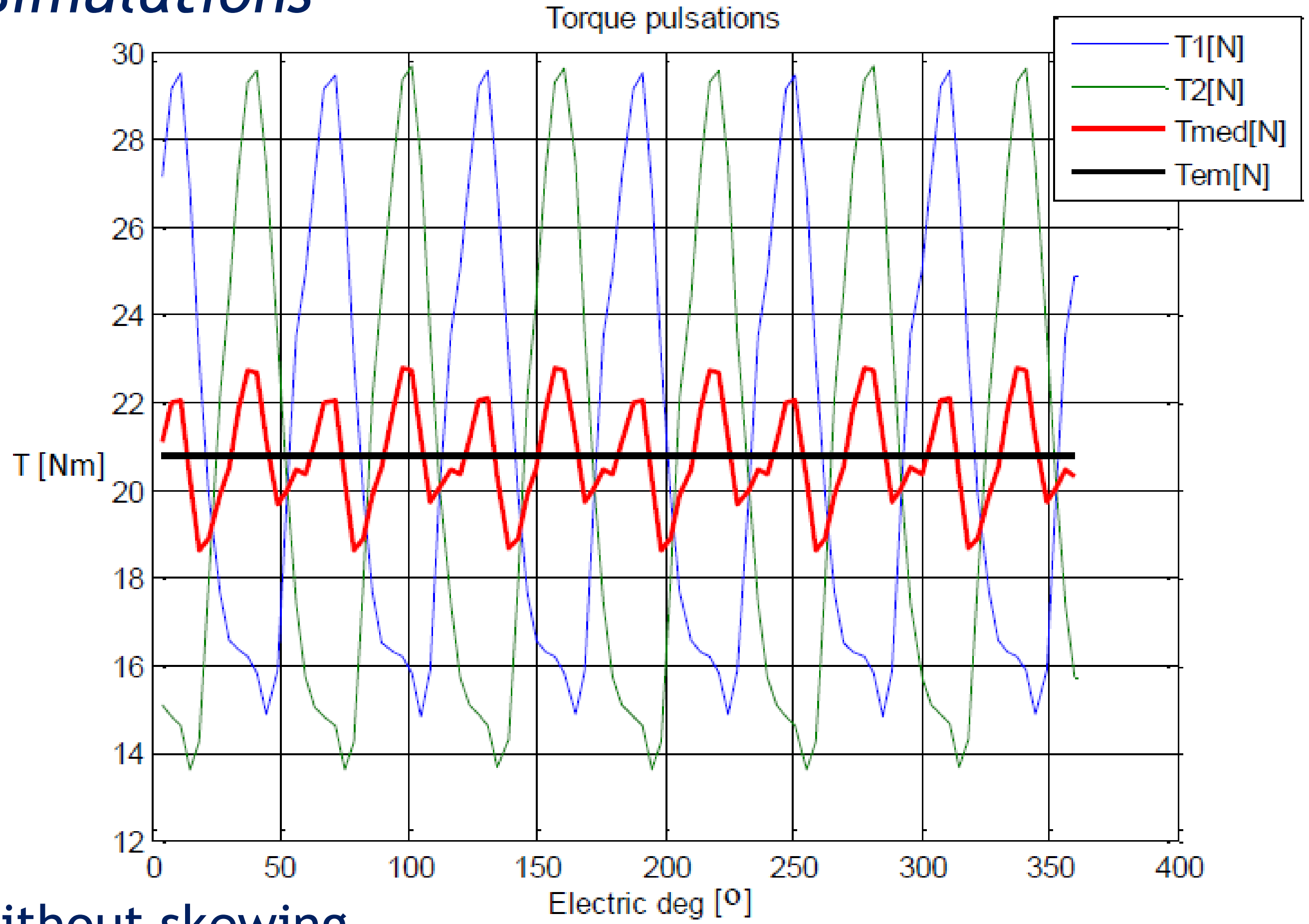
- Inductances variations depending on the stator's currents



- The influences of the coil ends were not considered

5 kW IPMSM preliminary design

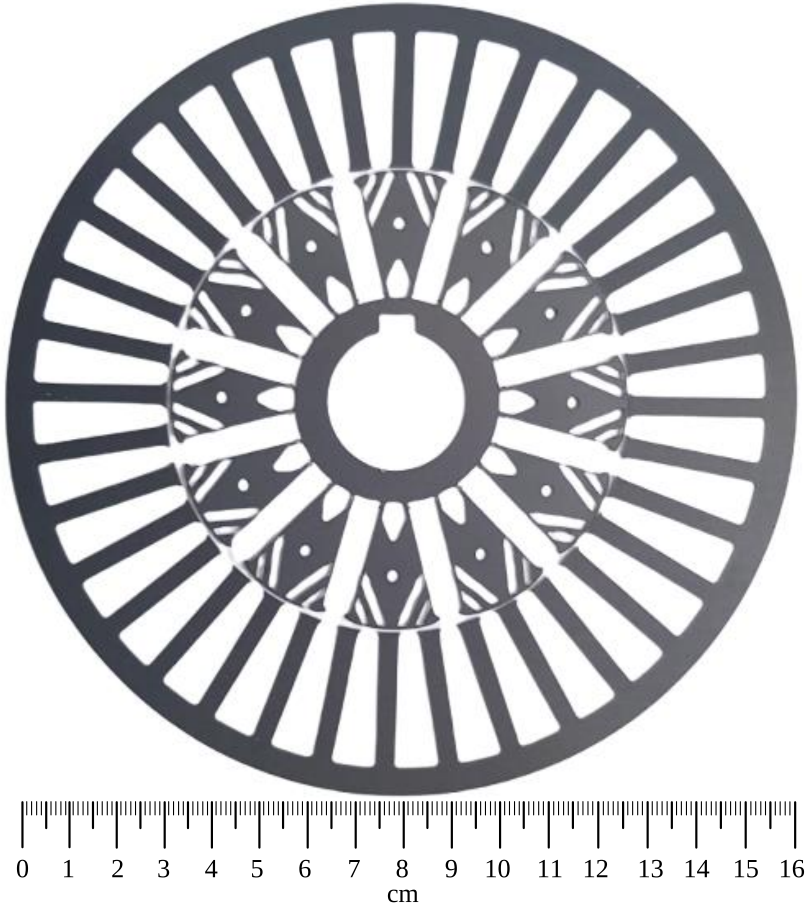
2D FEM Simulations



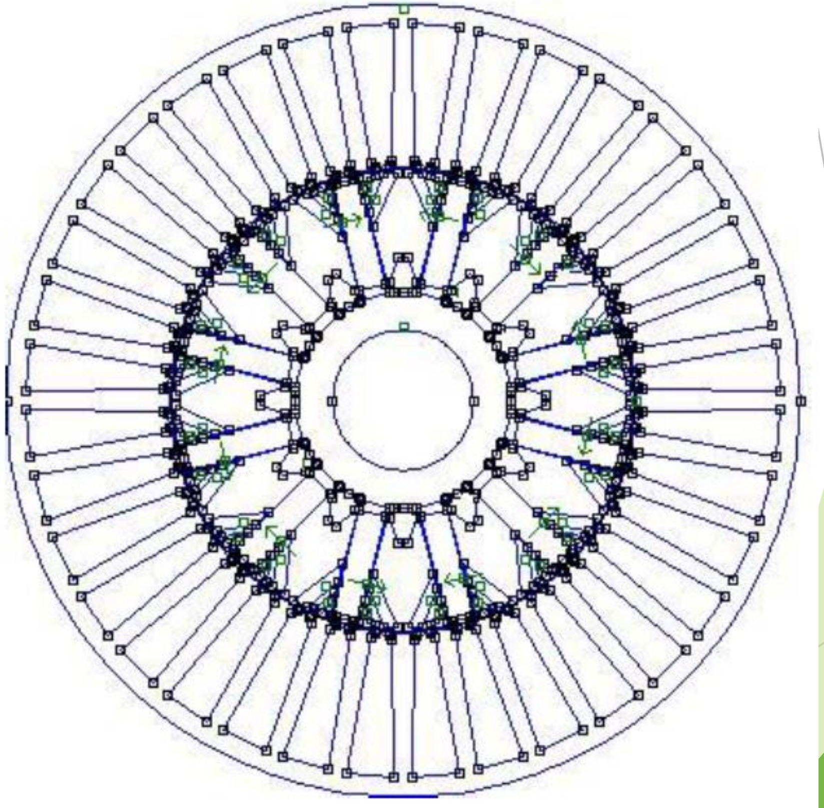
- T, T2 -> rotor without skewing
- Tmed -> 5° radially segmented rotor (two segments)
- Tem -> mean value

5kW IPMSM stator and rotor laminations

- Stator and rotor lamination – prototype



- Stator and rotor lamination – simulation



INTELLIGENT CONTROL OF
ENERGY CONVERSION
AND STORAGE

ECON-BUS

PN-III-CERC-CO-PED-2-2019

Universitatea
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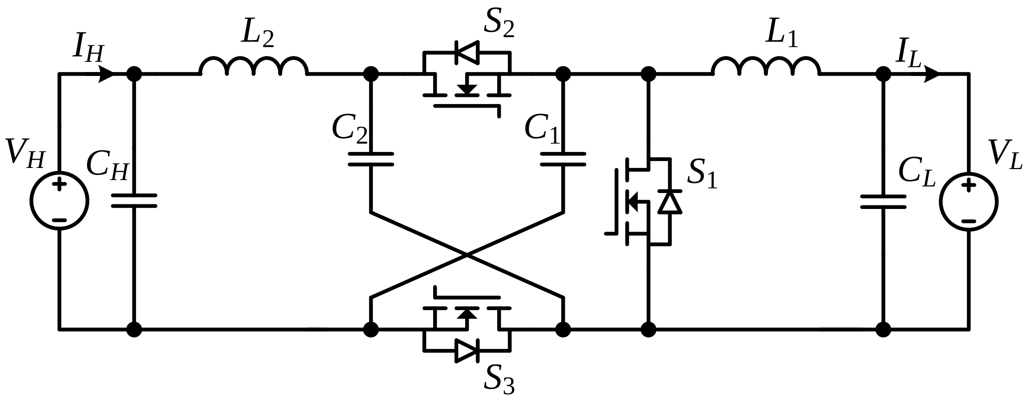
POWER CONVERTERS ANALYSIS, DESIGN AND SMALL SCALE EXPERIMENTAL RESULTS

Speaker : Mihaita-Constantin Gireada

Overview

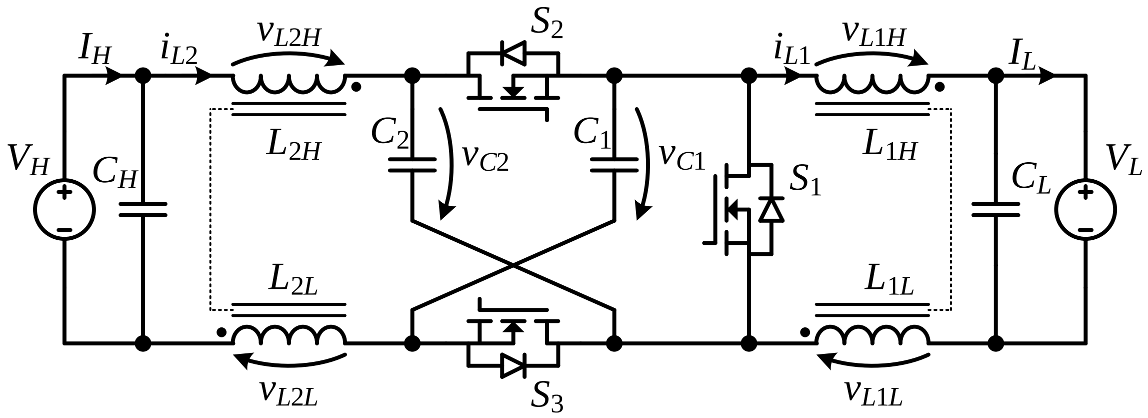
- Topology
- Operation
- Theoretical waveforms
- Comparisons
- Implementation
- Experimental results

Initial Topology



- Advantages:
  - Wide voltage ratio
  - Small passive components
  - Low active switch stress
- Disadvantages:
  - High frequency voltage between inputs
  - Difficulties for layout

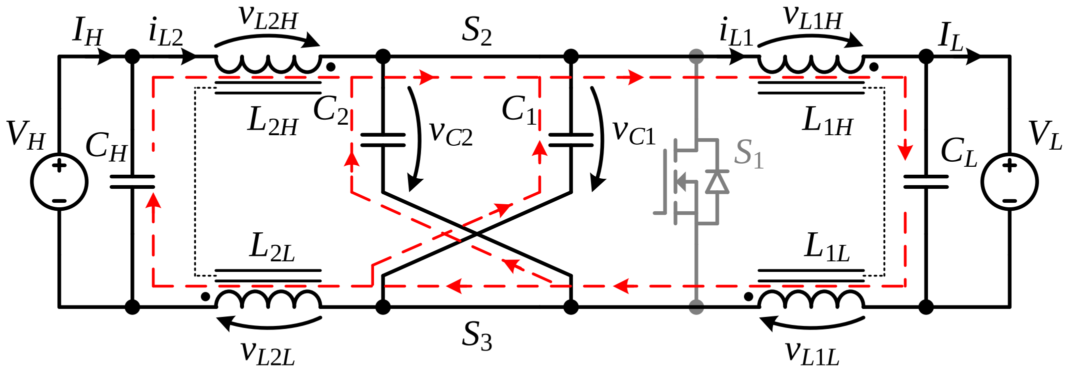
Improved Bidirectional Hybrid Switched-Capacitor DC-DC converter (I-BHSC)



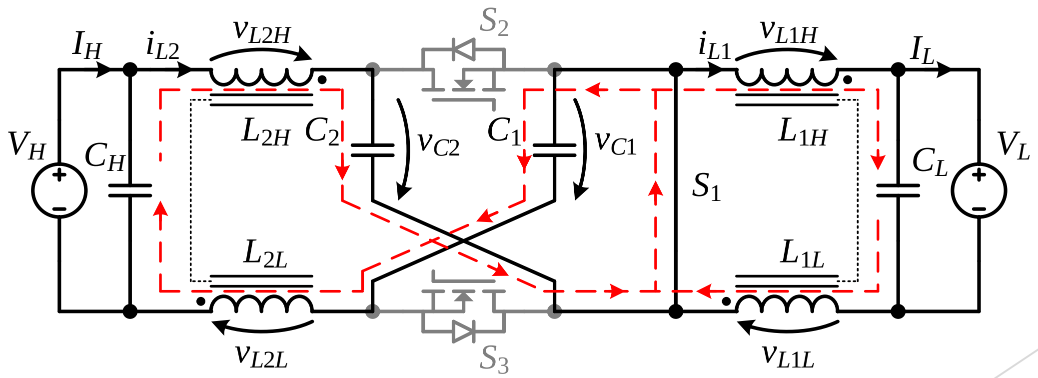
- Additional advantages:
  - DC voltage between inputs
  - Simplified manufacturing by using half bridges

Operation

- I-BHSC equivalent schematic during t_{on}



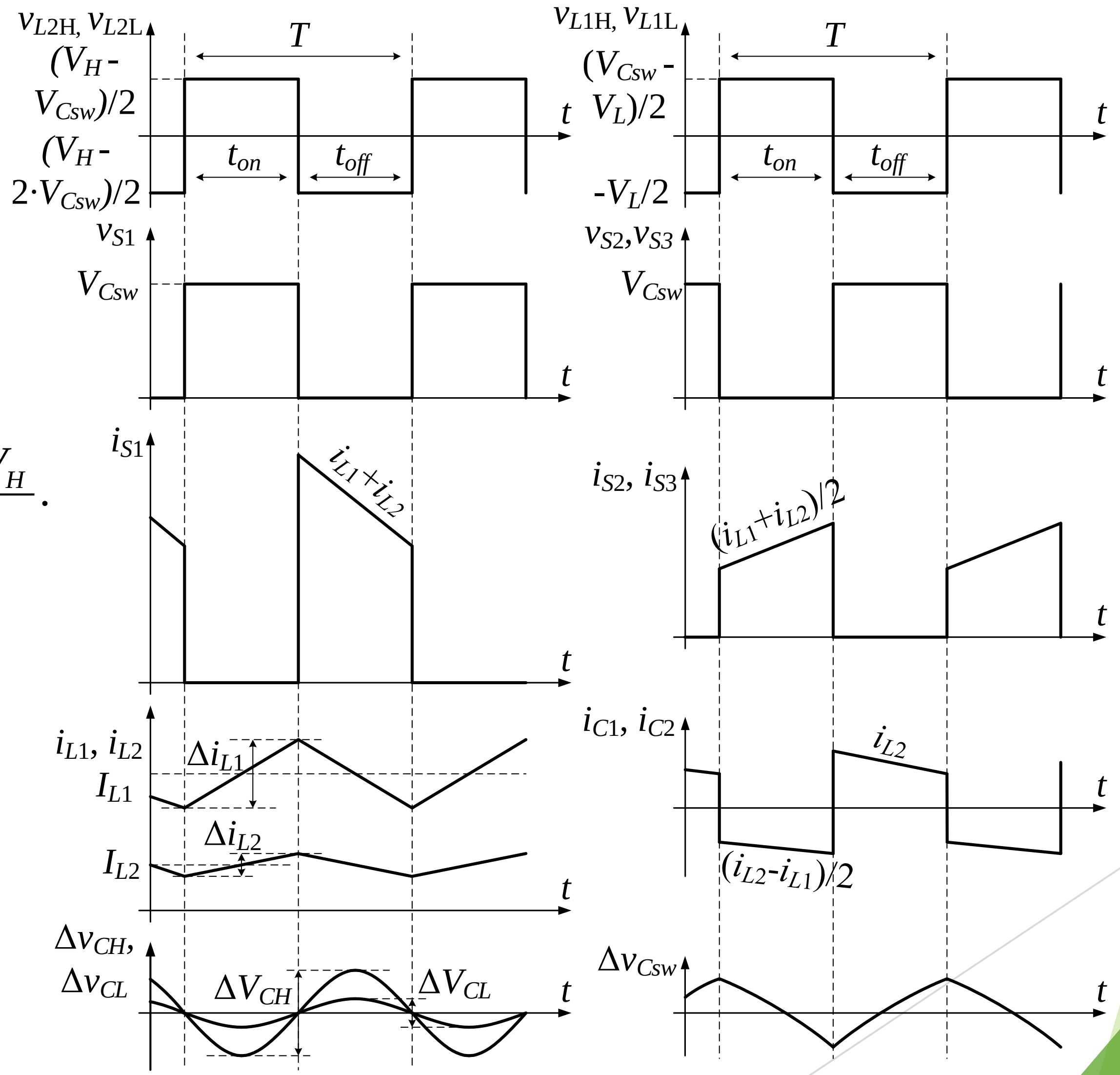
- I-BHSC equivalent schematic during t_{off}



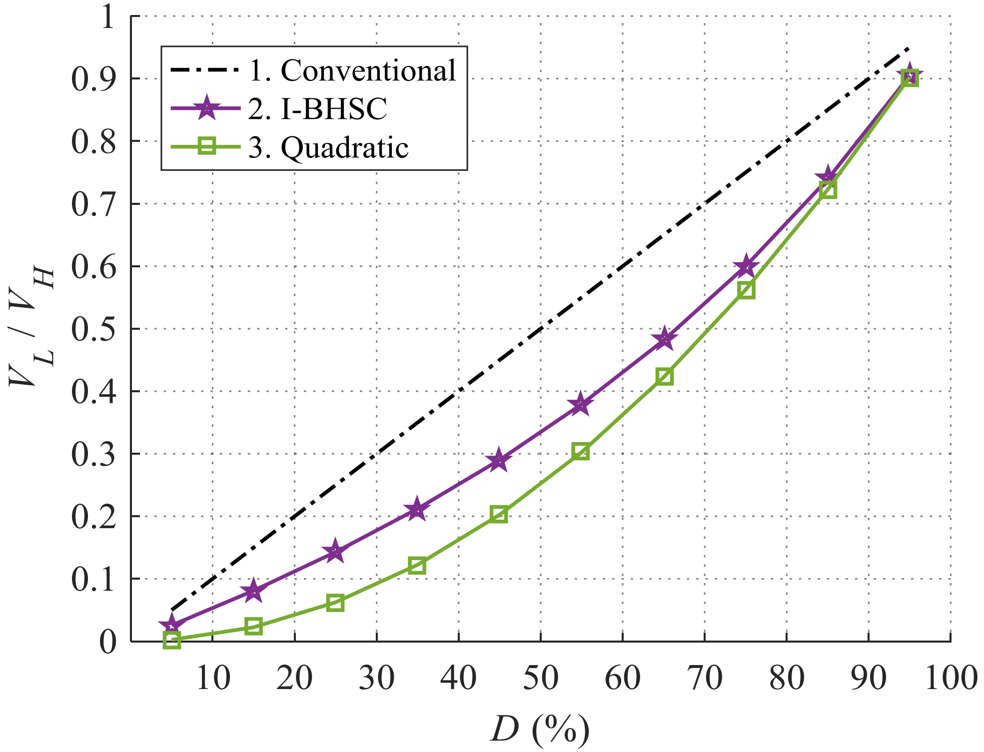
Theoretical waveforms

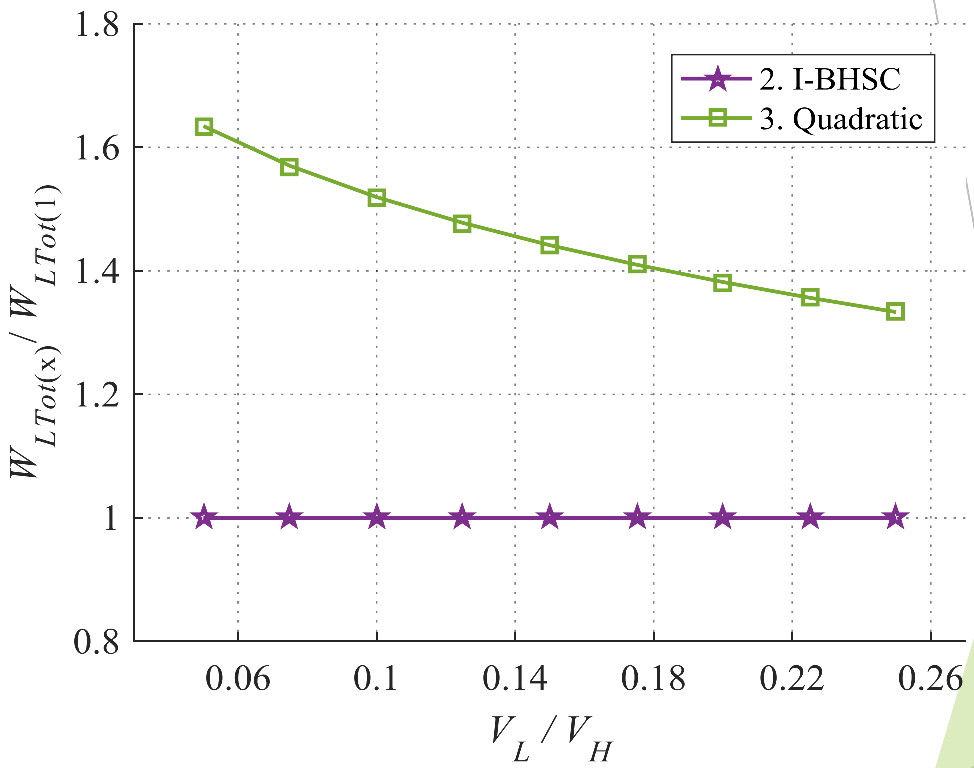
$$V_L = V_H \cdot \frac{D}{2-D}.$$

$$V_{Csw} = \frac{V_L}{D} = \frac{V_H}{2-D} = \frac{V_L + V_H}{2}.$$



Comparisons

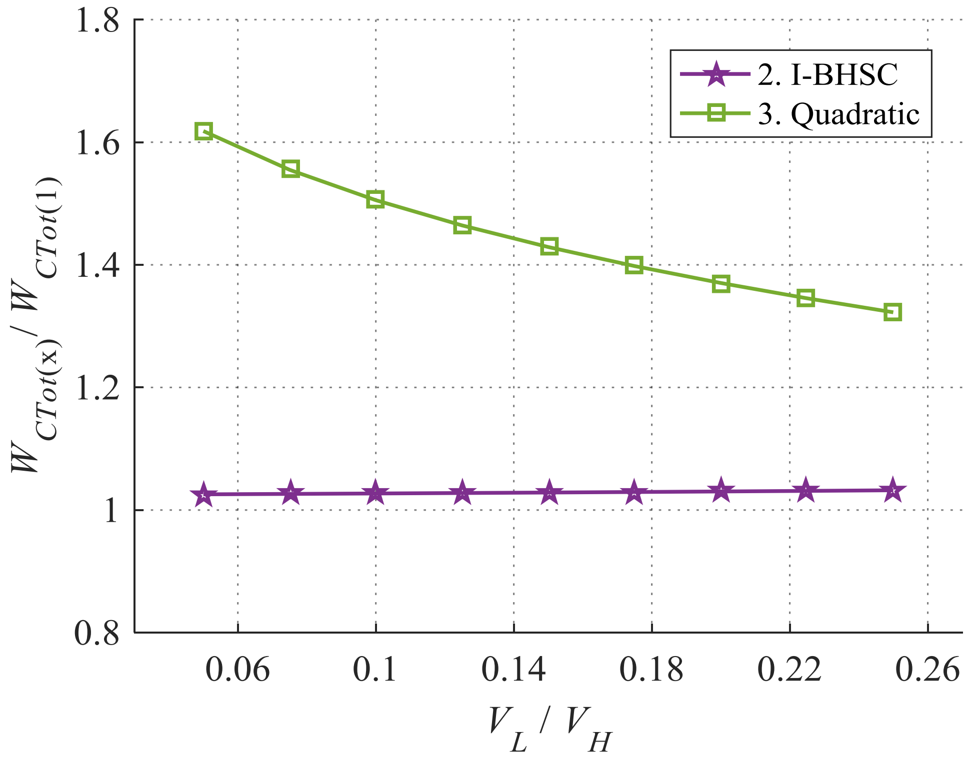


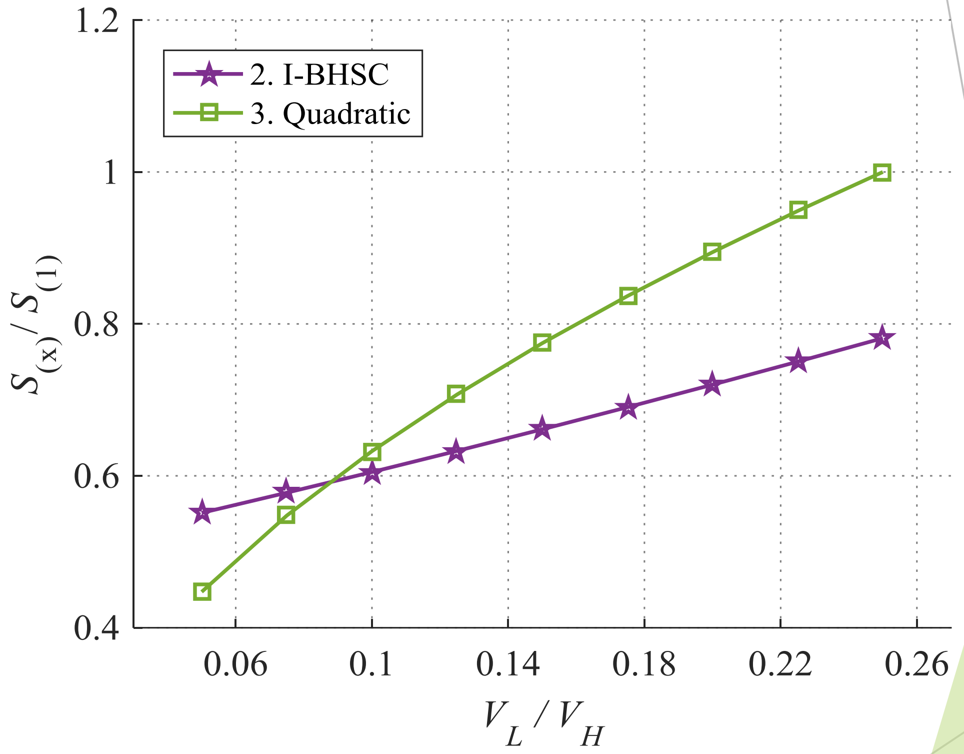


$$V_L = V_H \cdot \frac{D}{2-D}.$$

$$W_{LTot} = \frac{I_L \cdot V_L \cdot (V_H - V_L)}{2 \cdot r_i \cdot f \cdot V_H}.$$

Comparisons



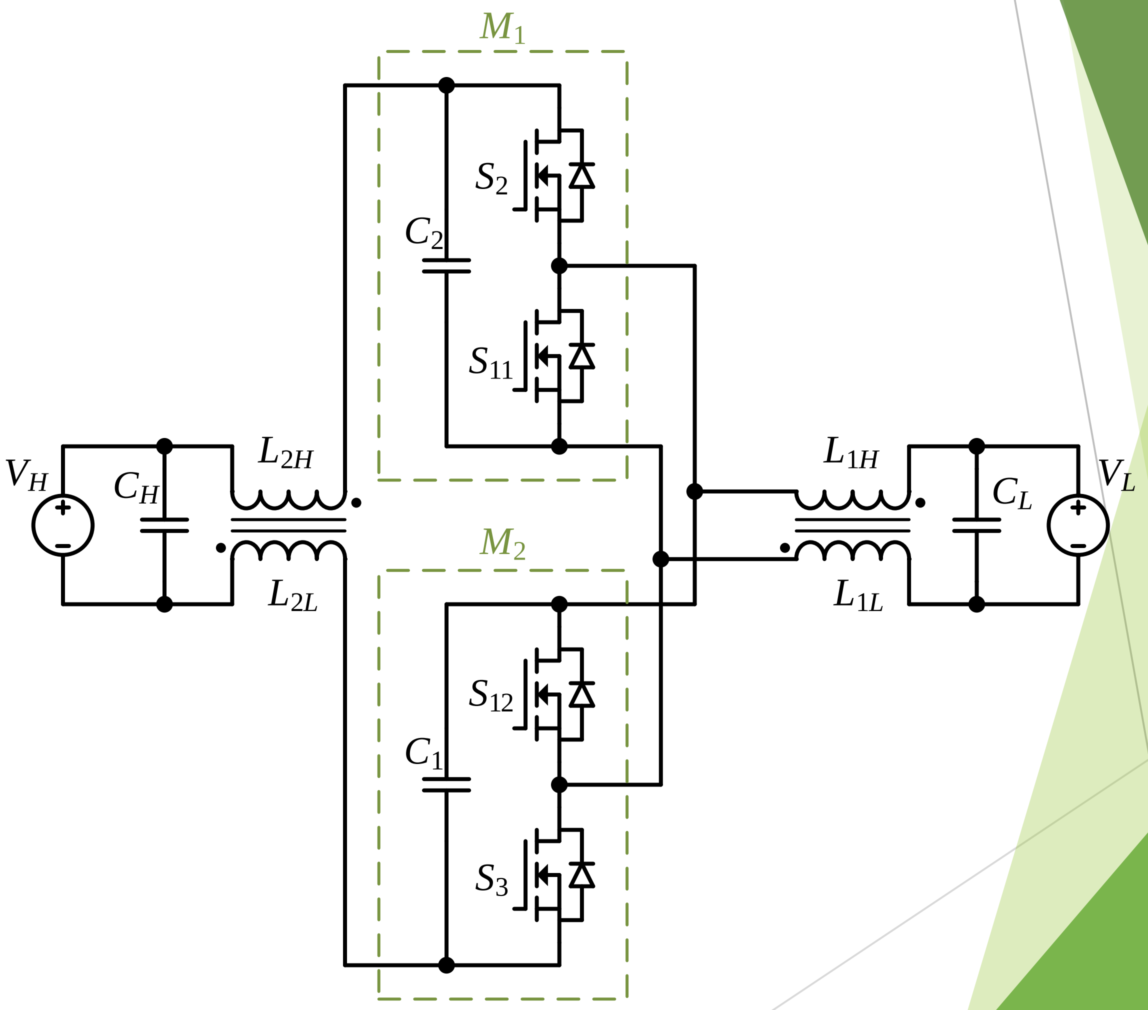


$$W_{CTot} = \frac{I_L \cdot V_L \cdot (4 \cdot V_H - 4 \cdot V_L + r_i \cdot V_H)}{8 \cdot r_v \cdot f \cdot V_H}.$$

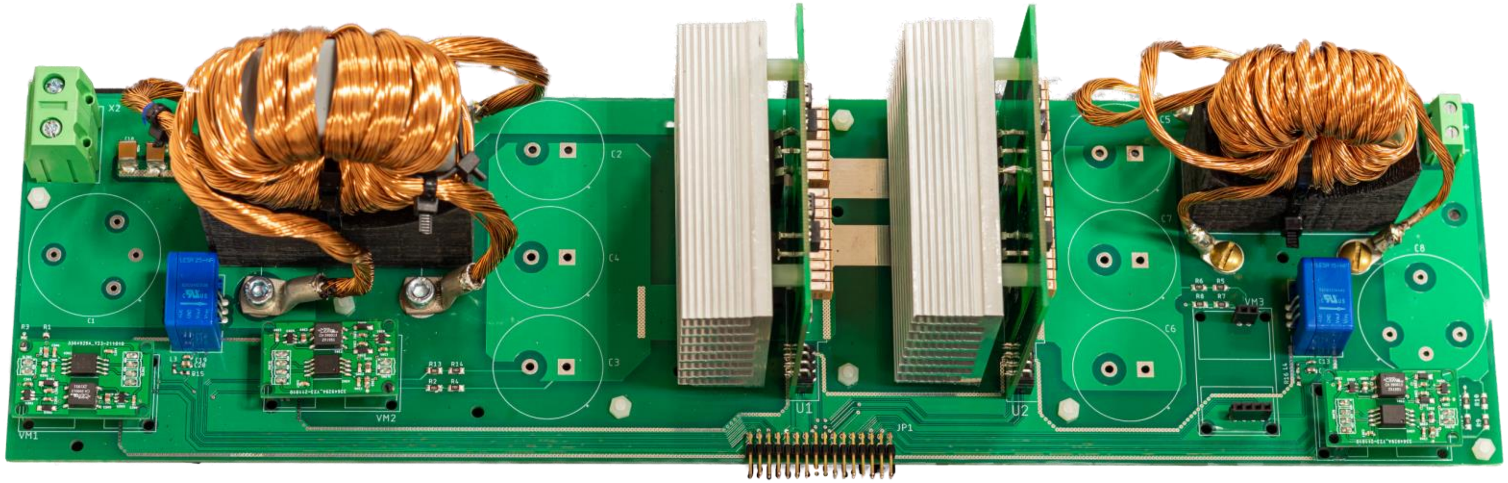
$$S = \frac{I_L \cdot (V_H + V_L)^2}{V_H}.$$

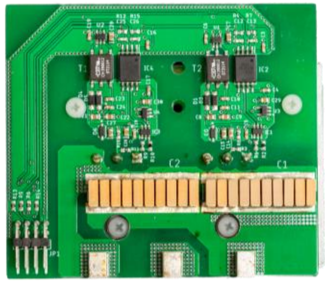
Topology Implementation

Element	Value	Unit	Description
Input values			
V_H	400	V	High voltage input maximum value
V_L	0-160	V	Low voltage input maximum value
I_H	17.5	A	High voltage input maximum current
I_L	43.75	A	Low voltage input maximum current
f	200	kHz	Switching frequency
L_1 Inductor			
L_1	39	μH	Design value inductance
I_{L1}	44	A	Nominal current
Δi_{L1}	8.75	A	Ripple current
L_{1H}, L_{1L}	9.75	μH	Inductance of each winding
N_{1H}, N_{1L}	9	-	Number of turns for each winding
Core	55617	-	inductor core – Magnetics MPP
L_2 Inductor			
L_2	98	μH	Design value inductance
I_{L2}	17.5	A	Nominal current
Δi_{L2}	3.5	A	Ripple current
L_{2H}, L_{2L}	24.5	μH	Inductance of each winding
N_{2H}, N_{2L}	19	-	Number of turns for each winding
Core	58090		inductor core – Magnetics High Flux
Capacitors			
C_1, C_2	20	μF	Switched capacitors 2 x B58035U5106M001
V_C	280	V	Switched capacitor maximum voltatge
C_H	500	nF	High voltage input capacitance
C_L	3.4	μF	Low voltage input capacitance
rv	1	%	Voltage ripple percentage
Transistors			
S_{11}, S_{12}, S_2, S_3	TP65H035WS		Transphorm GaN 650V, 41mΩ, 24nC



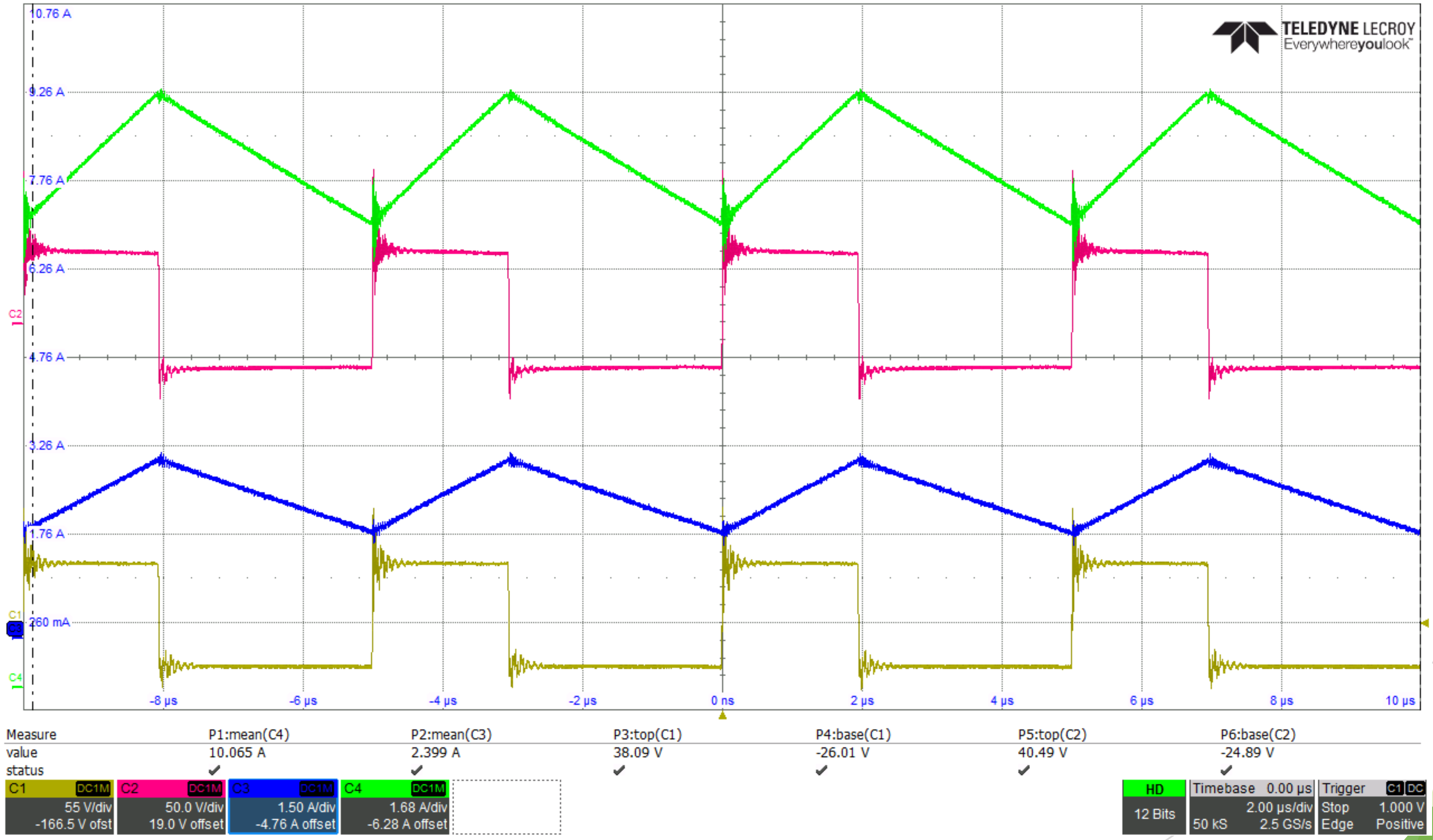
Prototype





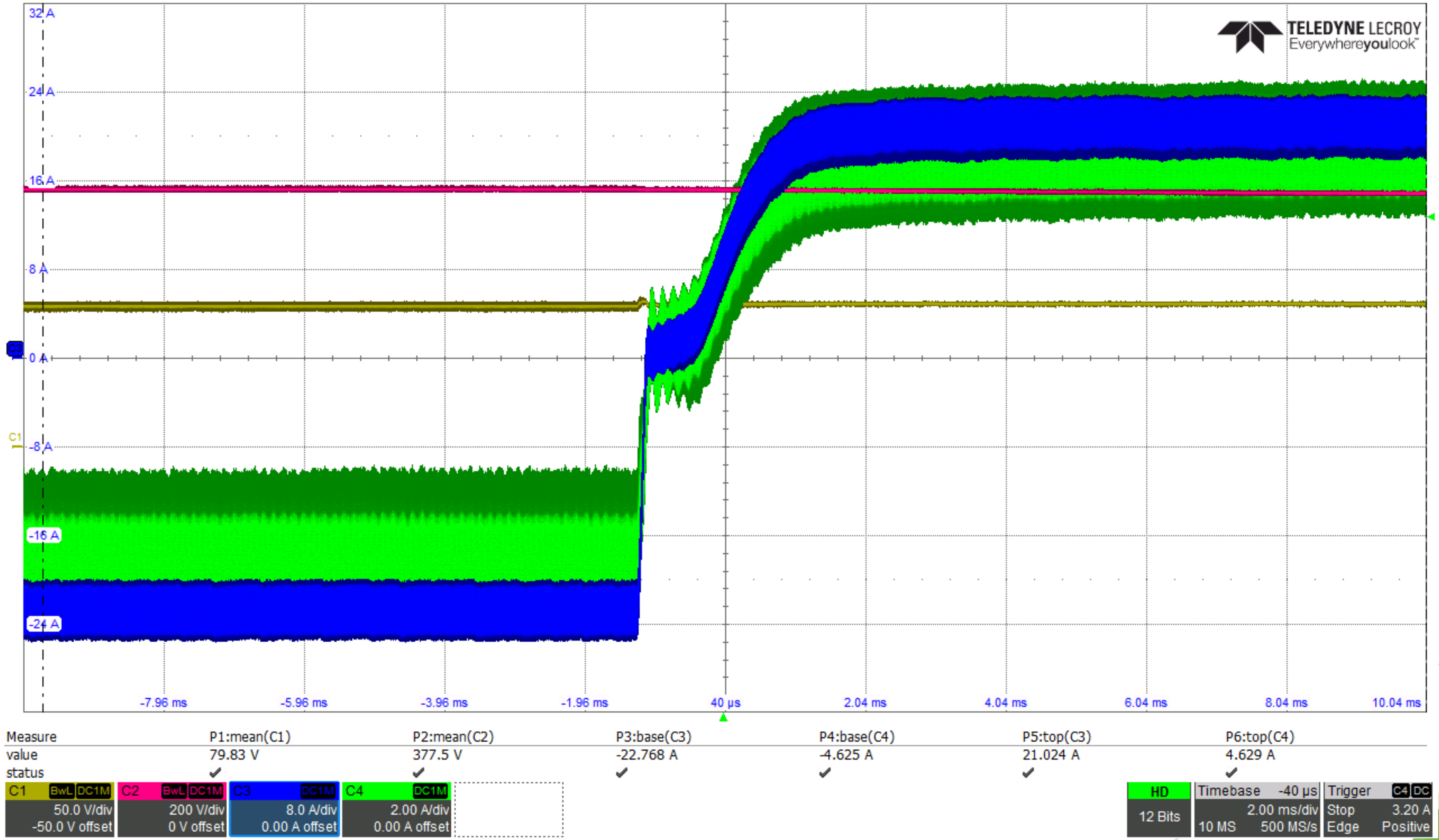
Experimental results

- Inductor current and voltage waveforms



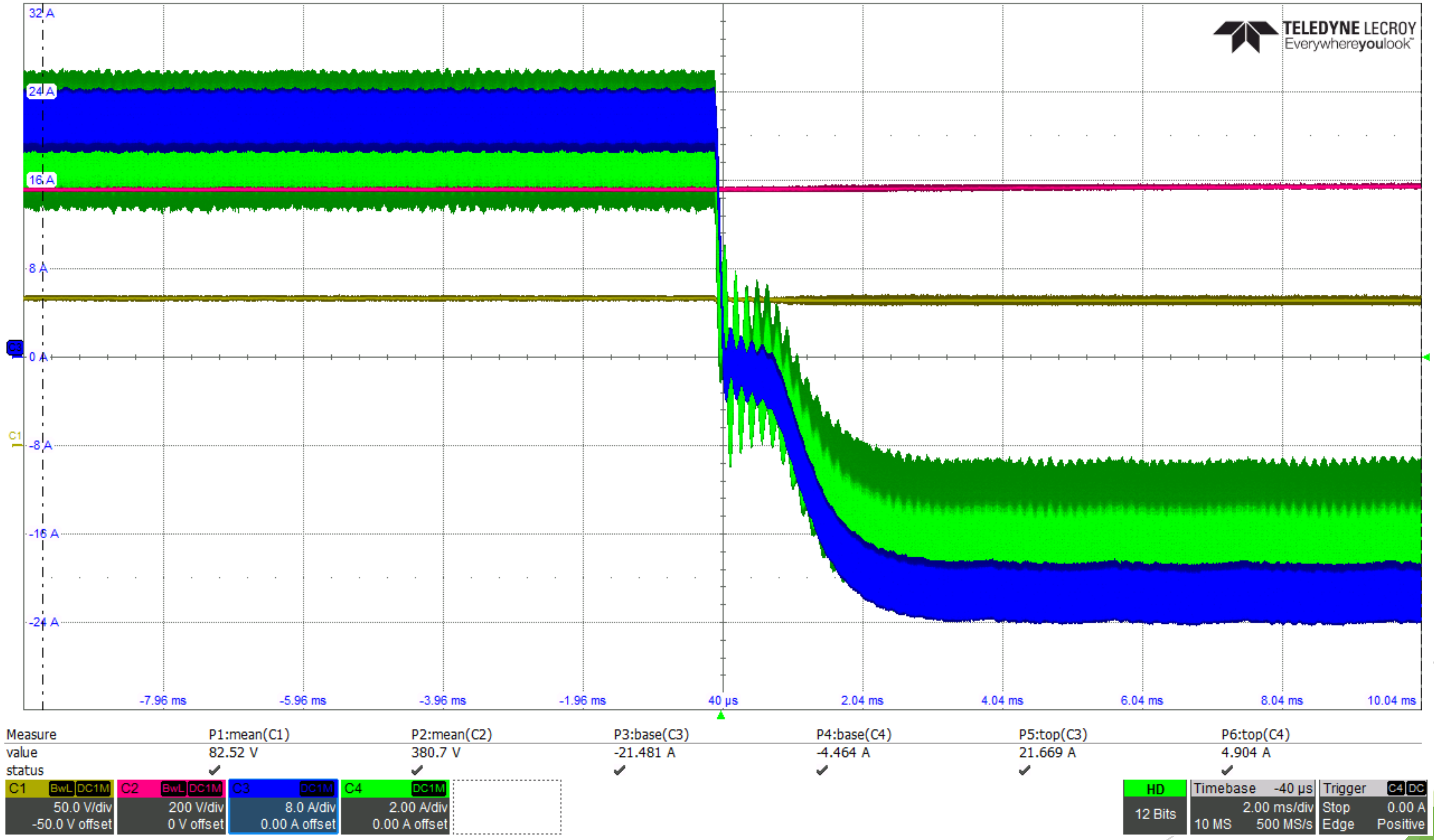
Experimental results

- Boost to Buck transition - inductor currents and output voltages



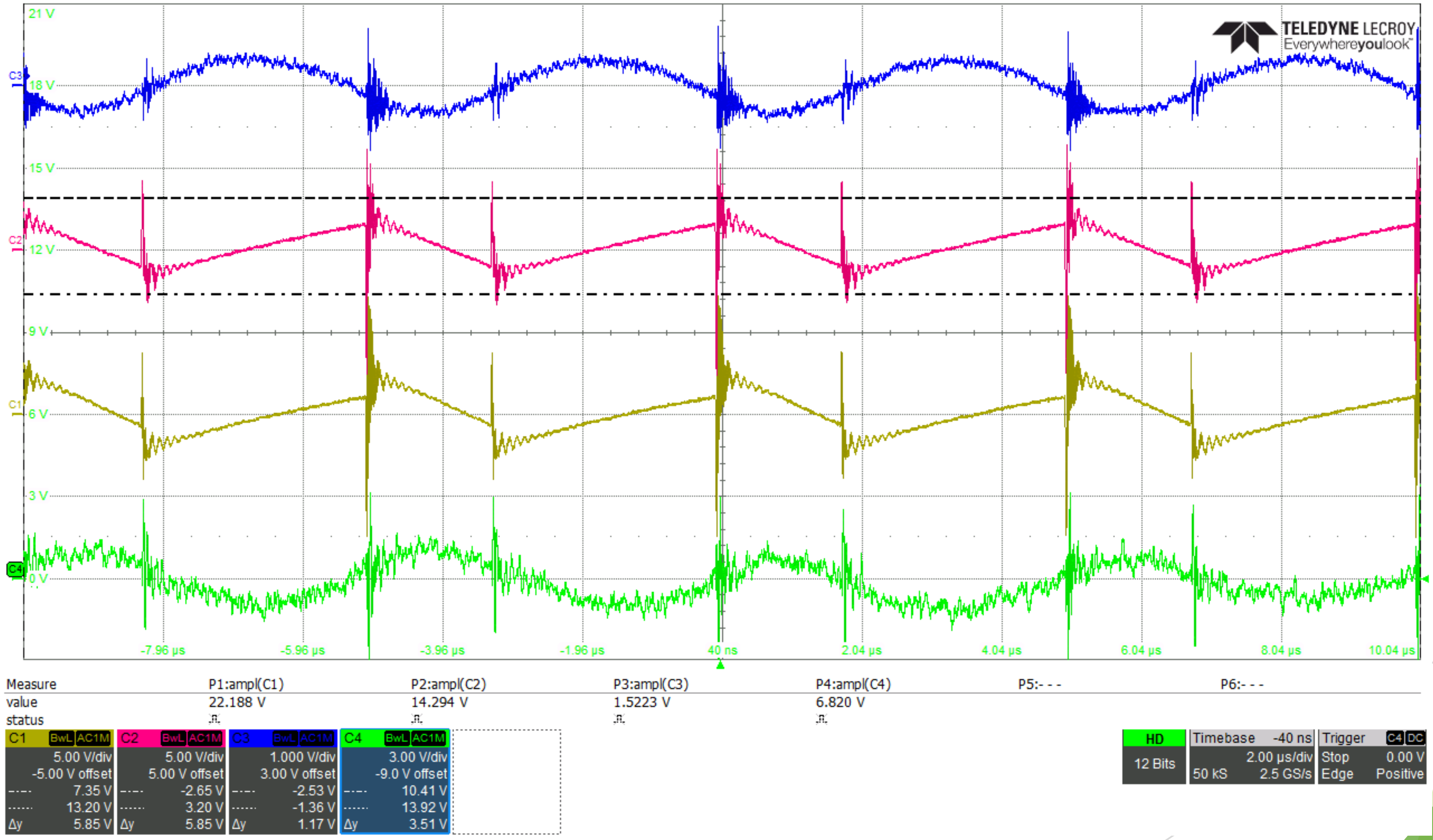
Experimental results

- Buck to Boost transition - inductor currents and output voltages



Experimental results

- Capacitor voltage ripple waveforms



INTELLIGENT CONTROL OF ENERGY CONVERSION AND STORAGE

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Universitatea Politehnica Timișoara

DRIVE ANALYSIS, SIMULATIONS AND SMALL SCALE EXPERIMENTS

Speaker: Liviu-Dănuț VITAN

Overview

- City Minibus Structure
  a. IPMSM Model
  b. Supercapacitor Model
  c. Bidirectional DC/DC Converter Model
  d. Transmission Model
- IPMSM Drive Control Methodology
- Propulsion System Simulation Results (scale 1:1)
- Case Study – Simulation in Real Traffic Condition (scale 1:1)
- Preliminary Experimental Results (scale 1:20)

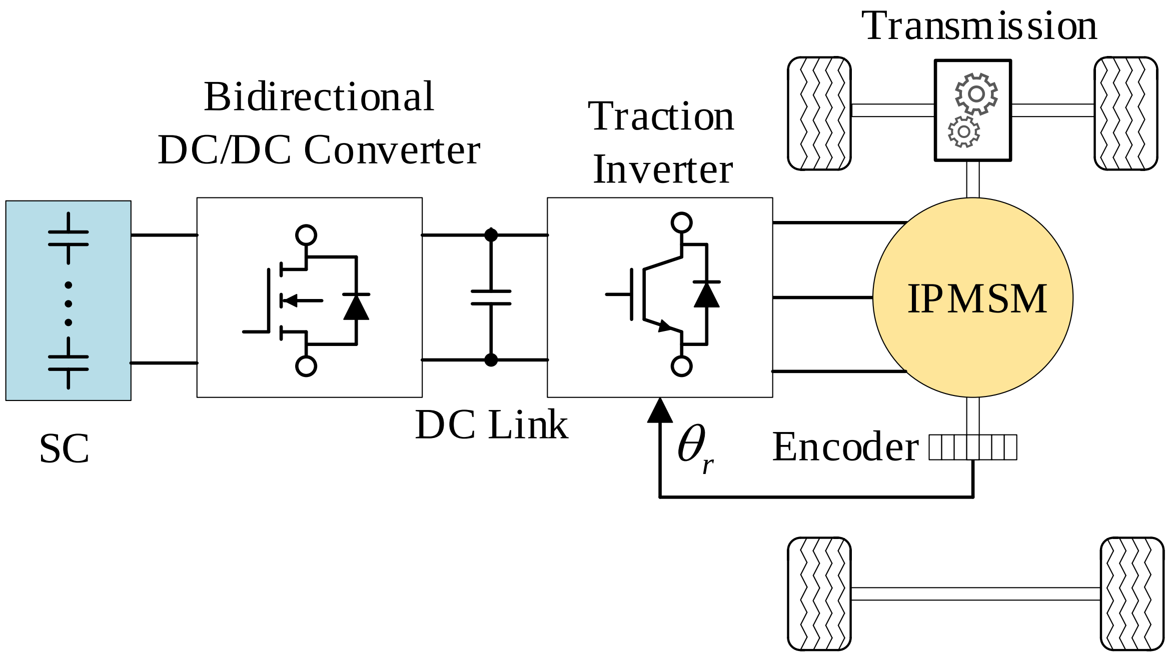
City Minibus Structure

Targeted minibus:

- total weight: 7t
- 38 passenger load

- length: 8.5m
- width: 2.1m
- height: 2.3m

Minibus electric powertrain – block diagram



- Average passenger weight of 75kg

  => up to 28 passenger load

Weight

Reduction:
- the internal combustion engine
- the automatic gearbox
- fuel tank

Gain:
- the electric machine
- the supercapacitors
- power converters

City Minibus Structure

A. IPMSM Model

- The d and q-axis linkage flux

$$\frac{d\psi_d}{dt} = V_d - i_d \cdot R_s + p_1 \cdot \omega_r \cdot \psi_q$$

$$\frac{d\psi_q}{dt} = V_q - i_q \cdot R_s - p_1 \cdot \omega_r \cdot \psi_d$$

- Relationships of the flux linkage-currents

$$I_d = \frac{\psi_d - \psi_{PM}}{L_d} \qquad I_q = \frac{\psi_q}{L_q}$$

- The electromagnetic torque

$$P_e = T_{em} \cdot \frac{\omega_1}{p_1}, \quad T_{em} = p_1 \left(\psi_d \cdot i_q - \psi_q \cdot i_d \right)$$

- The angular speed

$$\frac{d\omega_r}{dt} = \frac{1}{J}\left(T_{em} - T_{Load}\right), \quad \frac{d\theta_r}{dt} = \omega_r$$

City Minibus Structure

B. Supercapacitor Model

- The output voltage of the SC

$$V_{sc} = V_{SC0} - R_{SC} \cdot I_{SC}$$

- The internal SC voltage

$$V_{SC0} = \frac{1}{C} \cdot \left(Q_0 - \int_0^t I_{SC}(t)\,dt \right)$$

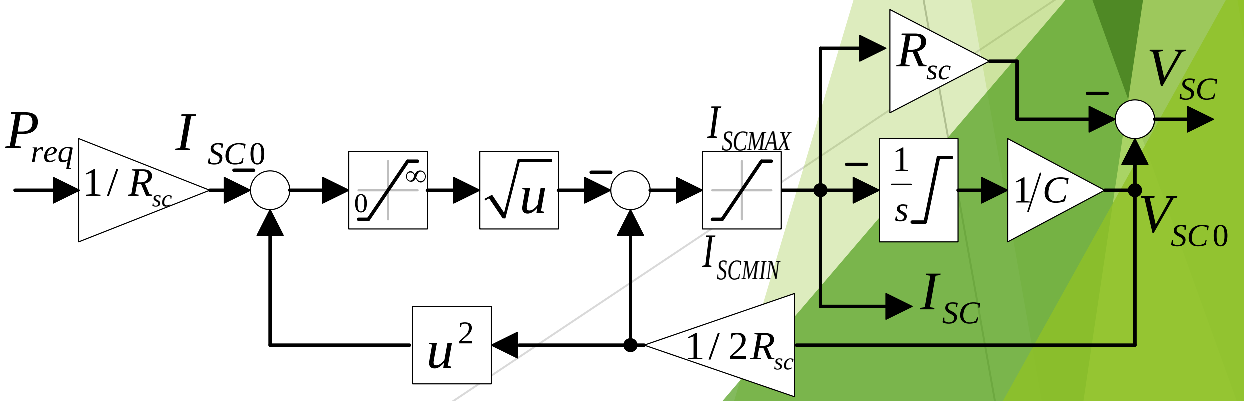
- Solving:

$$P_{req} = V_{SC} \cdot I_{SC} = V_{SC0} \cdot I_{SC} - R_{SC} \cdot I_{SC}^2$$

=> the output current of the SC

$$I_{SC} = \frac{V_{SC0}}{2R_{SC0}} - \sqrt{\left(\frac{V_{SC0}}{2R_{SC0}}\right)^2 - \frac{P_{req}}{R_{SC}}}$$

- Supercapacitor module – block diagram



City Minibus Structure

C. Bidirectional DC/DC Converter Model Model

- Implemented as a proportional regulator:

$$P_{req} = k_p \left(V_{dc}^* - V_{dc} \right) + P_{el}$$

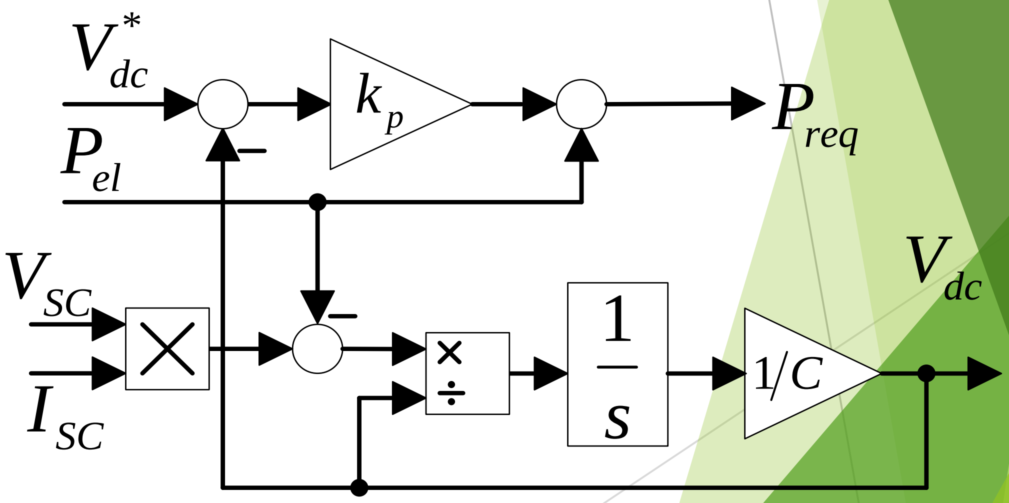
- The actual DC link voltage:

$$V_{dc} = \frac{1}{C} \int i_{dc} dt$$

- The DC link capacitor current:

$$i_{dc} = \frac{V_{SC} \cdot I_{SC} - P_{el}}{V_{dc}}$$

- Block Diagram



City Minibus Structure

D. Transmission Model

- Considered through the loading torque

$$T_{Load} = F_r \cdot \frac{v_b}{3,6 \cdot \omega_b} \cdot \frac{1}{\eta_{transmission}}$$

- The resistant force:

$$F_r = F_{af} + F_{rol} + F_{ramp}$$

- The aerodynamic force:

$$F_{af} = A_f \cdot c_f \cdot \left(v_{bus} + v_{wind}\right)^2$$

- The actual speed of the minibus:

$$v_{bus} = \omega \cdot \frac{v_b}{3,6 \cdot \omega_b}$$

- The rolling force:

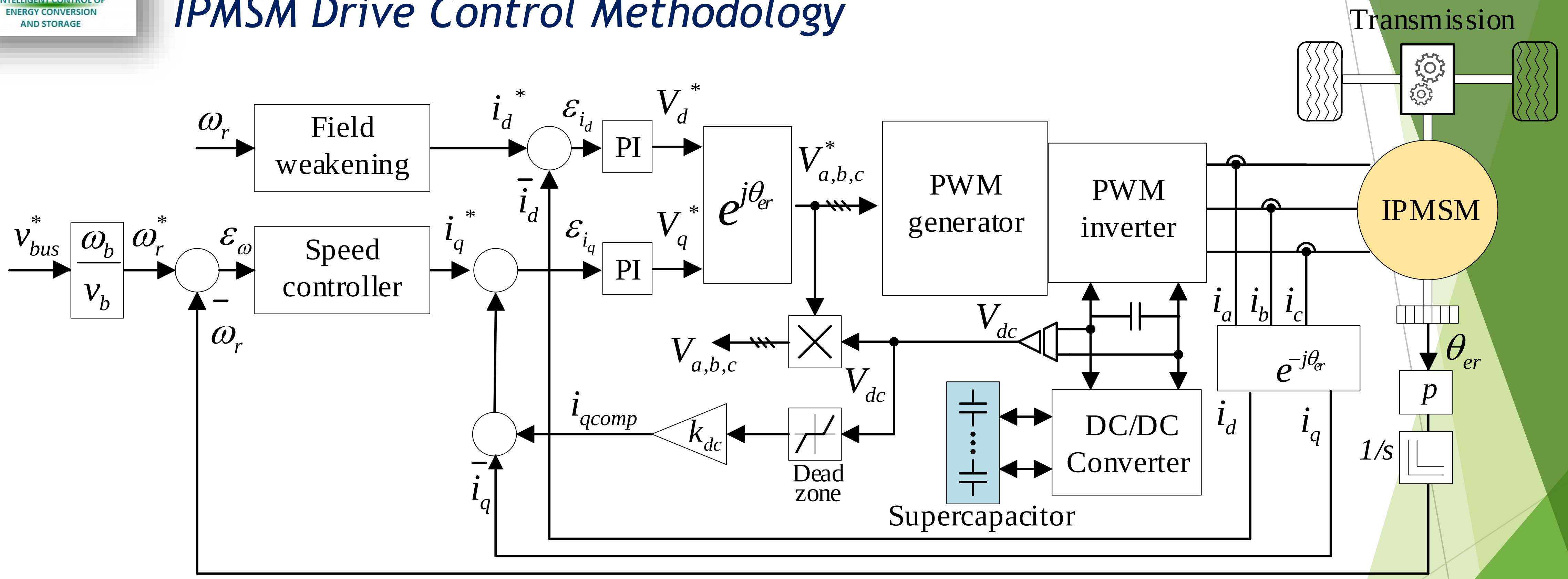
$$F_{rol} = m_t \cdot g \cdot c_r$$

- The rolling force:

$$F_{ramp} = g \cdot m_t \cdot \sin\left(\arctan(r_{\max})\right)$$

IPMSM Drive Control Methodology

IPMSM Drive Control Methodology



- Speed controller: $i_q^* = k_p \cdot sign(\varepsilon) \cdot \sqrt{|\varepsilon|} + \int k_i \cdot sign(\varepsilon) dt$
- Field weakening: $i_d^* = \left(\frac{\omega_b}{|\omega|} - 1 \right) \cdot 0.75 \cdot \frac{\psi_{PM}}{L_d}$

Propulsion System Simulation Results

Urban transportation => Maximum speed 72 km/h

- IPMSM designed to meet the speed and torque conditions considering:
  - Acceleration up to 1.1 m/s^2
  - full load
  - 5 m/s wind speed
  - 0% road slope
  - 140% load current for the inverter

Parameters		***IPMSM Scale***		***Unit***
		1:1	***1:20***	
Rated power	P_N	100	5	kW
Line voltage	V_N	430	400	V
Rated current	I_N	162	9.7	A
Rated base speed	n_b	2400	2400	rpm
Rated base frequency	f_b	240	240	Hz
Stator phase resistance	R_s	18.36	1	Ω
d-axis inductance	L_d	0.216	8.6	mH
q-axis inductance	L_q	0.339	8.5	mH
PM flux	Ψ_{PM}	0.1885	0.1556	Wb
Efficiency	η	0.96	0.85	-
Pole pairs	p_1	6	6	-

Propulsion System Simulation Results

The amount of energy stored in SC ≈ 8.52kWh

Determined based on:

- - 6.2 km length driving cycle
- - 5 intermediate stops
- - 17.1 m/s wind speed
- - 200m of 10% road slope
- - weight of 7t
- - running speeds: 30, 50 and 70 km/h
- - 2.5 kWh auxiliary energy consumption
- - discharge limit of the SC up to 25%
- - time limit of 1 minute for full charging

Rated voltage of the DC link: 600V

SC module voltage: 480V

- existing SC module at 240V
- Conversion ratio of the DC/DC converter

Supercapacitor Cells and Module Parameters

Parameters	*Value*		*Unit*
	SC cell	*SC Module*	
Rated voltage	2.85	480	V
Rated capacitance	3200	266	F
DC 10ms ESR rated	0.14	1.69	m Ω
Energy	3.6	8512	Wh
Specific energy	6.8	6.8	Wh/kg
Mass	0.53	1254	Kg

Propulsion System Simulation Results

Two sets of simulation results

- normal operation
- operation in case of a DC/DC converter failure

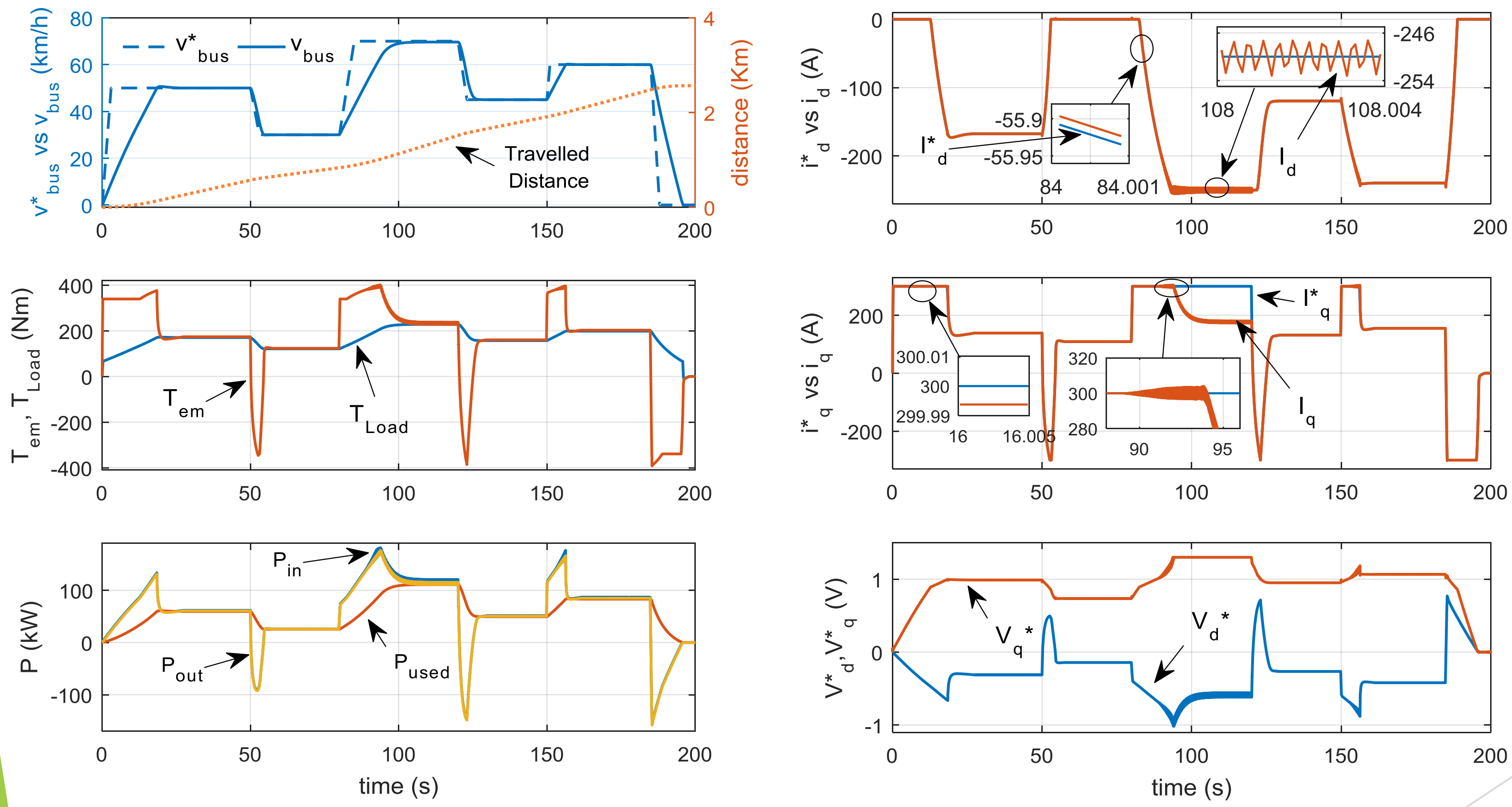
For both cases were considered:

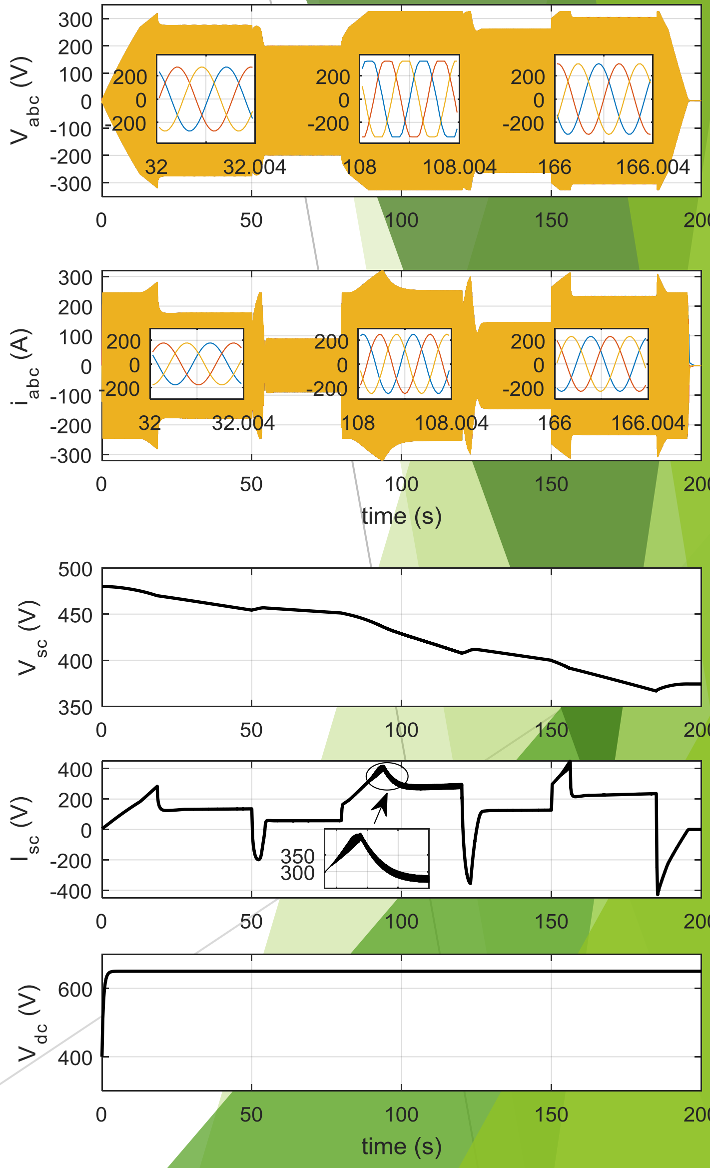
- 17.1 m/s wind speed
- the minibus at full load, 7 tones
- 0% road ramp
- 0.8 air friction coefficient
- 0.007 rolling friction coefficient
- 10mF internal DC/DC converter capacitor
- 400V initial voltage level of the DC Link

Propulsion System Simulation Results

Normal operation

- The SC module initially fully charged: V_{SC} = *480V*

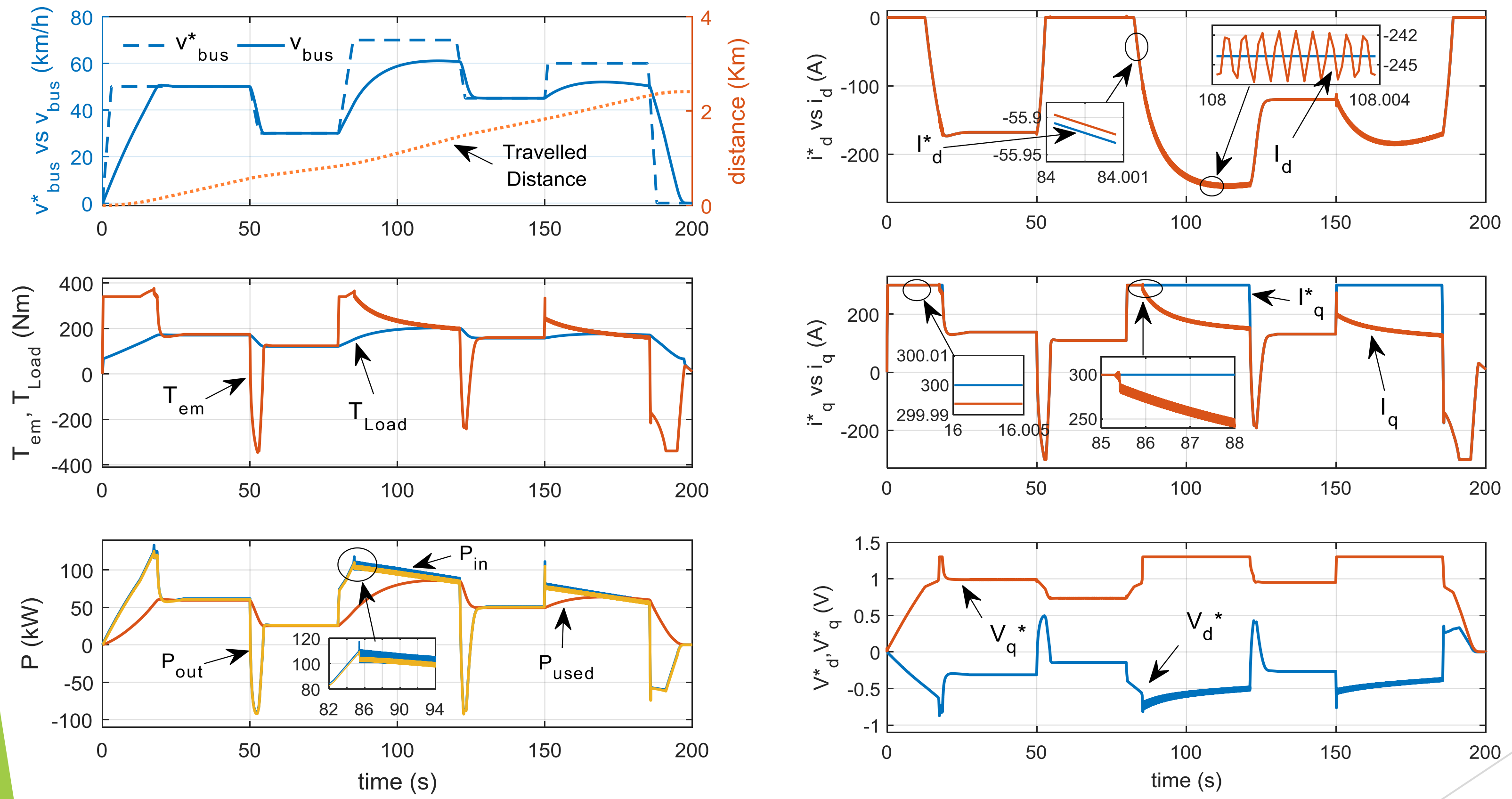


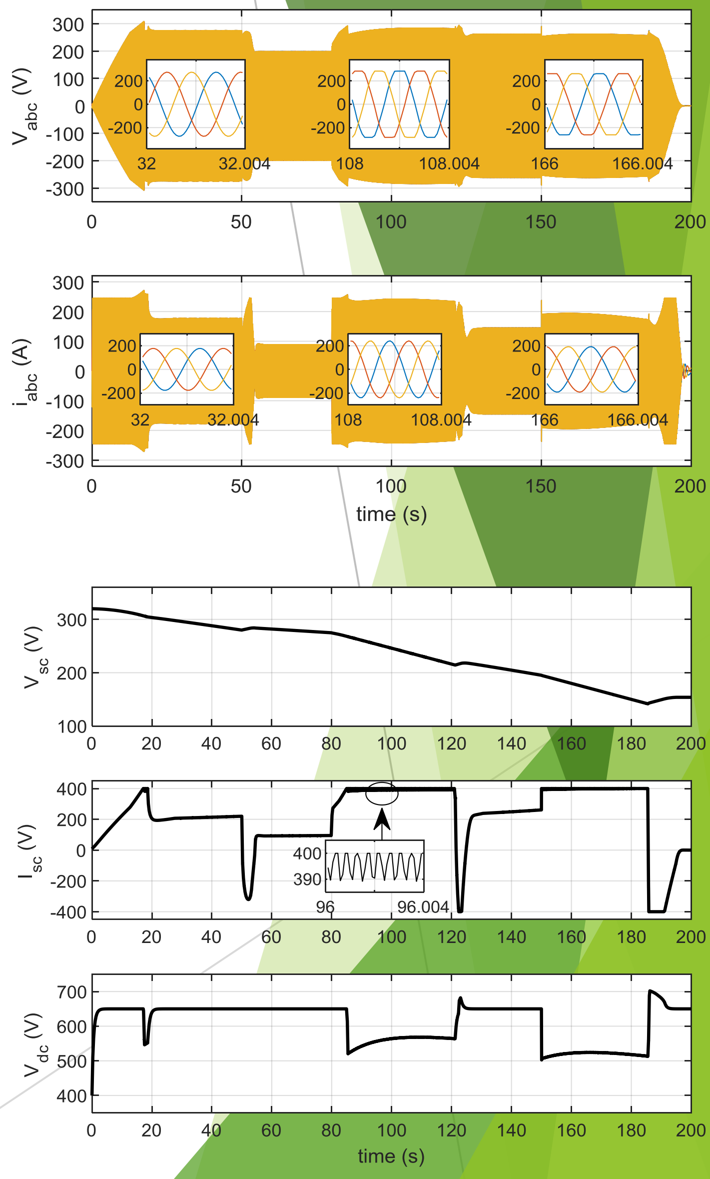


Propulsion System Simulation Results

Operation in case of a DC/DC converter failure

- The SC module initially discharged at 45% (V_{SC} = 320V)
- Limited current to 25% (I_{SC} = 400A)

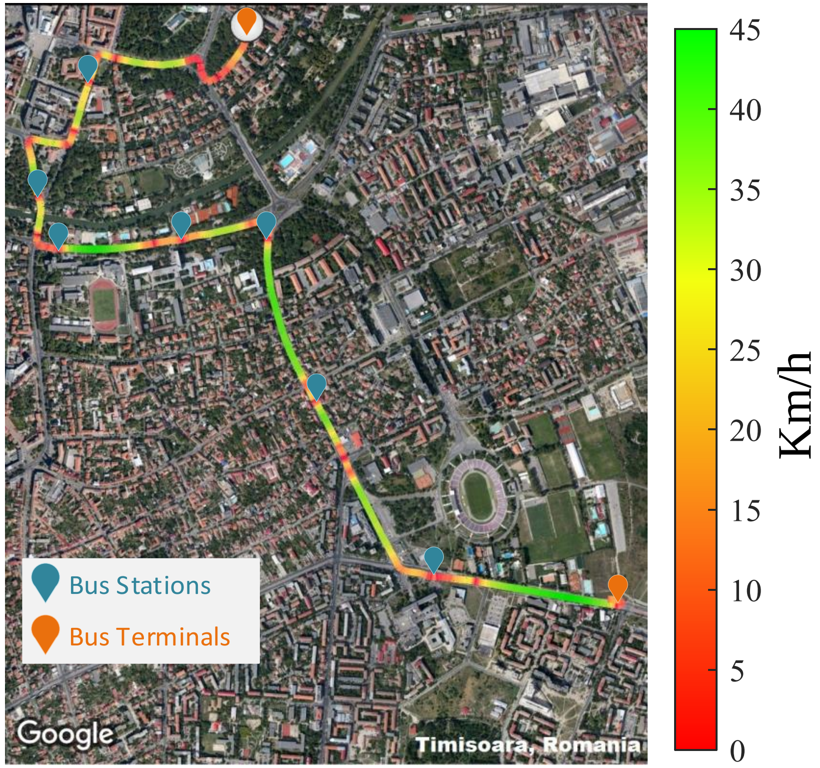




Case Study – Simulation in Real Traffic Conditions

Timisoara (Romania) bus line 16

- length: 4.26km
- 7 intermediate bus stops
- operated by a trolleybus



Timisoara (Romania) bus line 16 (Map data 2021 Google)

Acquisition of the bus speed profile and reduction of the measurement errors

- Several android smartphones
- dedicated race application
  - GPS location
  - x, y, z-axis accelerometer sensor
  - the delay between location updates
- the data were:
  - interpolated and indexed (time step of 50ms)
  - acquired on a sunny day

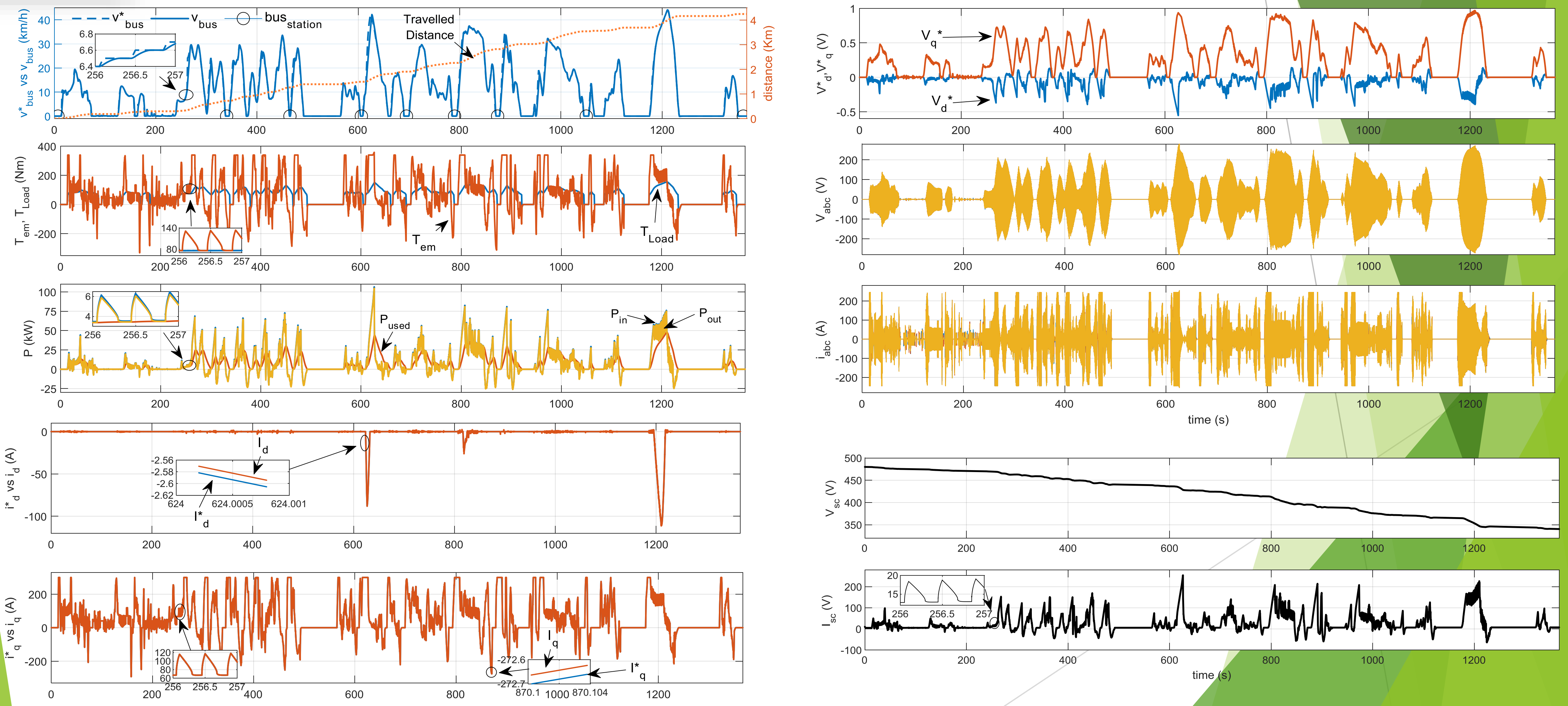
- Wind speed less than 1 m/s
- The passenger load ≈ 30% (due to pandemic situation)
- Road ramp ≈ 0% (Timisoara is in the Western Plains)

Case Study – Simulation in Real Traffic Conditions

Simulation results

- *Unfavorable conditions were considered*

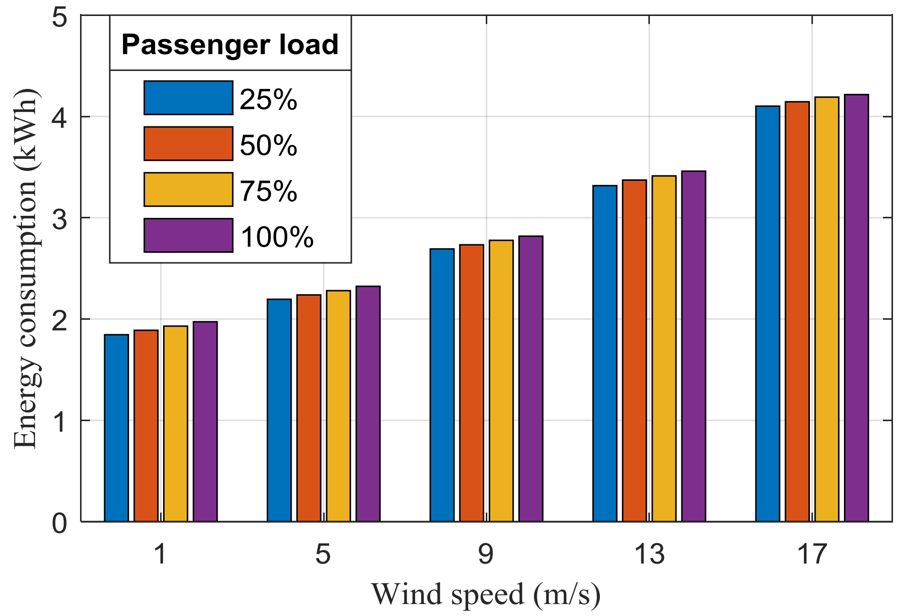
wind speed: 17m/s
passenger load: 100%



Case Study – Simulation in Real Traffic Conditions

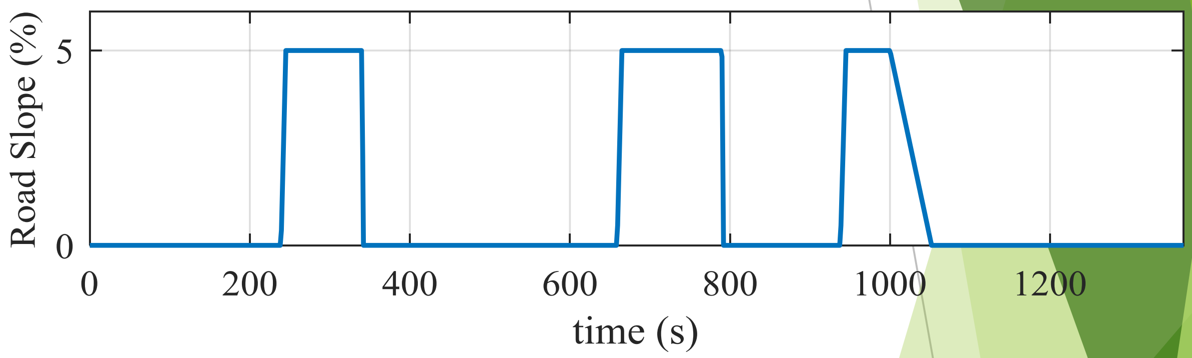
Analysis of the minibus energy consumption

- Varying conditions:
  - passengers load
  - wind speed



- Storage capacity reduction
  - up to ≈ 6kWh (190F SC module)
  - - 300kg => 4 more passengers

Considering the next road slope profile



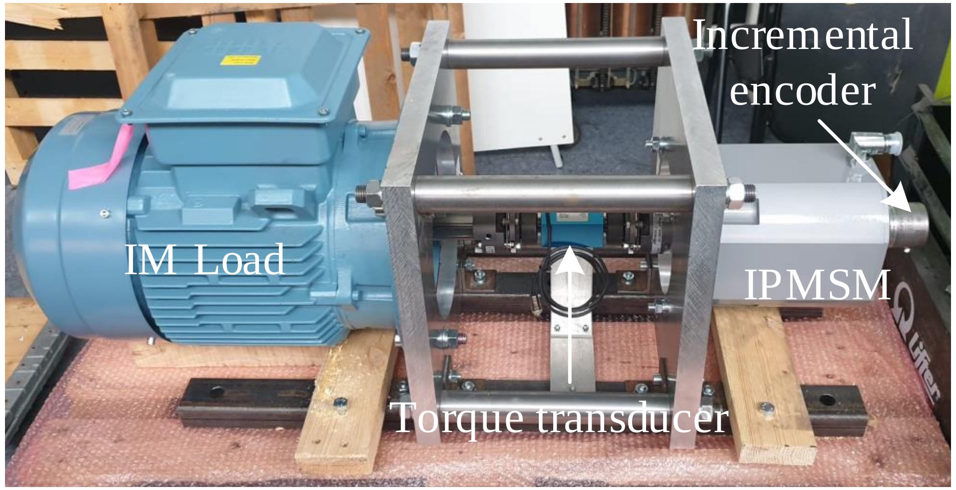
and increasing the auxiliary energy consumption to 5kWh

⇩

The total energy consumption ≈ 6.3 kWh

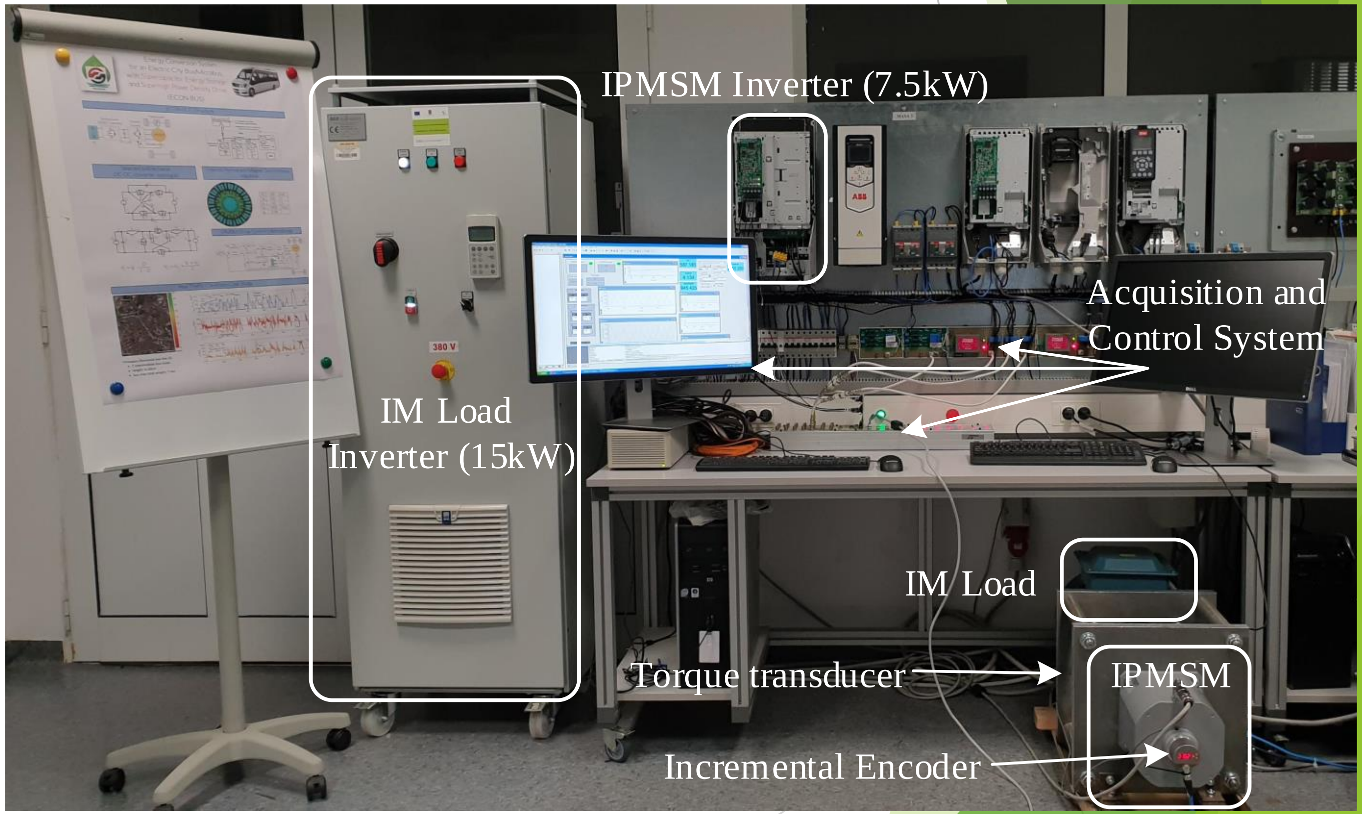
Preliminary Experimental Results

- IPMSM Prototype



- Scale 1:20
- 5kW, 2400rpm base speed, 20Nm

- Experimental Platform



Preliminary Experimental Results

- Motion-induced voltages compensation

$$V_d^* = \left(k_p \cdot \varepsilon_{i_d} + k_i \int \varepsilon_{i_d} dt\right) + V_{d0}$$

$$V_q^* = \left(k_p \cdot \varepsilon_{i_q} + k_i \int \varepsilon_{i_q} dt\right) + V_{q0}$$

$$V_{d0} = -\omega_r \cdot L_q \cdot i_q, \quad V_{q0} = \omega_r \cdot \left(\psi_{PM} + L_d \cdot i_d\right)$$

- Simplified supertwisting sliding mode regulator

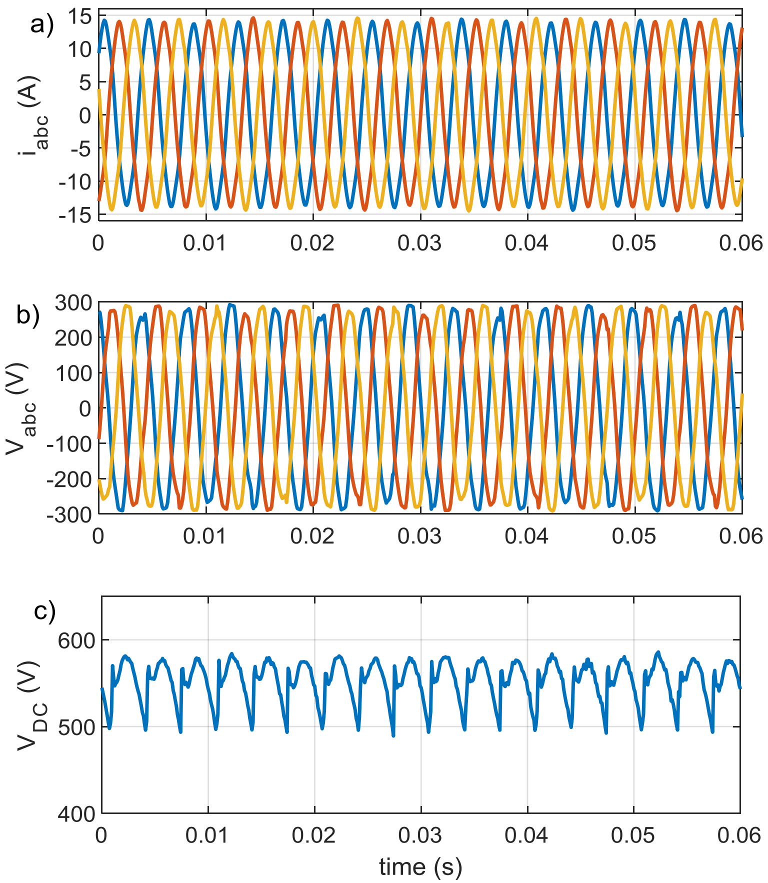
$$i_q^* = k_p \cdot \varepsilon + \int k_i \cdot sign(\varepsilon) dt$$

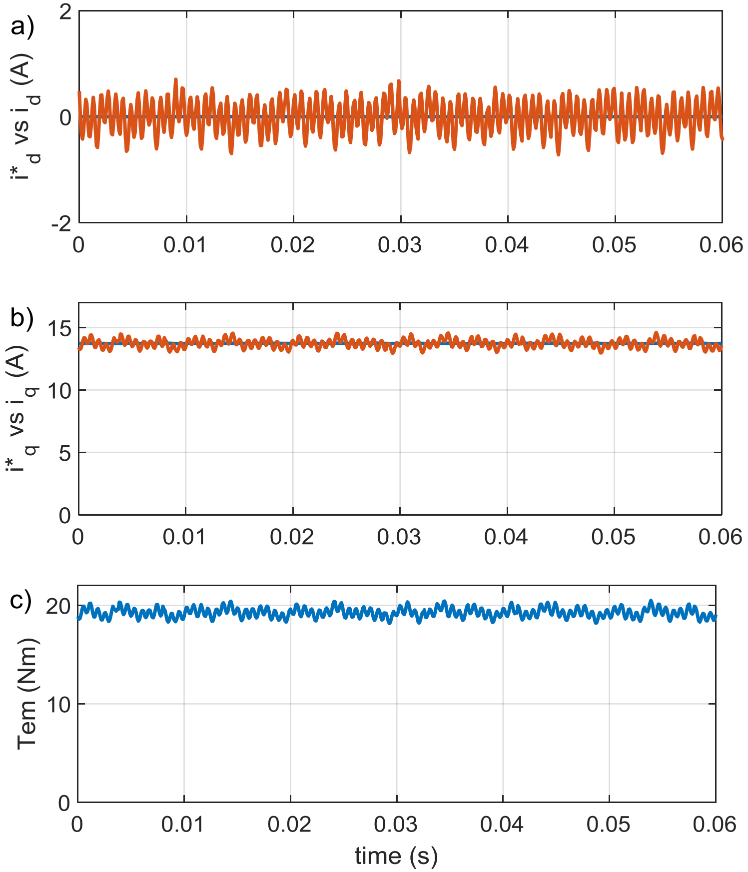
- Limiting the power generated by the IPMSM during braking periods
- Saturation of the input d- and q-axis current errors (~10%)

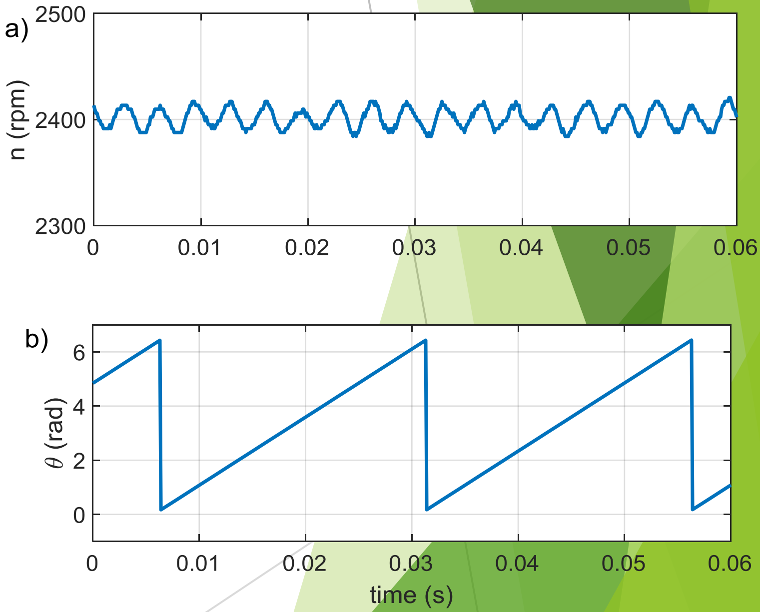
Preliminary Experimental Results

Operation of the IPMSM for

- 2400rpm base speed reference
- Full load 20Nm



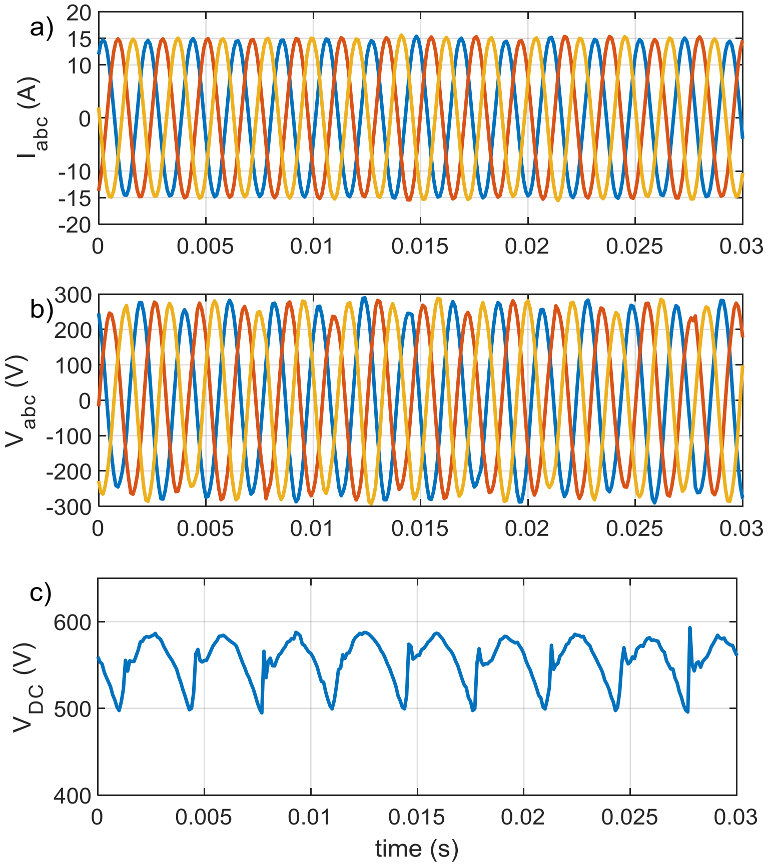


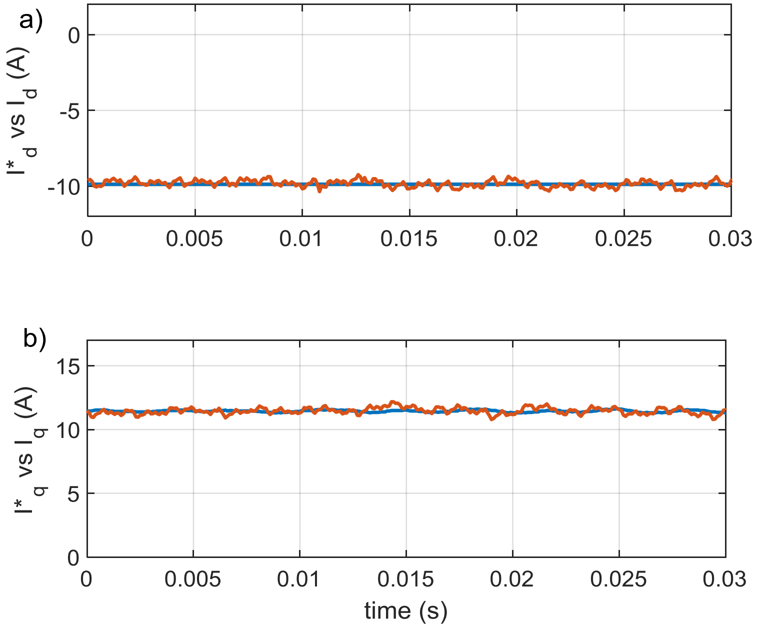


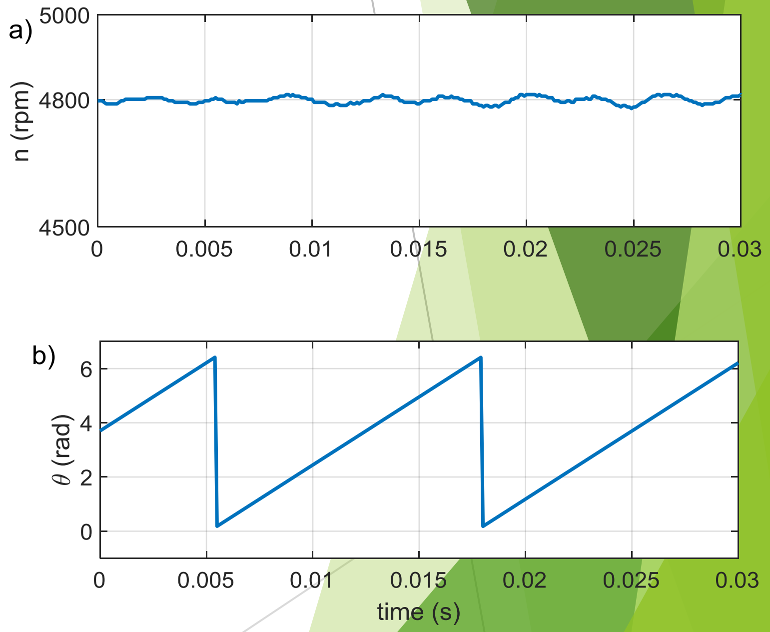
Preliminary Experimental Results

Operation of the IPMSM for

- 4800rpm base speed reference
- Load 10Nm







Preliminary Experimental Results

Operation of the IPMSM for
- Variable speed reference
- Variable loading torque computed by the plc