Twin Fabrica Software

Fast losses eMachine calculation

NEWTWEN

Twin Fabrica

Newtwen at a glance

Founded: **2020**

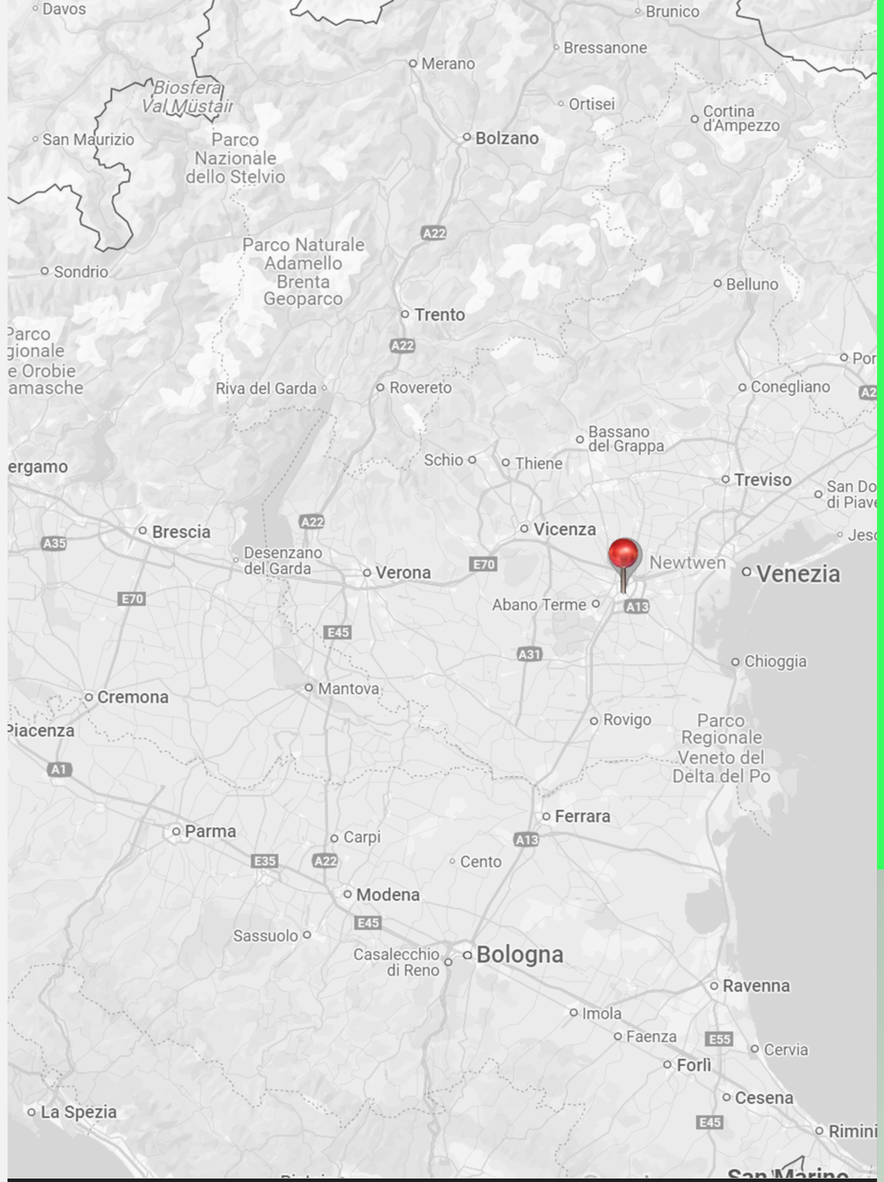
Headquarter: **Padova, Italy**

Value proposition: **ePowertrain thermal management and control strategies optimization**

Our expertise:

- **Multiphysics simulation**
- **Embedded system control**
- **Software development**
- **AI/ML research and development**

Our product: **Software Engineering platform for building embedded-grade virtual thermal sensors**

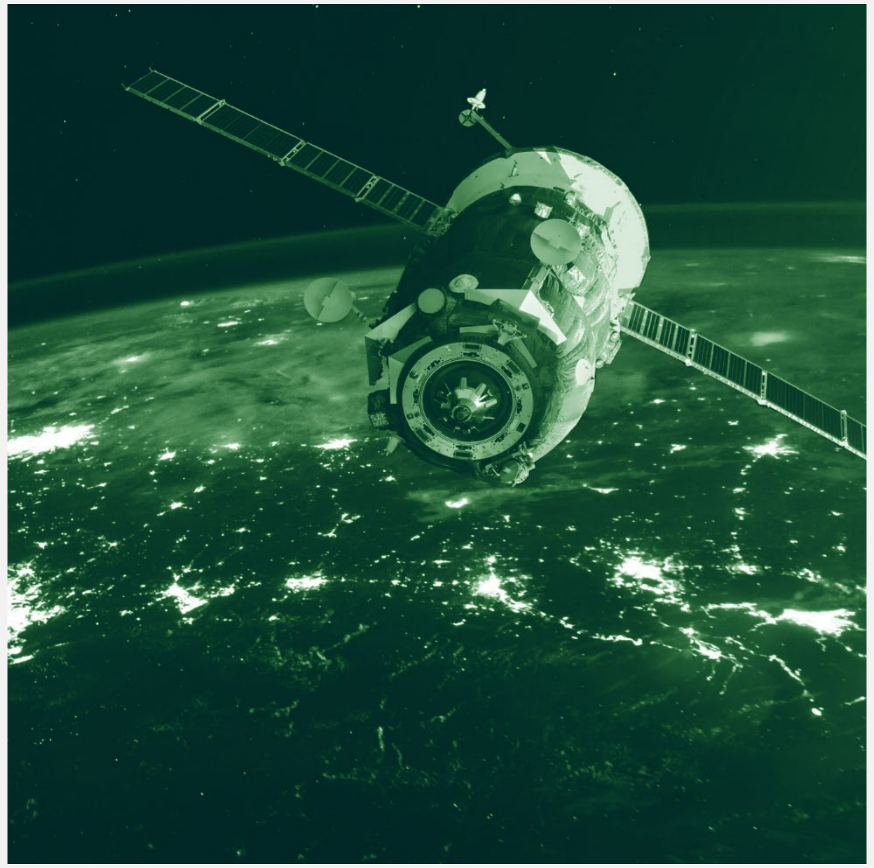


Challenges

- Inaccessible thermal hotspots in electrical and electronic components
- Limitations of traditional sensors and conventional software tools
- Long simulation times and high costs of traditional simulation environments
- Insufficient temperature accuracy for effective control and derating strategies
- Existing software requires deep expertise and lacks scalability
- High computational demand for integrating real-time models on microcontrollers
- Need to overdesign components, leading to increased material costs and sub-optimal performance

Vertical Application

Automotive



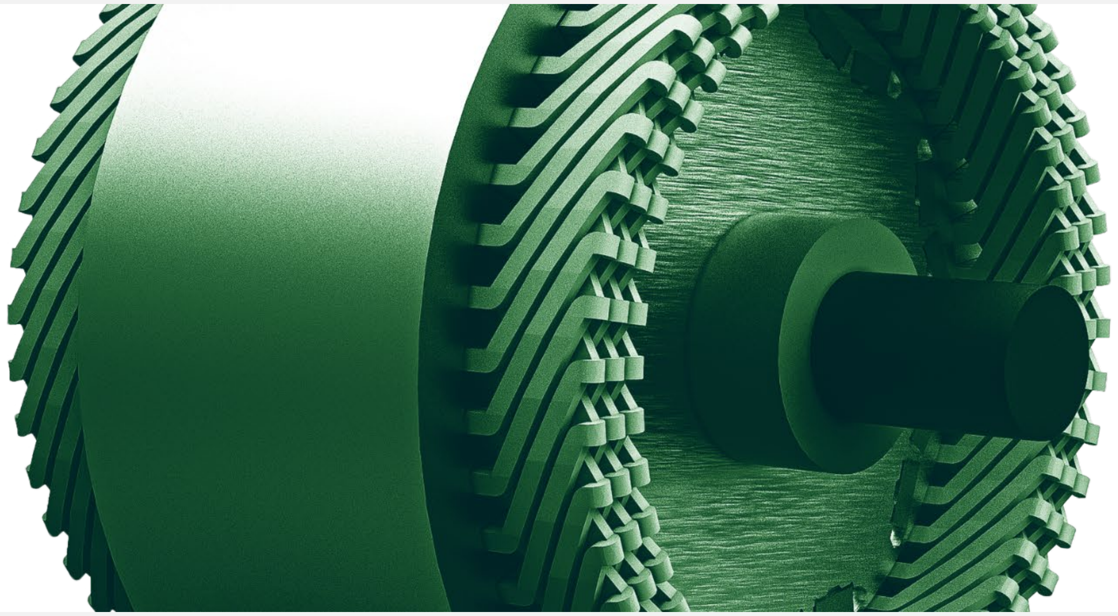
Aerospace

Datacenter

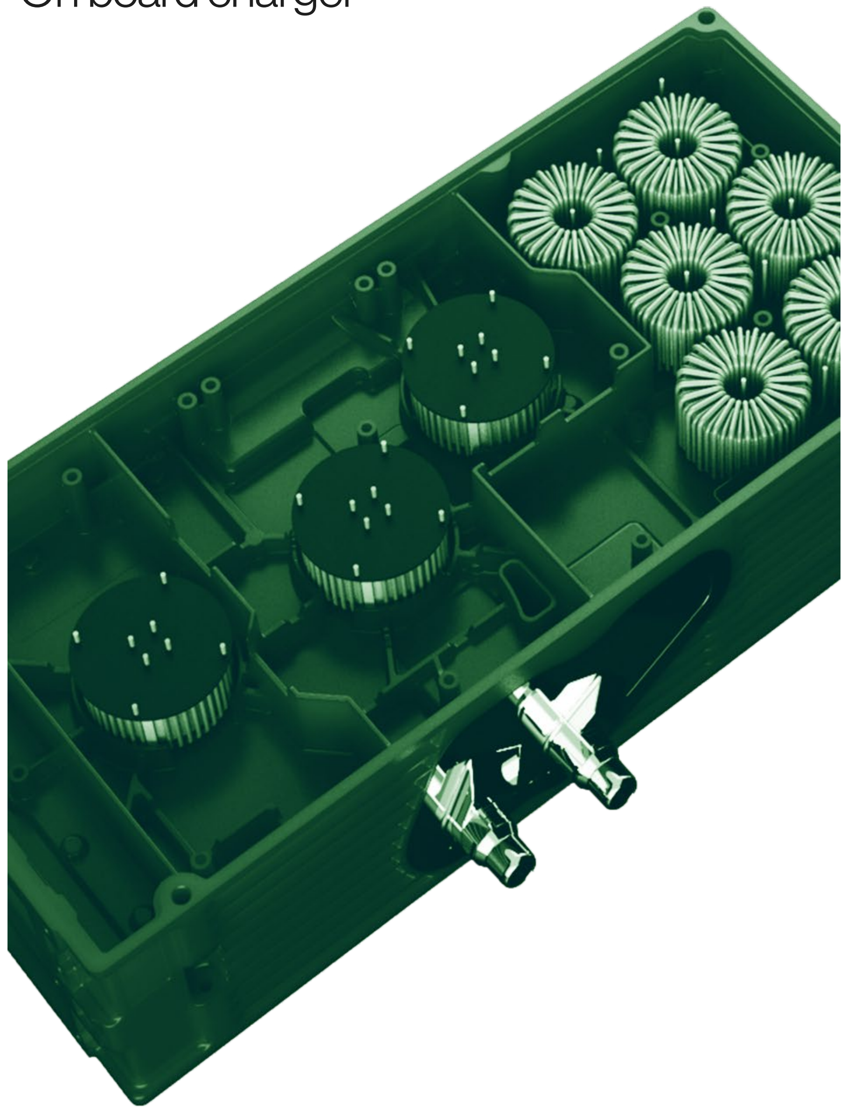
Renewable energy

Virtual Thermal Sensing use cases

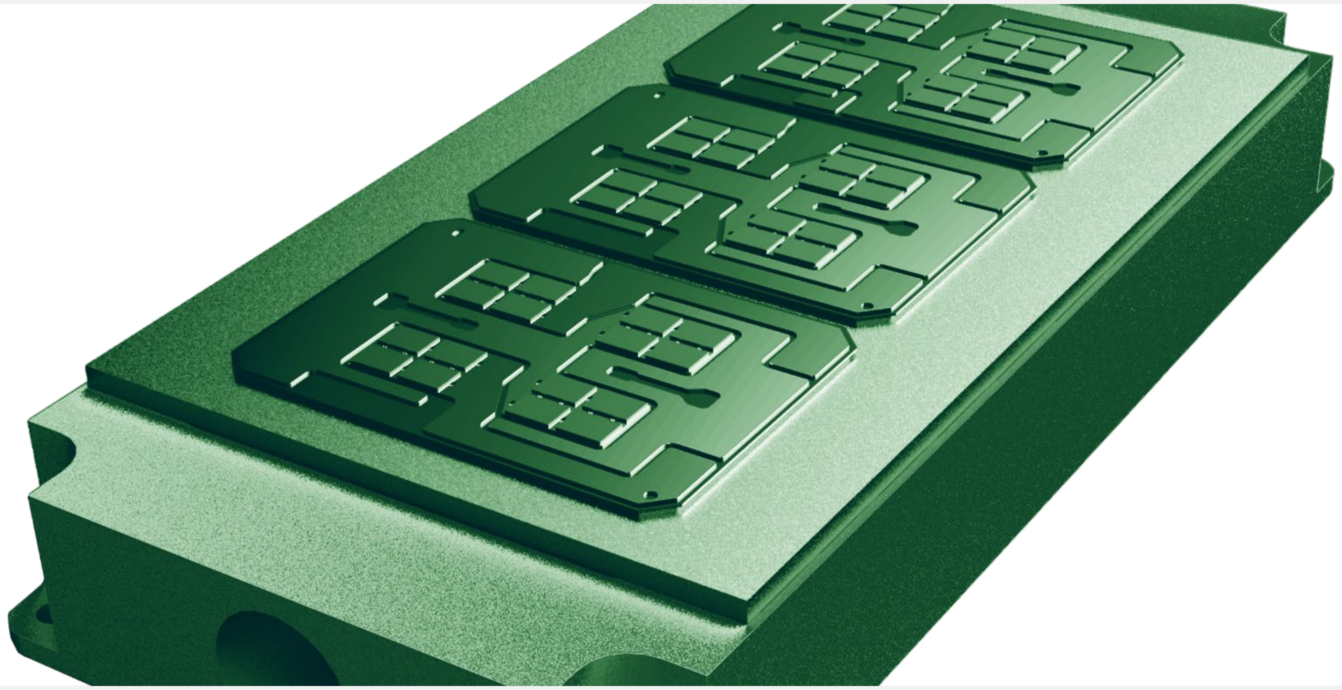
E-motors



On board charger



Inverter

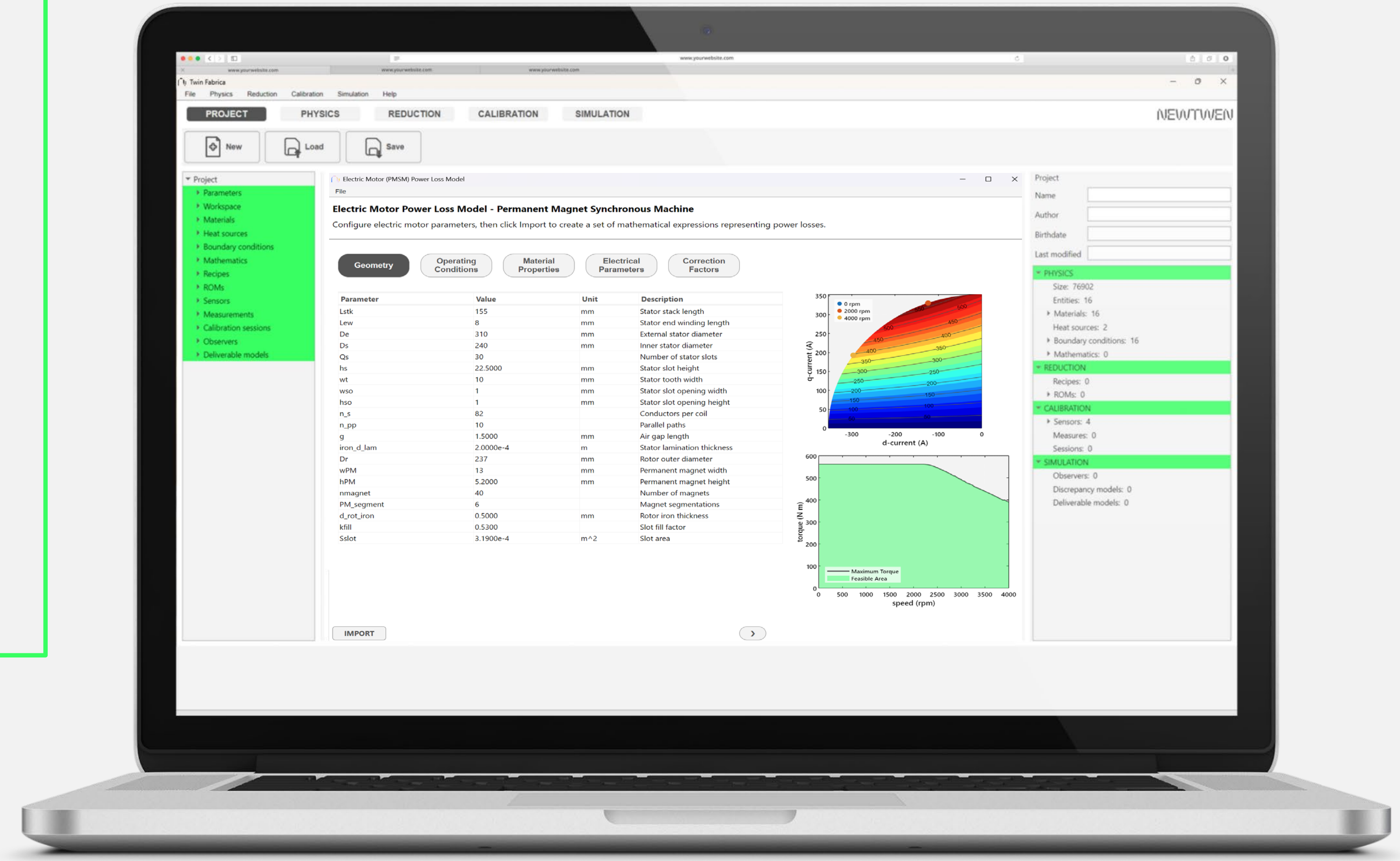


And more

Twin Fabrica

An all-in-one solution that bridges the gap between complex thermal simulations and real-world applications

- End-to-end thermal modelling workflow from CAD to embedded code.
- Power loss model: construction (if unavailable) or adoption (if available).
- Nonlinear parametric Model Order Reduction (MOR).
- Physics-based model calibration using experimental data.
- Automatic estimation of unknown thermal properties.
- AI-enhanced discrepancy model for unmodeled dynamics.
- Flexible virtual sensor definition and placement.
- White box export to Simulink, embedded C code, or state-space models.



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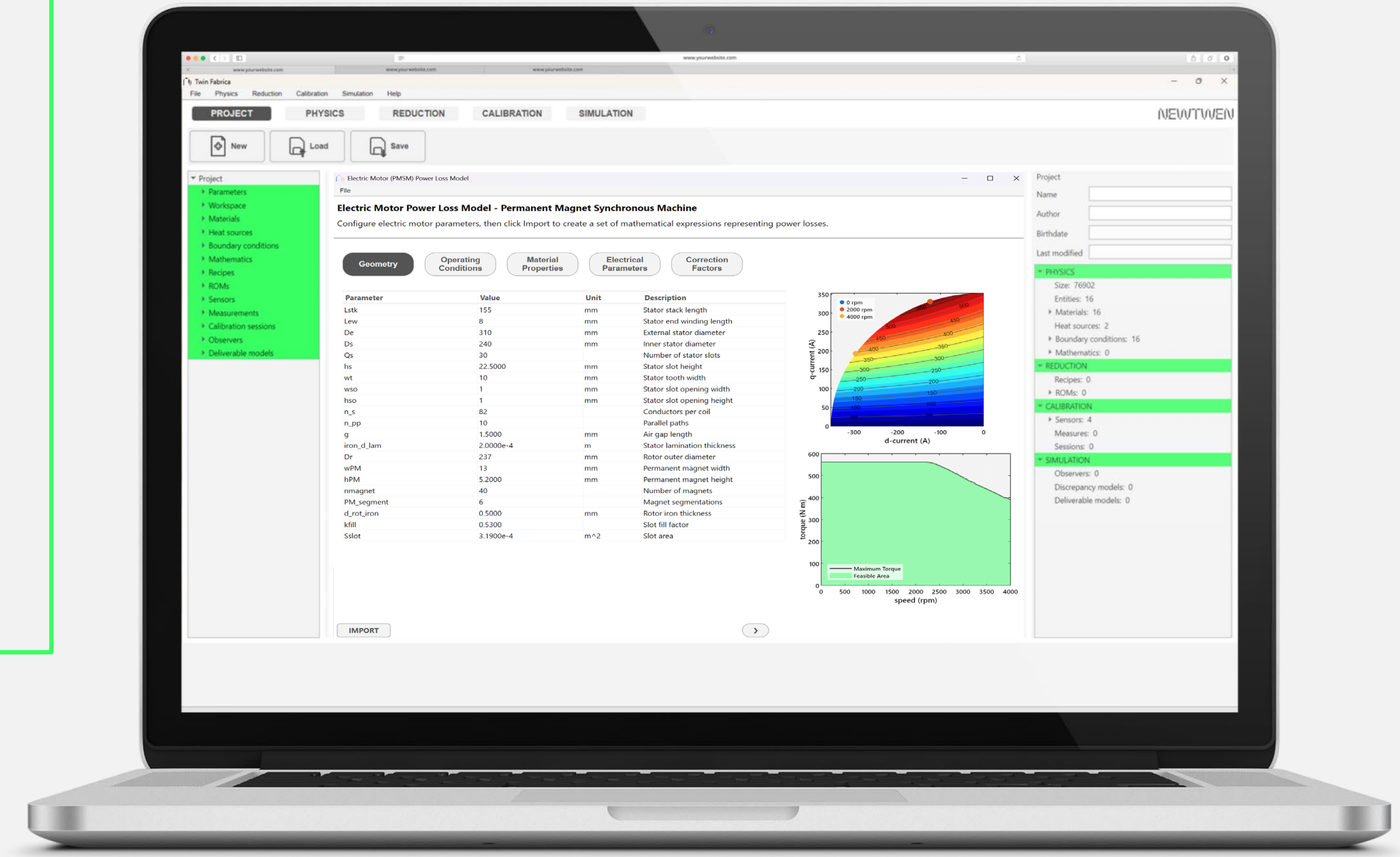


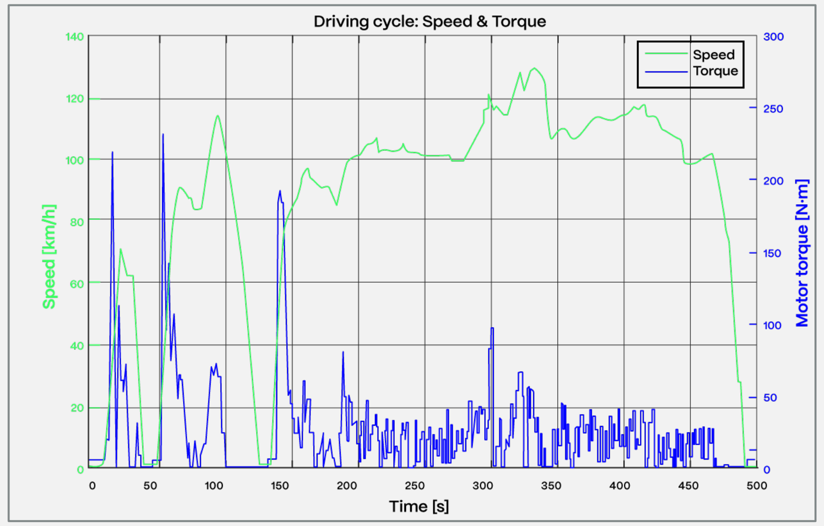
Where and how accurate losses model can be crucial?

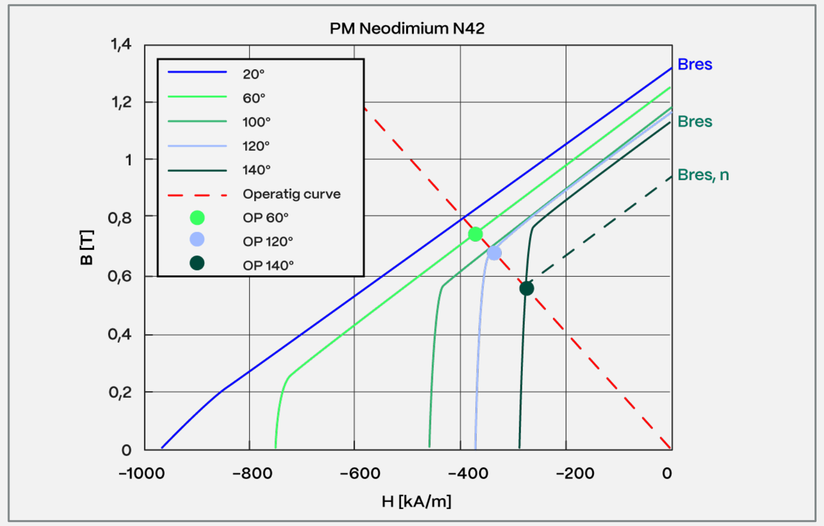
In many application where:

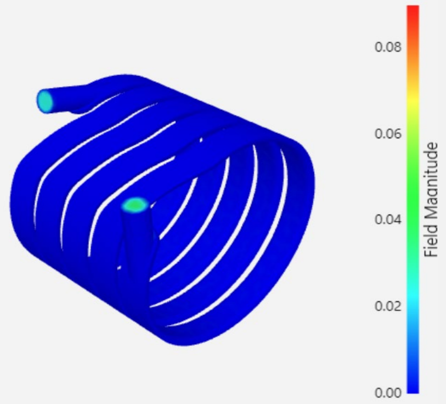
- eMotor **design are oversized**
- eMotor **control strategies**

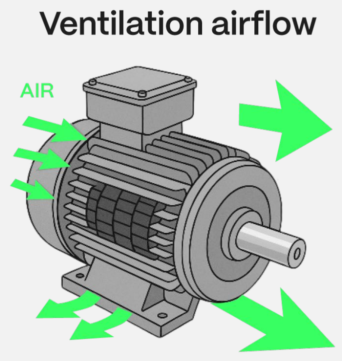
The main reasons are:

- Unknown driving cycle
- Cooling and ambient temperature variation according to external condition
- Air or fluid flowrate variation
- Losses variation with temperature variation, in particular with the Permanent Magnet (PM)



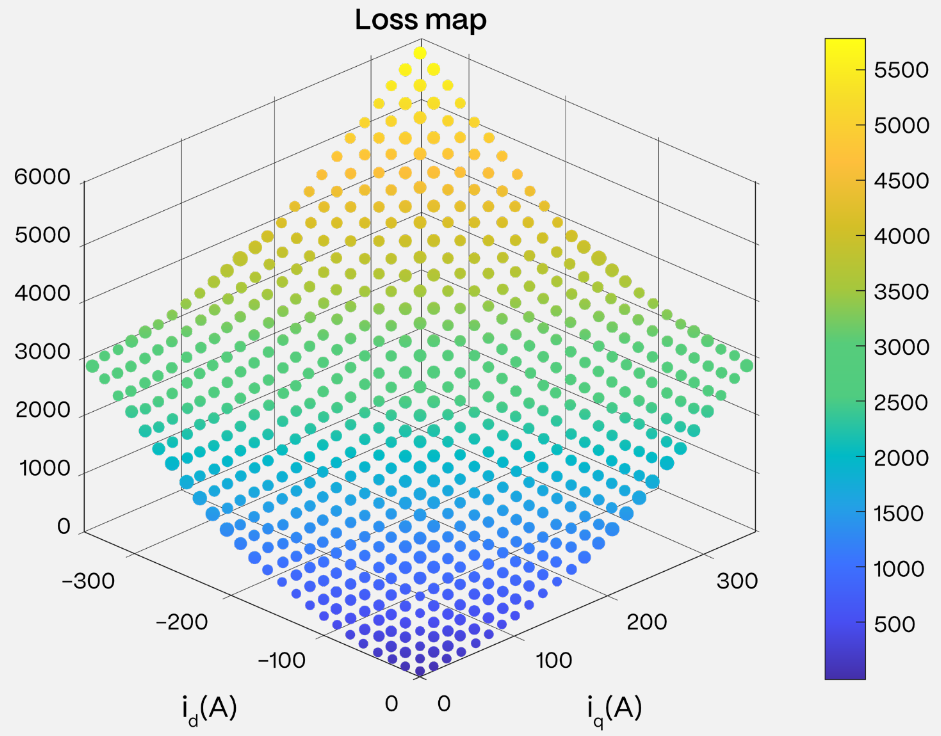






Power loss model

LUT:



✅ Good rated points accuracy before testing

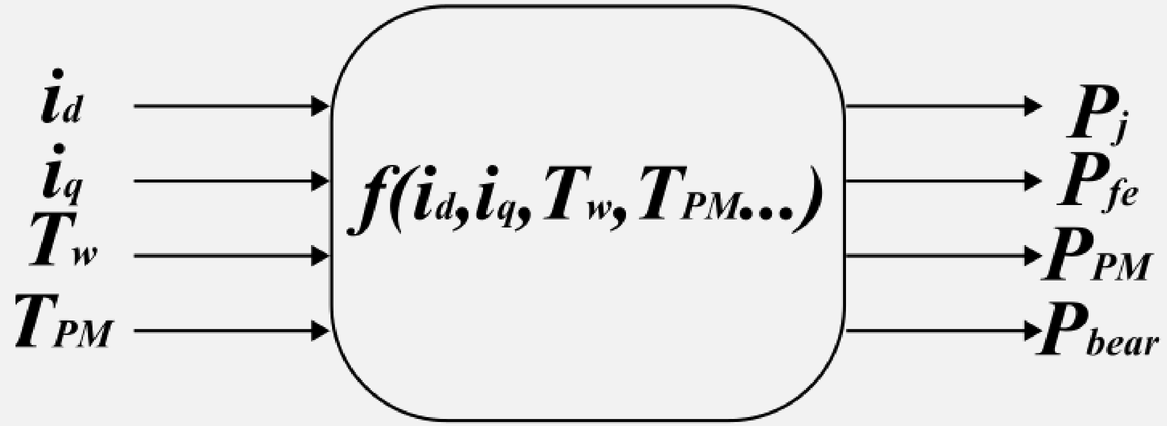
❌ Very expensive in time and cost to be built

❌ Low flexibility to be tuned with real sample

❌ Not optimal fitting after sampling

❌ Inaccurate torque, losses and efficiency estimation and higher memory weight

Analytical functions:



❌ Smaller rated points accuracy compared to LUT

✅ Small effort in time building and cost

✅ Very high flexibility to be tuned with real sample,

✅ Optimal fitting after sampling in torque, losses and efficiency estimation

✅ Very small memory weight, fast task execution in the microcontroller

Power losses components

Losses considered:

Types of losses evaluated:

- Stator Joule losses (Including AC leakage flux losses in the slot)
- Stator iron losses (Steinmetz equation)
- Rotor iron losses (Eddy current formulation for solid pole shoes)
- Permanent Magnet losses correlated to stator MMF and PWM harmonics
- Bearing losses (empirical formulation)

Advantages of the model:

- Flexible and tunable to experimental data.
- Reduced simulation complexity and computation time.
- Provides a practical link between motor physical effects and thermal behavior

Parameter for losses building:

Parameter	Symbol	Unit
Stator stack length	L_{stk}	mm
End winding length	(L_{ew})	mm
Outer diameter stator	D_e	mm
Diameter at airgap	D_s	mm
Number of stator slots	Q_s	–
Slot height	h_s	mm
Tooth width	w_t	mm
Slot opening width	w_{so}	mm
Slot opening height	h_{so}	mm
Slot surface	S_{slot}	mm^2
Slot filling factor	k_{slot}	–
Conductors per slot	n_s	mm
Parallel paths	n_{pp}	–
Airgap length	g	mm
Rotor shaft diameter	D_{sh}	mm
PM width	w_{PM}	mm
PM height	h_{PM}	mm

Parameter	Symbol	Unit
Direct axis current	I_d	A
Quadrature current	I_q	A
DC voltage	V_{dc}	V
Motor speed	n_{RPM}	rpm
Direct inductance	L_d	mH
Quadrature inductance	L_q	mH
Inductance ratio	L	–
PM flux	Φ_{PM}	V·s
Number of pole pairs	p	–
Switching frequency	f_{sw}	Hz
Current limit	I_{lim}	A
Winding temperature	$T_{winding}$	°C
PM temperature	T_{PM}	°C
Ambient temperature	T_{amb}	°C

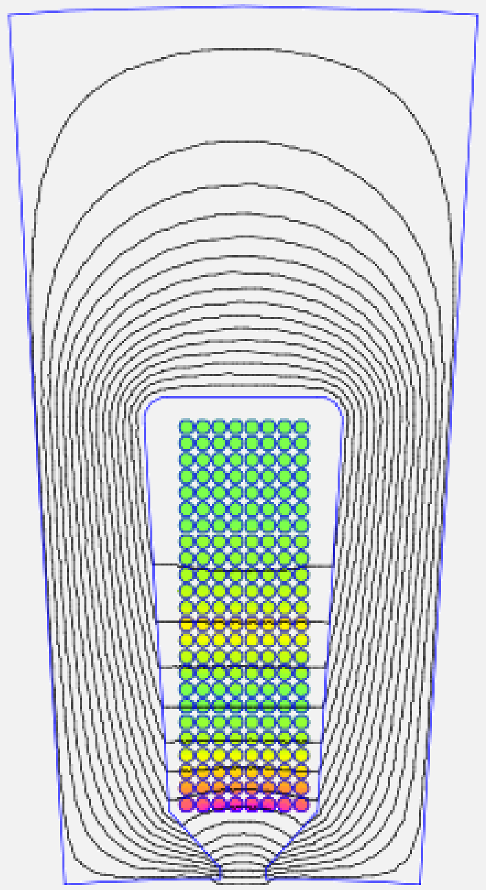
Power losses components

Joule losses are computed as:

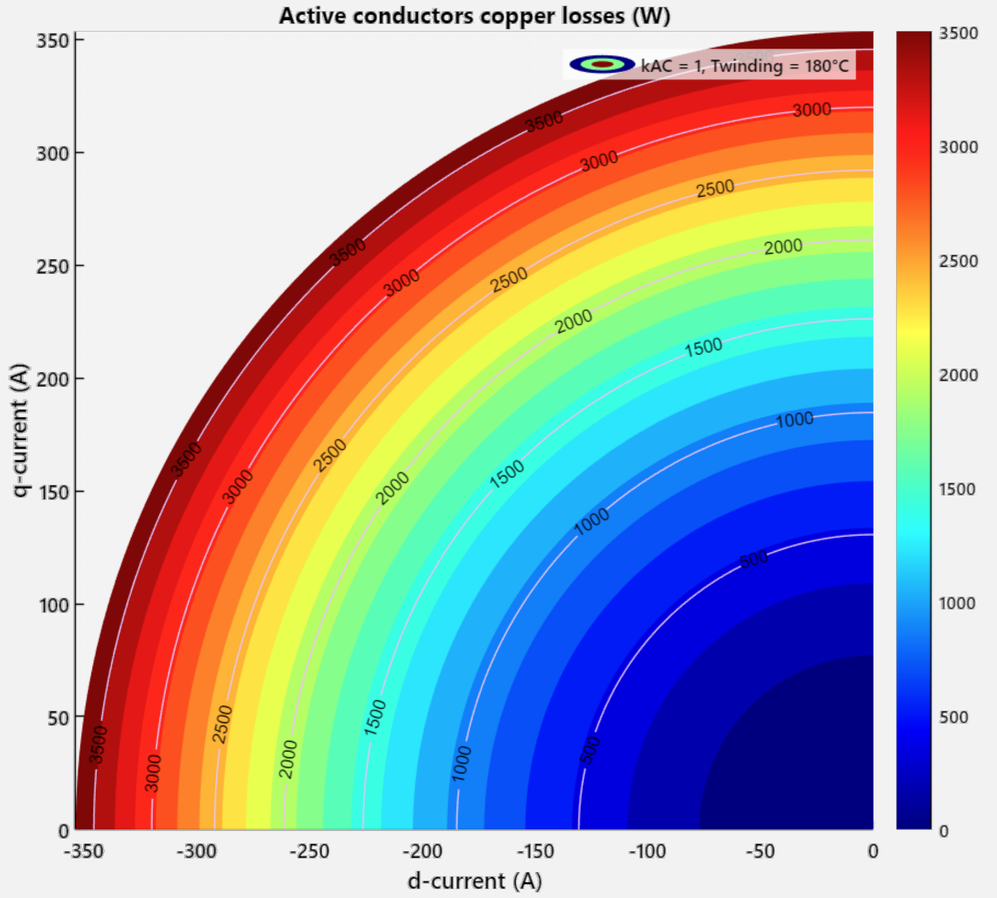
- $P_{js,DC} = \rho_{Cu} J^2_{RMS} V_{Cu}$
- ρ_{Cu} : Temperature-dependent copper resistivity
- J_{RMS} : RMS current density
- V_{Cu} : Volume of copper winding
- Losses increase with both current density and copper resistivity.
- Base reference for evaluating DC Joule losses before adding AC effects.

$P_{js,AC} = k_{AC}\, k_{increase} P_{js,DC}$ where: $k_{increase}(\delta, n_c, \rho_{Cu}, \ldots)$

k_{AC} is tunable parameter



AC losses in a slot



Joule losses distribution

Power losses components

Stator Iron losses are computed:

Starting from stator steel data sheet:

NO20-1200H Data sheet

thin non-oriented electrical steel

Typical specific total loss

J_{peak} (T)	Typical specific total loss (W/kg)								
	50 Hz	100 Hz	200 Hz	400 Hz	700 Hz	1000 Hz	2500 Hz	5000 Hz	10000 Hz
0.1	0.02	0.03	0.07	0.16	0.37	0.64	2.57	8.17	24.3
0.2	0.06	0.12	0.27	0.66	1.45	2.42	9.61	28.4	83.8
0.3	0.11	0.25	0.57	1.39	3.03	5.06	20.0	58.3	172
0.4	0.18	0.40	0.93	2.31	5.04	8.38	33.1	96.9	287
0.5	0.25	0.57	1.36	3.41	7.41	12.4	49.1	145	432
0.6	0.34	0.76	1.85	4.64	10.2	17.1	67.7	201	
0.7	0.44	0.98	2.38	6.05	13.3	22.4	89.3	268	
0.8	0.54	1.23	2.97	7.60	16.8	28.3	114	347	
0.9	0.66	1.50	3.63	9.32	20.6	35.0	142	441	
1.0	0.80	1.81	4.37	11.2	24.9	42.4	175		
1.1	0.96	2.16	5.22	13.4	29.7	50.7	212		
1.2	1.15	2.59	6.24	16.1	35.3	60.2	256		
1.3	1.40	3.13	7.47	19.6	42.0	71.5	307		
1.4	1.69	3.83	9.09	23.5	50.4	85.7	368		
1.5	2.02	4.53	10.8	28.0	59.9	102			
1.6	2.33	5.19	12.2	31.9	68.9	117			
1.7	2.60	5.75							
1.8	2.91	6.37							
1.9	3.32	7.21							

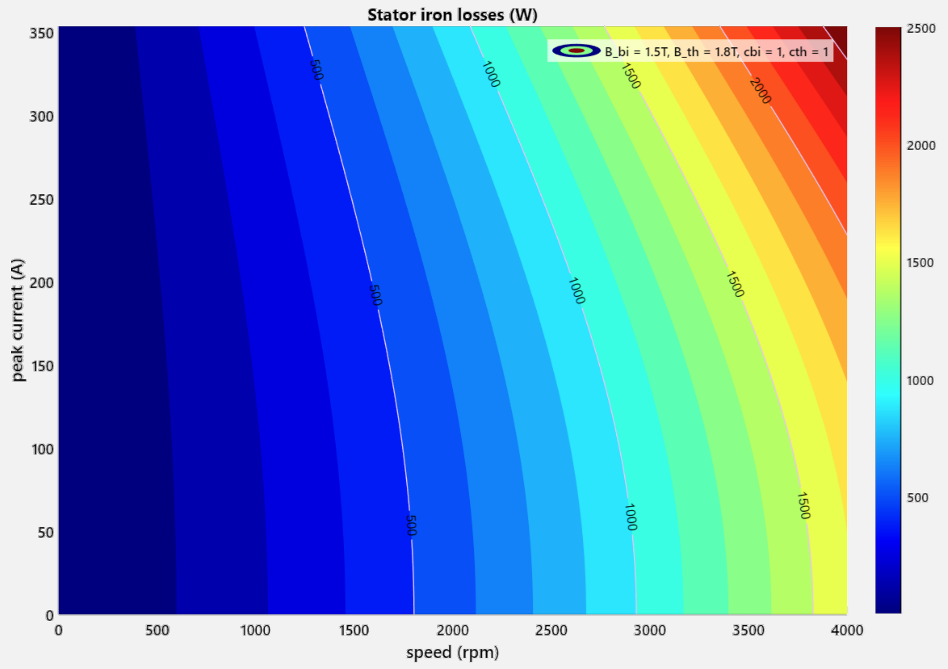
According to Steinmetz equation the specific core losses are:

$$p_{th} = \left(k_{hyst}\frac{f_e}{f_{ref}} + k_{ec}\left(\frac{f_e}{f_{ref}}\right)^2\right)\left(\frac{B_{th}(\mathrm{I})}{B_{ref}}\right)^{\alpha} p_{fe,ref}$$

$$p_{\mathrm{bi}} = \left(k_{hyst}\frac{f_e}{f_{ref}} + k_{ec}\left(\frac{f_e}{f_{ref}}\right)^2\right)\left(\frac{B_{\mathrm{bi}}(\mathrm{I})}{B_{ref}}\right)^{\alpha} p_{fe,ref}$$

where: f_e is the actual frequency

B_{th}, B_{bi} *are the flux density* in teeth and back iron



Iron losses distribution

Then the final losses are:

$$P_{fe} = c_{th}\, p_{th}\, W_{th} + c_{bi}\, p_{bi}\, W_{bi}$$

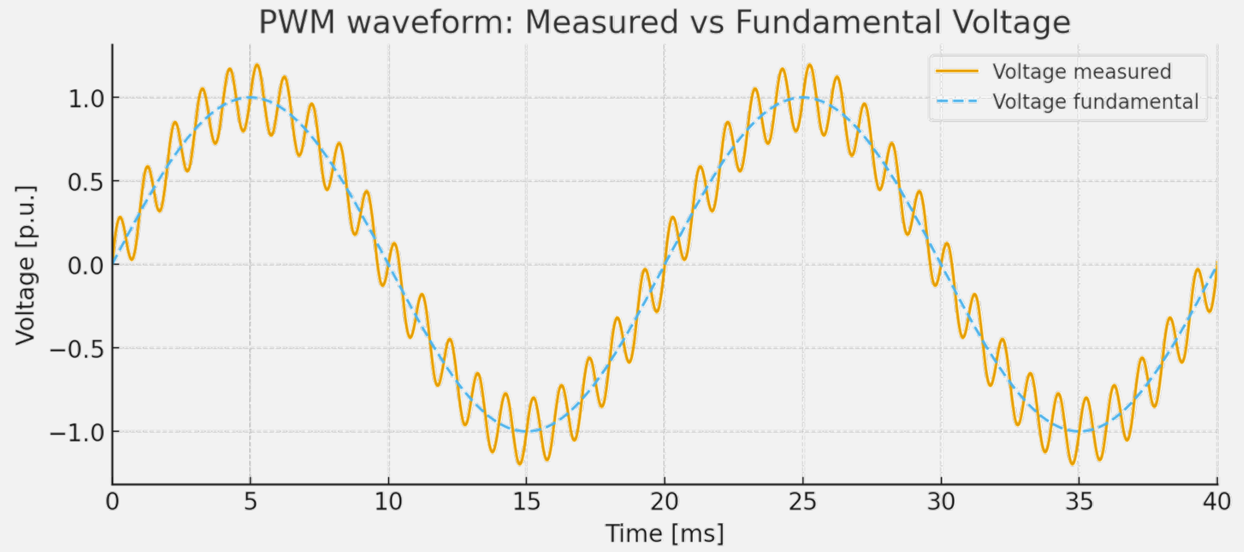
where: W_{th}, W_{bi} are teeth and back ironweight

k_{th}, k_{bi} are tunable parameter

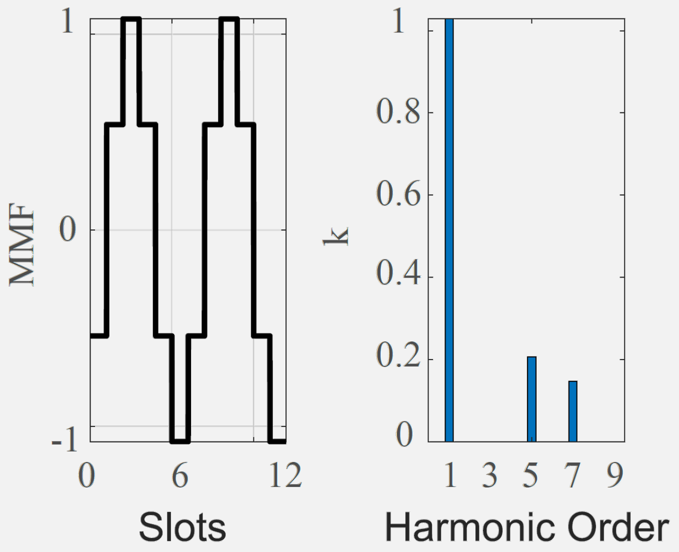
Power losses components

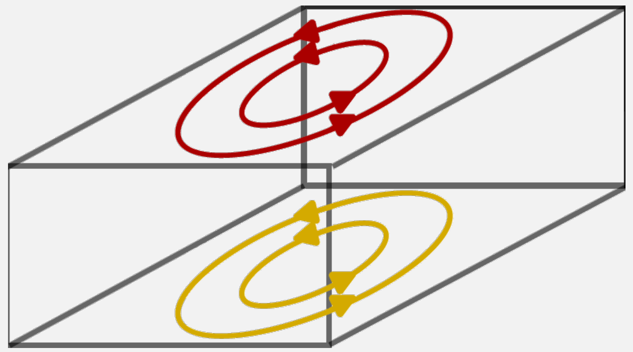
Permanent Magnet (PM) Losses are related with:

- **PWM Harmonic Losses:** switching harmonics from the inverter.



- **MMF Harmonic Losses:** spatial harmonics from slotting and winding distribution





- **Both induce:**
  - **Eddy currents in PMs**
  - Reduced motor efficiency
  - PMs Demagnetization
  - Extra heat generation

Power losses components

Permanent Magnet (PM) Losses are:

$$P_{\mathrm{PM}} = \sum_{\mathrm{h}=\mathrm{h}_{\mathrm{x},1}}^{\mathrm{h}_{\mathrm{x,end}}} c_{h,\mathrm{x}} \frac{e_{PM,h,\mathrm{x}}^2}{R_{PM,\mathrm{h,x}}}$$

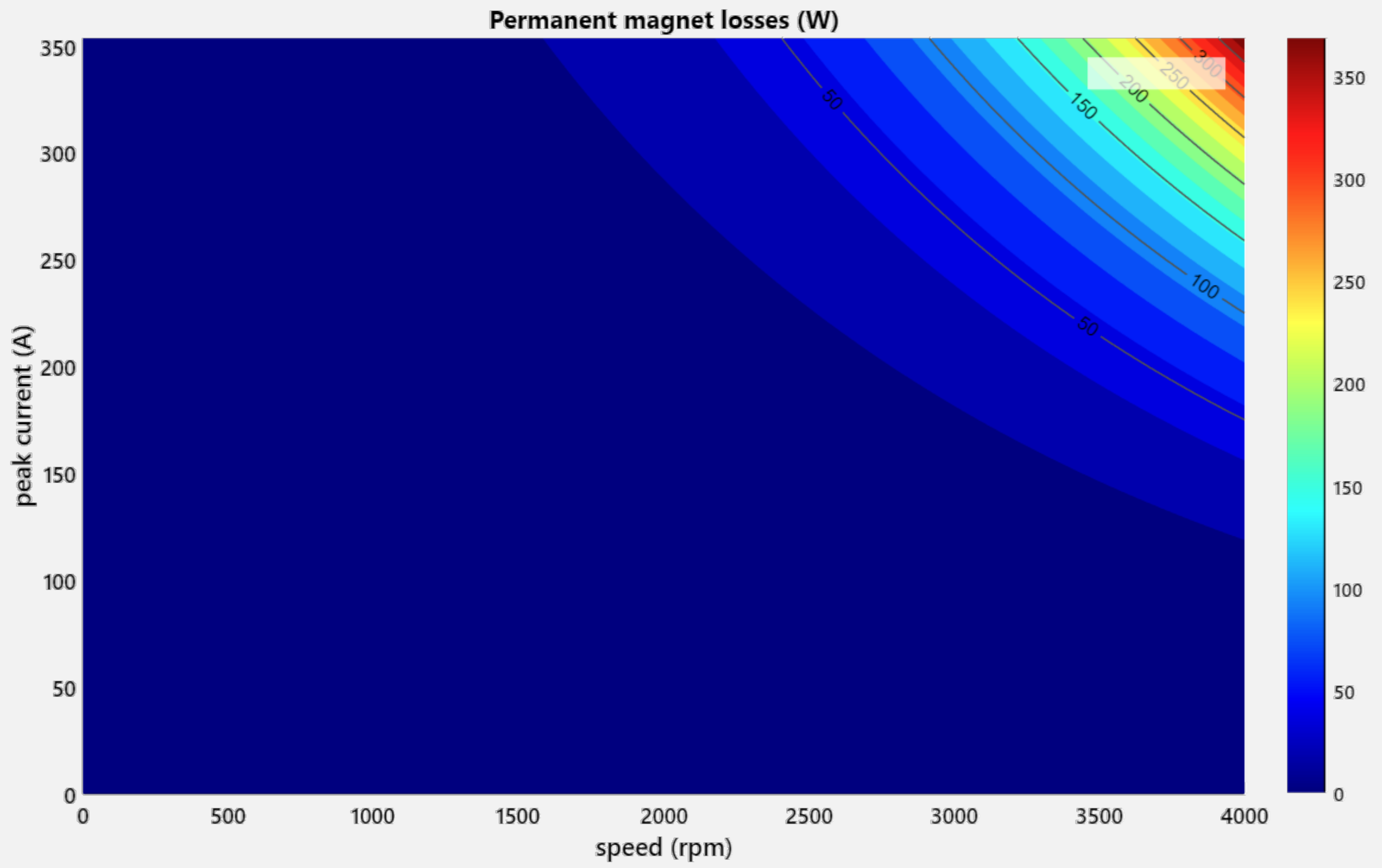
where: h is the PWM or MMF harmonic order

$_{\mathrm{x}}$ is PWM or MMF

$e_{PM,h,\mathrm{x}}$ is the voltage induced on the magnets

$R_{PM,\mathrm{h,x}}$ is the equivalent resistance of the corresponding hamonic

$c_{h,\mathrm{x}}$ is tunable coefficient of the corresponding hamonic



PM losses distribution

Power losses components

Rotor Iron losses are:

$$P_{\mathrm{fe,rot}} = \sum_{\mathrm{h}=\mathrm{h}_{\mathrm{x,1}}}^{\mathrm{h}_{\mathrm{x,end}}} c_{h,\mathrm{x}} \frac{e_{\mathrm{fe},h,\mathrm{x}}^2}{R_{\mathrm{fe,h,x}}}$$

where: h   is the PWM or MMF harmonic order

$_{\mathrm{x}}$ is PWM or MMF

$e_{PM,h,\mathrm{x}}$ is the voltage induced on the magnets

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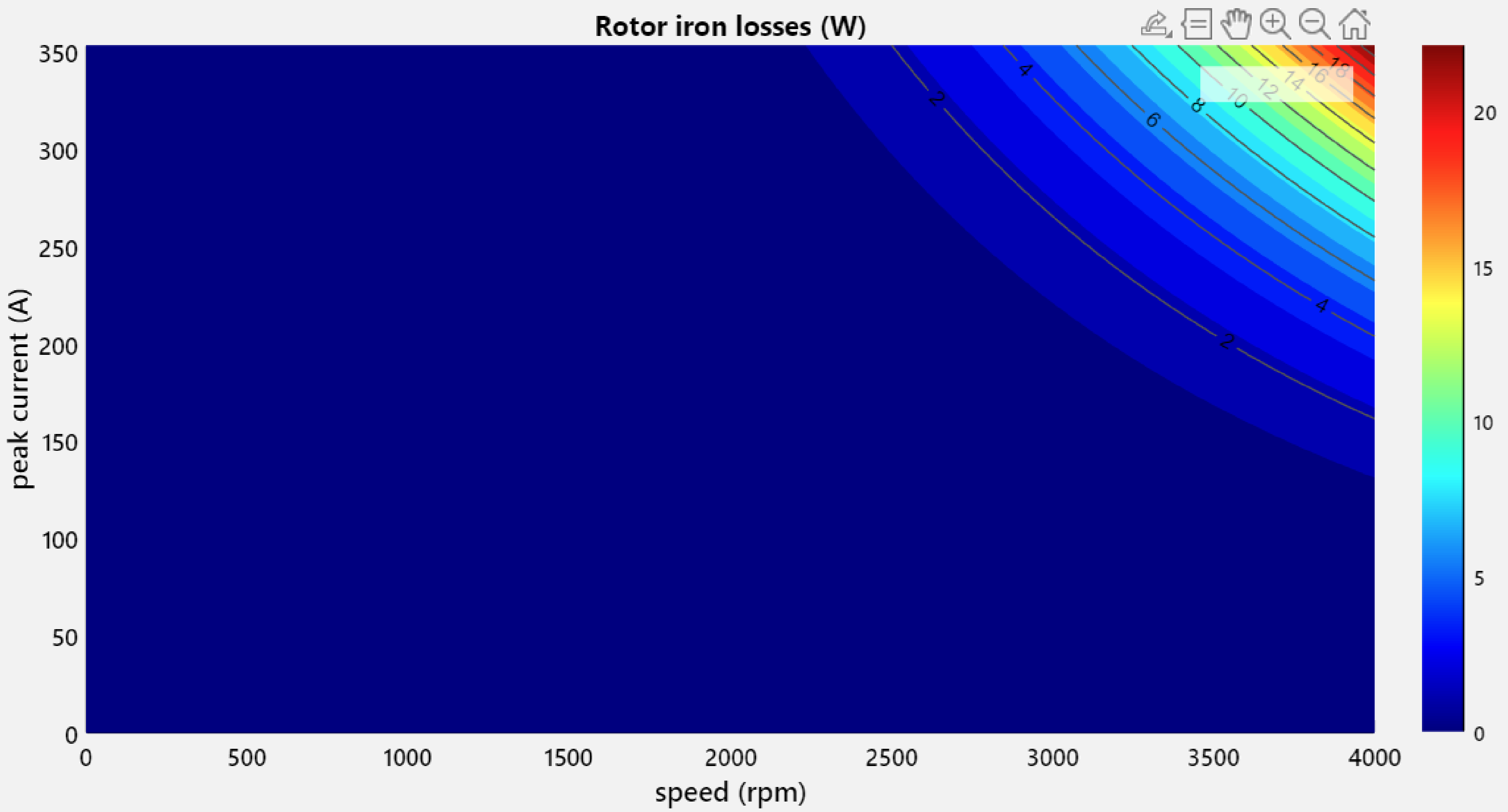


Rotor Iron losses distribution

Power losses components

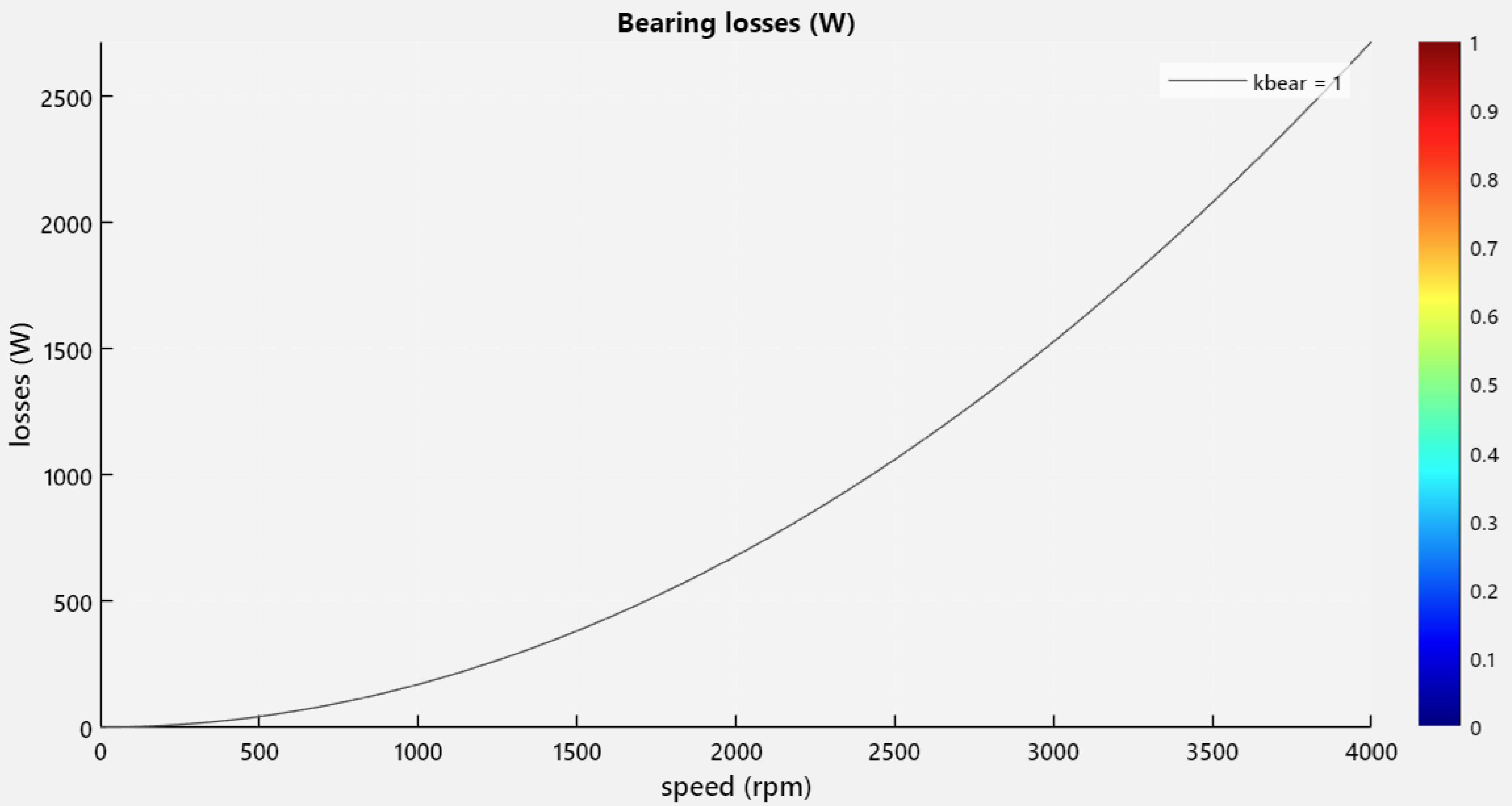
Bearing losses are:

$$P_{bear} = k_{bear} \cdot D_r^3\, L_{stk} \left(\frac{2\pi n_{RPM}}{60}\right)^2$$

where: D_r is the rotor diameter

L_{stk} is axial length

n_{RPM} are revolution per minute

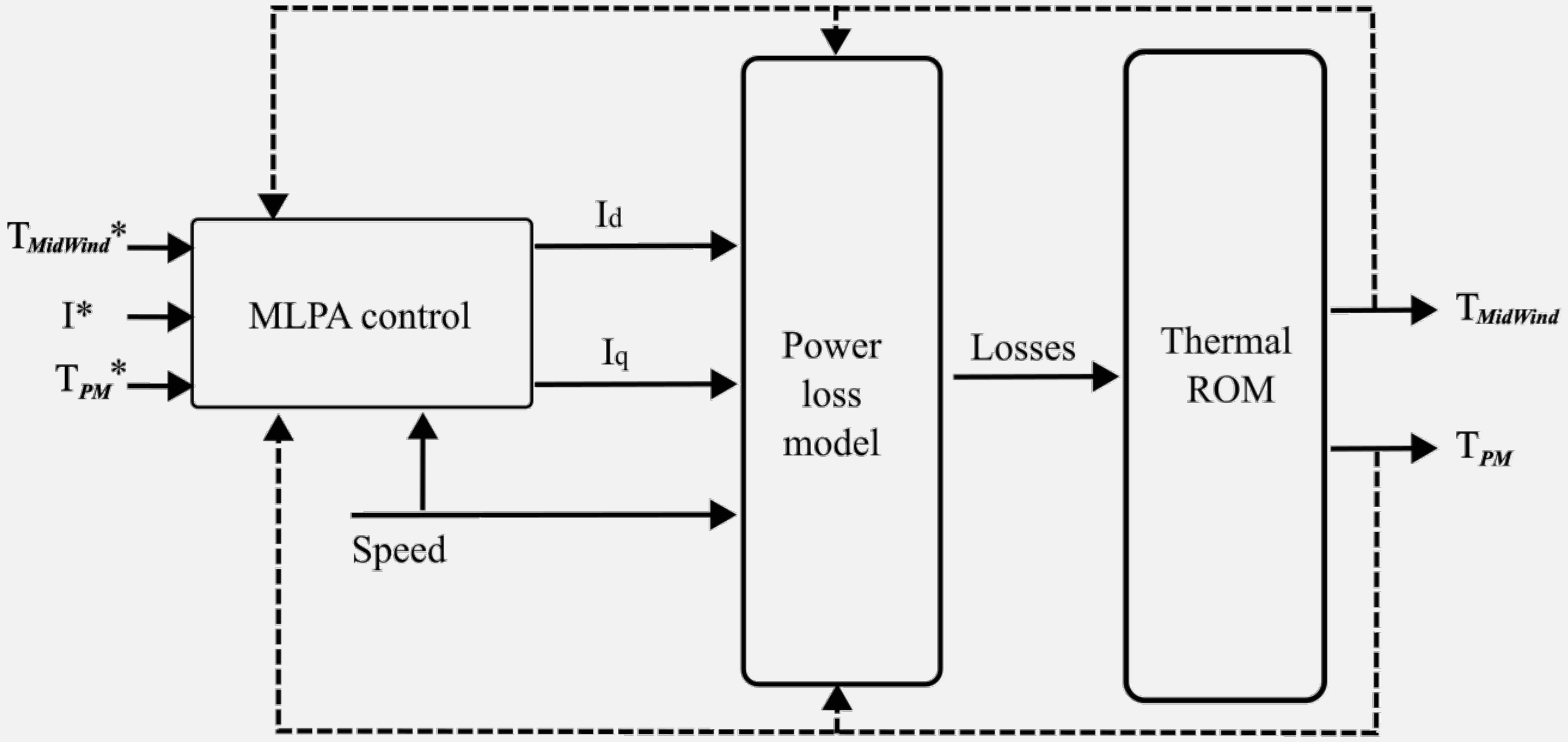


Bearing losses distribution

Minimum losses per Ampere

Full chain emotor model:

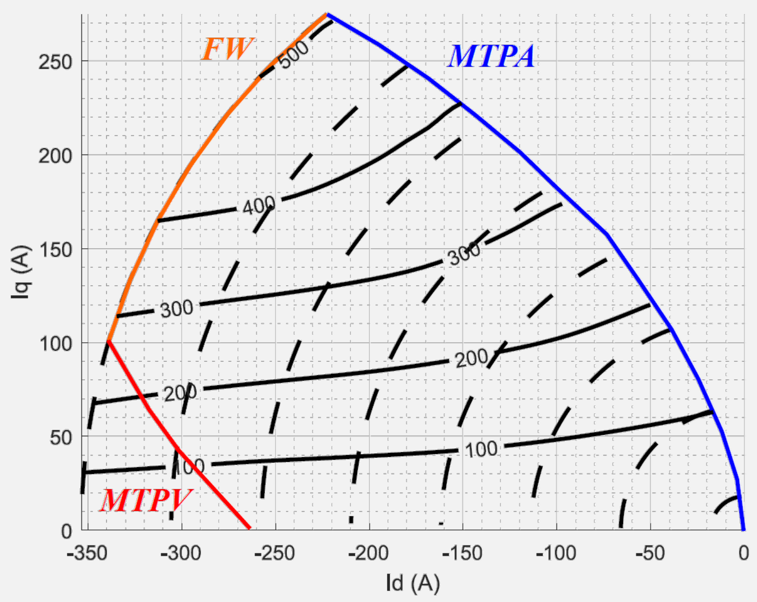
- Once the Power Loss model and Thermal ROM are tuned according to experimental data, the knowledge of the real time stator and rotor temperature is in a range of +-5°C compared to real measured and also the losses are reflecting exactly the one affecting the motor.
- These values can be used control algorithm to obtain for all the operation conditions the Minimum Losses combination of the Stator current that can deliver that torque at the corresponding speed.
- The MLPA condition is obtained also considering boundary condition variation (fluid flow and temperature variation, oil spray cooling, …), transient and steady state operating points.
- In all cases, one of the two thermal limits is reached, ensuring that the maximum allowable current is being fully utilized.



Minimum losses per Ampere

State of the Art comparison:

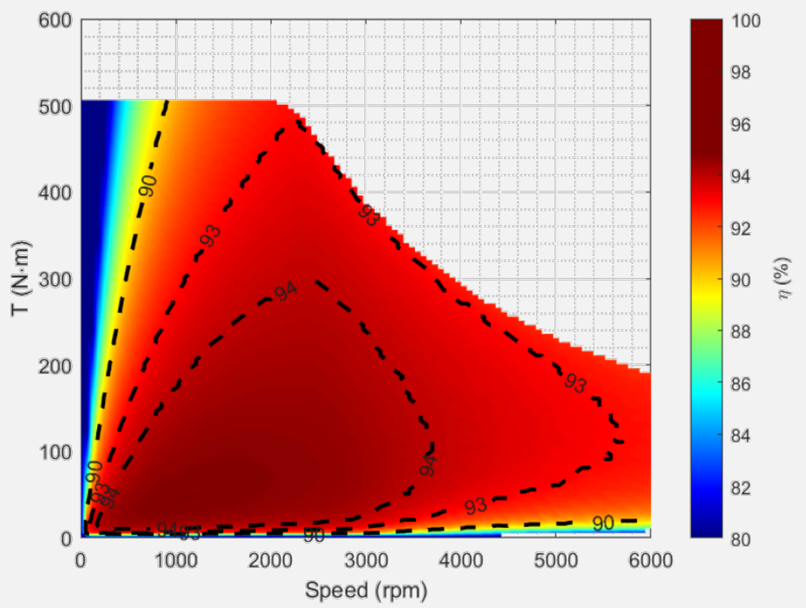
Standard MTPA-FW-MTPV strategy:



- MTPA-FW-MTPV is the most common strategy used in common application
- It can be extracted from single Id-Iq map plane
- It takes in to account stator joule losses only

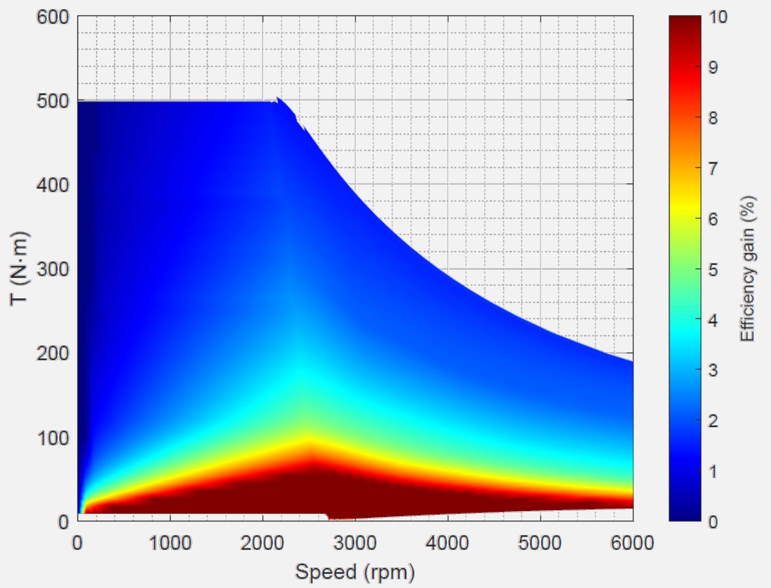
VS

Minimum Losses Per Ampere strategy:



- Minimum Losses Per Ampere strategy takes into account of the overall losses
- It takes into account of the temperature variation

Efficiency gain:

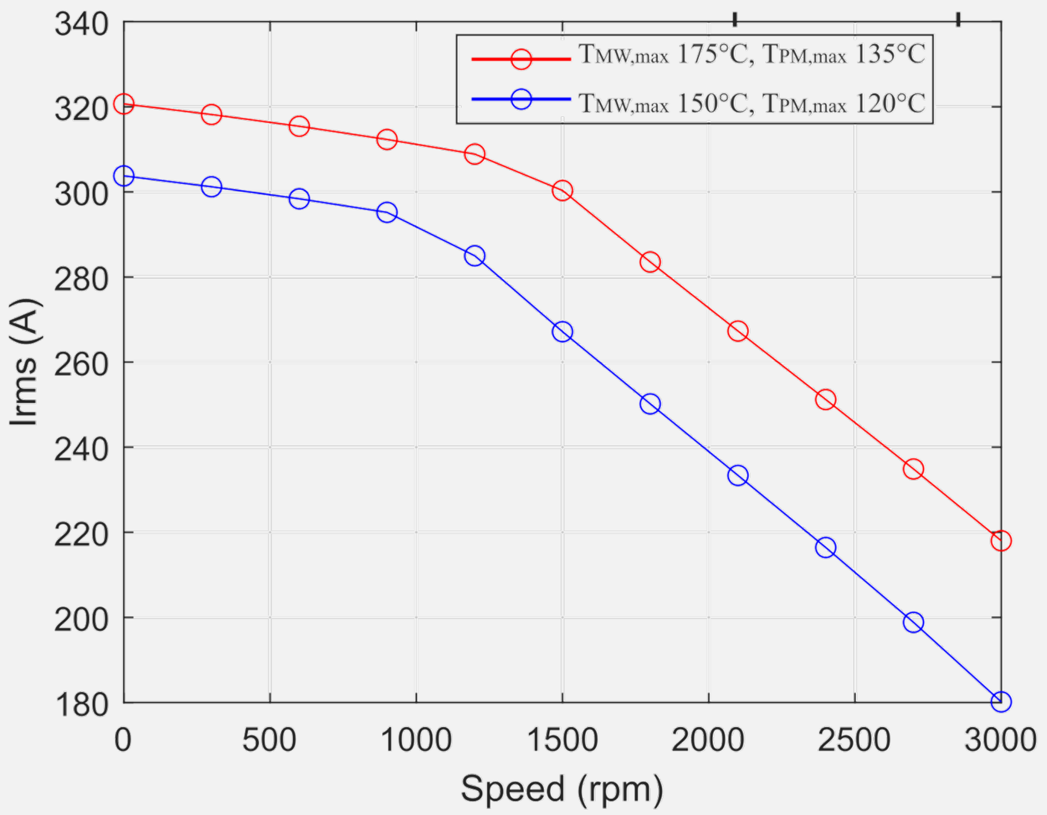


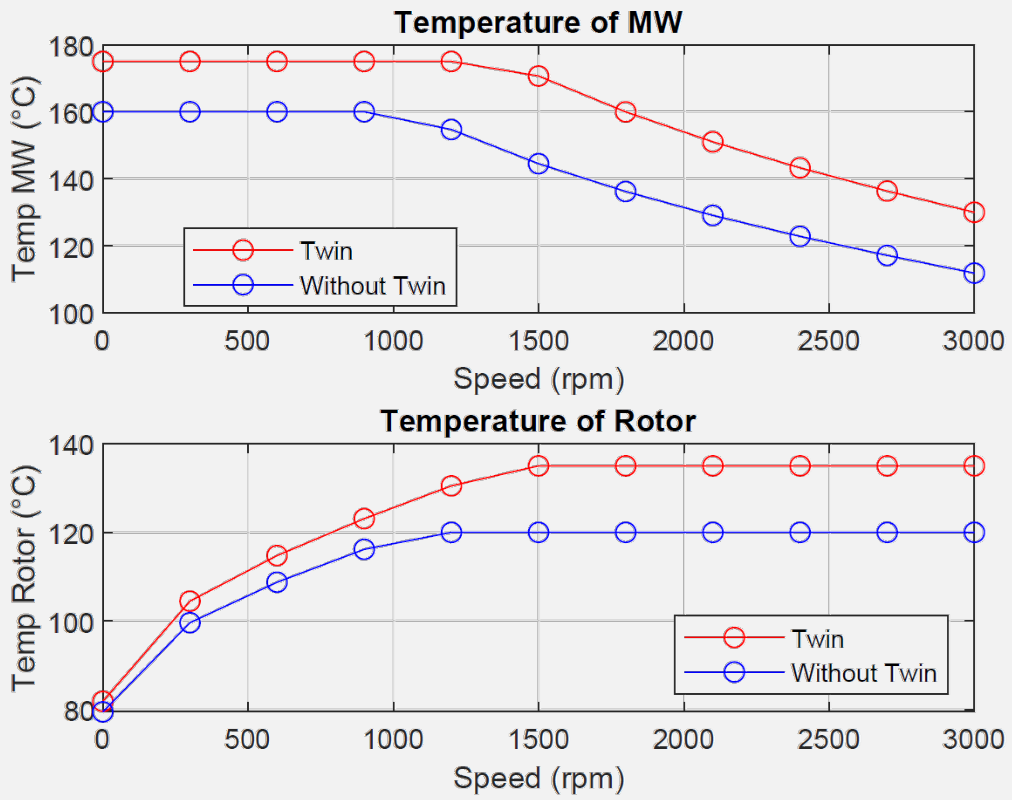
- The main gain in usign efficiency maps compared to MTPA-FW-MTPV strategy is prevalent in the low torque – high speed region
- In this zone the efficiency gain using efficiency map between the two method can be also of 10%

eMachine reduction size

Thermal model adoption:

- The Irms current increases by approximately 5% at zero speed and up to 20% at maximum speed when adopting the Twin.
- This increase is made possible by having accurate knowledge of the machine’s temperature, which allows for reduced safety margins and more efficient use of materials.
- In all cases, one of the two thermal limits is reached, ensuring that the maximum allowable current is being fully utilized.
- The increasing of the current is proportional to the decreasing of the machine size





Twin Fabrica recap

Twin Fabrica offers:

- High-fidelity physics-based models
- Real-time capability through **Model Order Reduction (MOR)**
- Flexible virtual thermal sensor placement even in places in which it is physically unfeasible to place a real sensor
- Dual-level calibration with physical and data-driven methods that handles nonlinearities, unmodeled effects and time-varying boundary conditions
- Seamless export to Simulink, C code, or state-space representation of the model.
- High fidelity electro-magnetic and thermal model
- Minimum Losses per Ampere (MPLA) control , yielding maximization of the motor efficiency in every working condition
- Intergrated control ready to plug and play, considering MLPA and not just MTPA control
- Optimize strategies in motor design, considering during the design stage both control strategies.

Twin Fabrica Software

Fast losses eMachine calculation