

PMSM Efficiency Map Calculation Considering PWM Losses

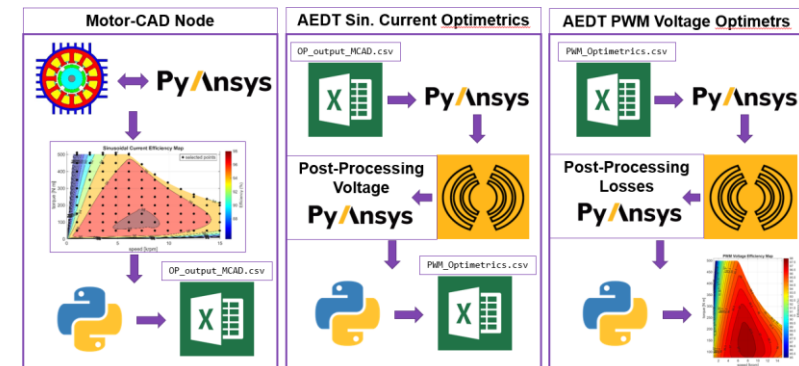
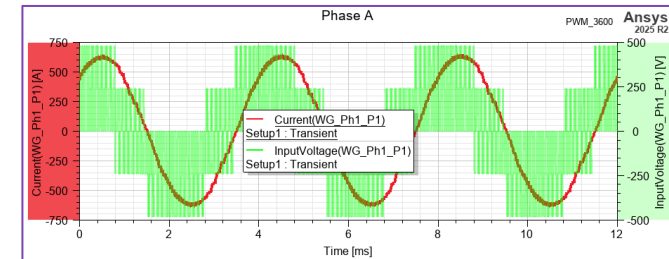
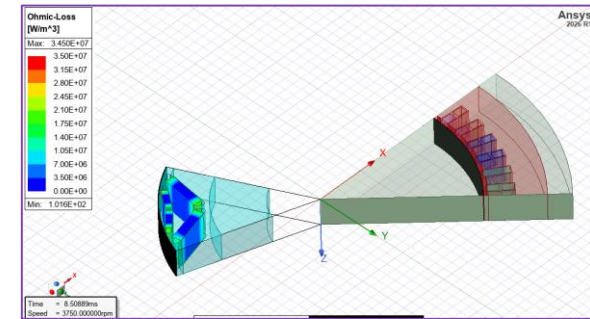
Matteo Carbonieri, *Application Eng., Staff Engineer*

Francesco Papini, *Application Eng., Staff Engineer*

Wenliang Chen, *Application Eng., Staff Engineer*

*Presented by Julius Saitz at SVS FEM Ansys
Conference*

Olomouc, Czech Republic, May 28, 2026



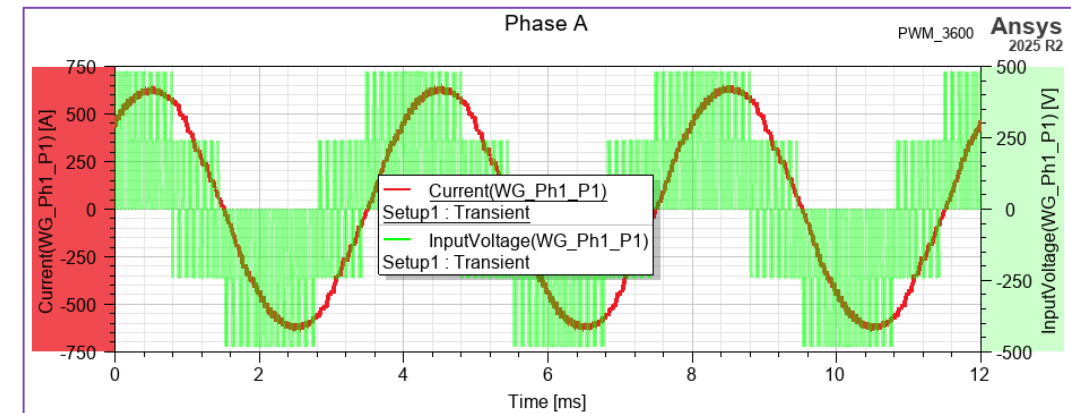
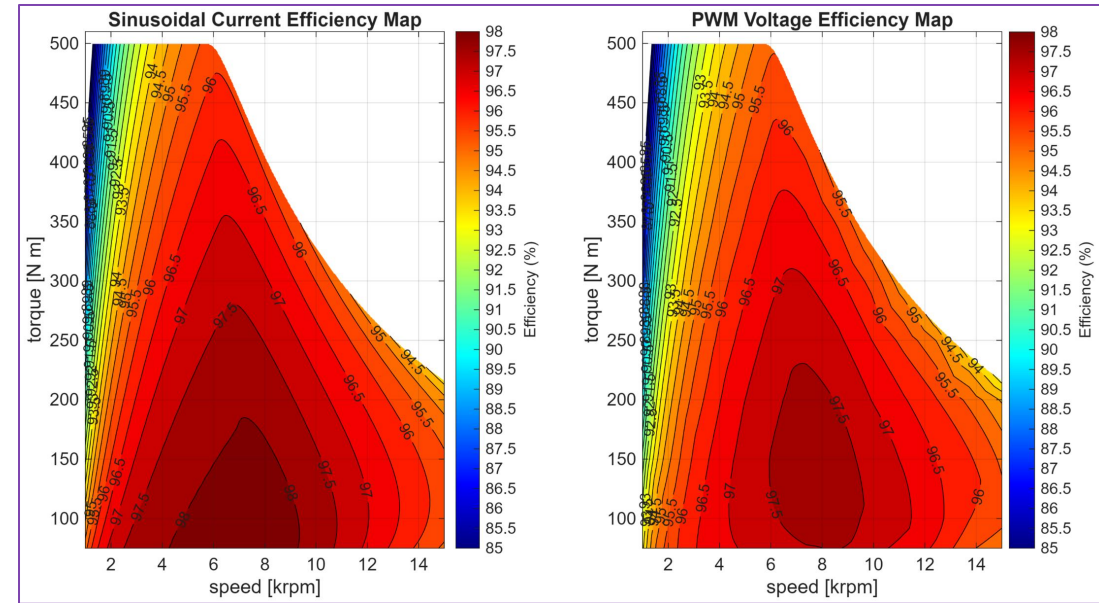
Agenda

- Quick summary of the proposed workflow and introduction.
- PWM Analysis workflow in Ansys Maxwell.
- Ansys Motor-CAD/Maxwell automated workflow with pymotorcad and pyaedt.
- Efficiency maps and loss results.
- More details about the several steps:
 - Extract operating points from Motor-CAD.
 - Run Maxwell Optimetrics with sinusoidal current driven simulations.
 - Run PWM analysis Optimetrics.
- Comments and next steps.

Introduction

Introduction

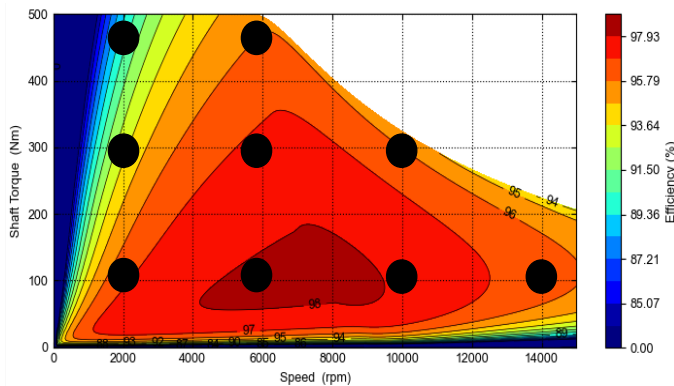
- The PWM induced losses calculation is crucial to evaluate the real efficiency of the electric powertrain.
- Correct preliminary evaluation allows to evaluate the effectiveness of the PWM strategy:
 - Balance between inverter and motor losses.
 - Impact of switching frequency.
 - Switching patterns.
- Early design stage analysis allows to know better the critical losses (magnets, winding) to properly design the cooling system.
- It is important to create an intuitive and easily approachable workflow to compute these losses in the most convenient way to balance the value of advanced analysis with the simulation time.



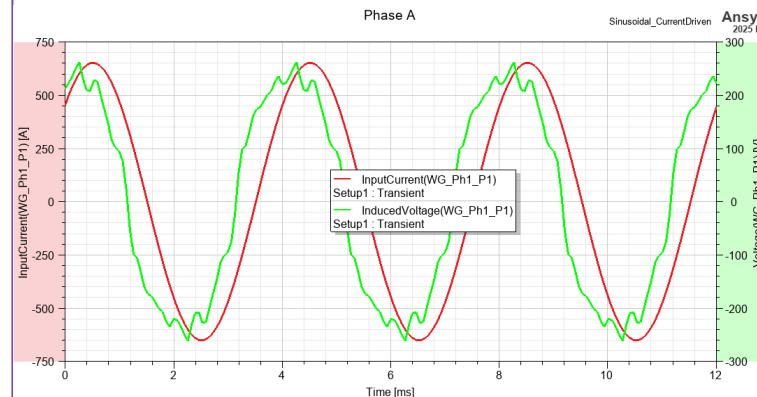
Workflow Description

Workflow Concept

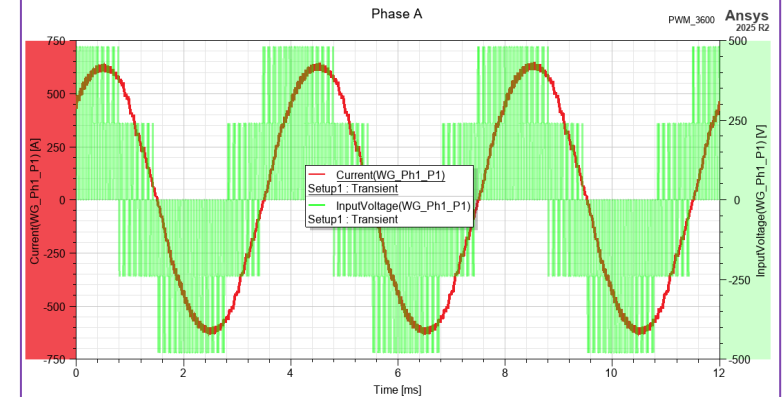
- **Motor-CAD** to calculate the requested current and phase advance in the several torque/speed points.
- The MTPA approach is used to derive the efficiency maps.



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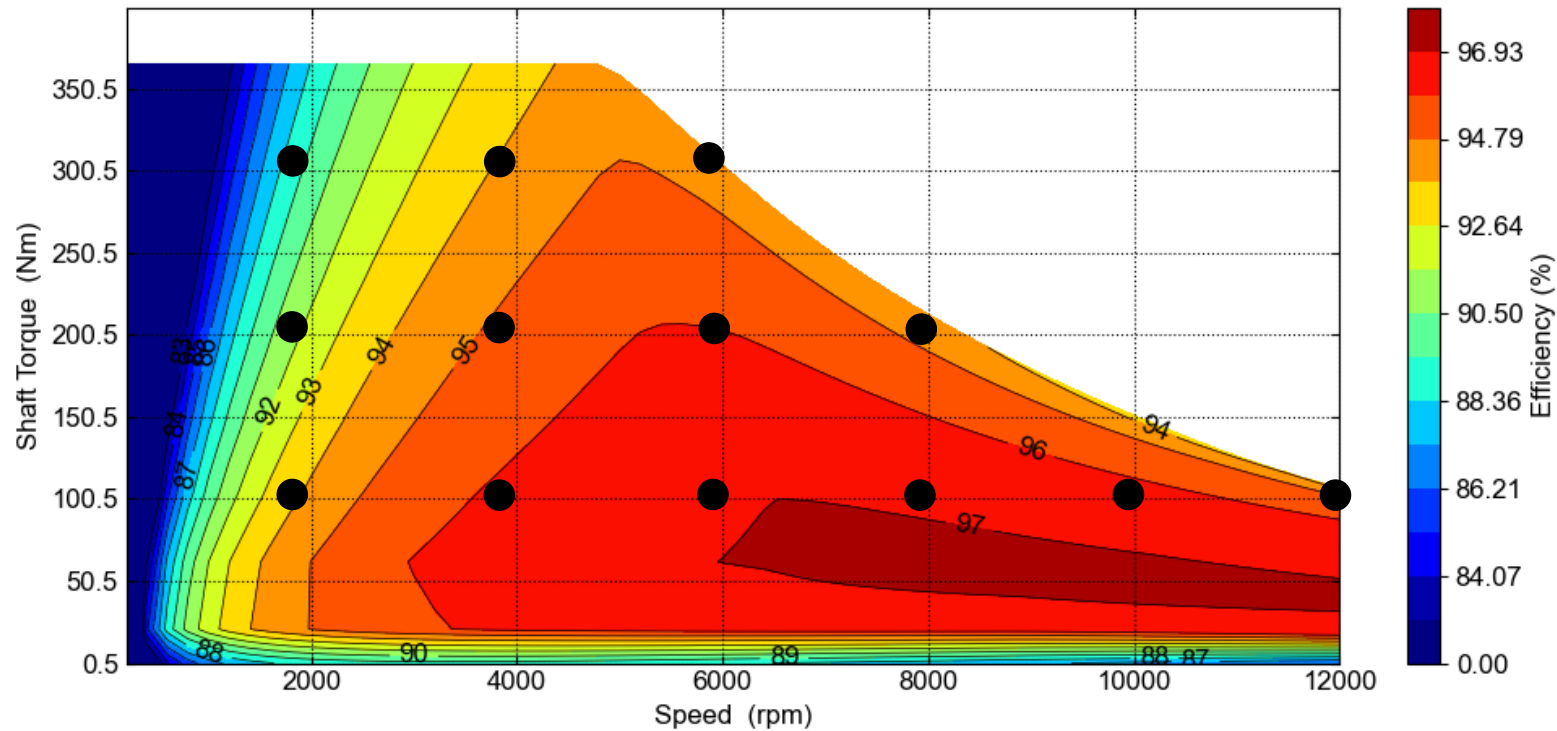


- **Maxwell voltage driven with SVPWM** is carried out with amplitude and phase form previous simulation.
- Additional losses due to PWM are calculated



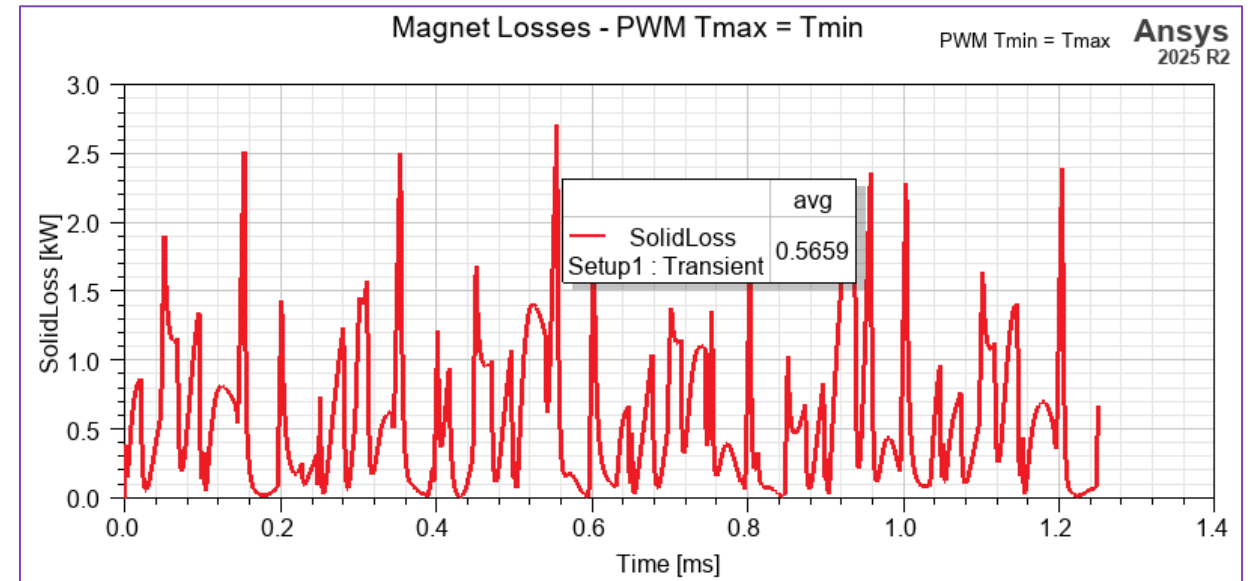
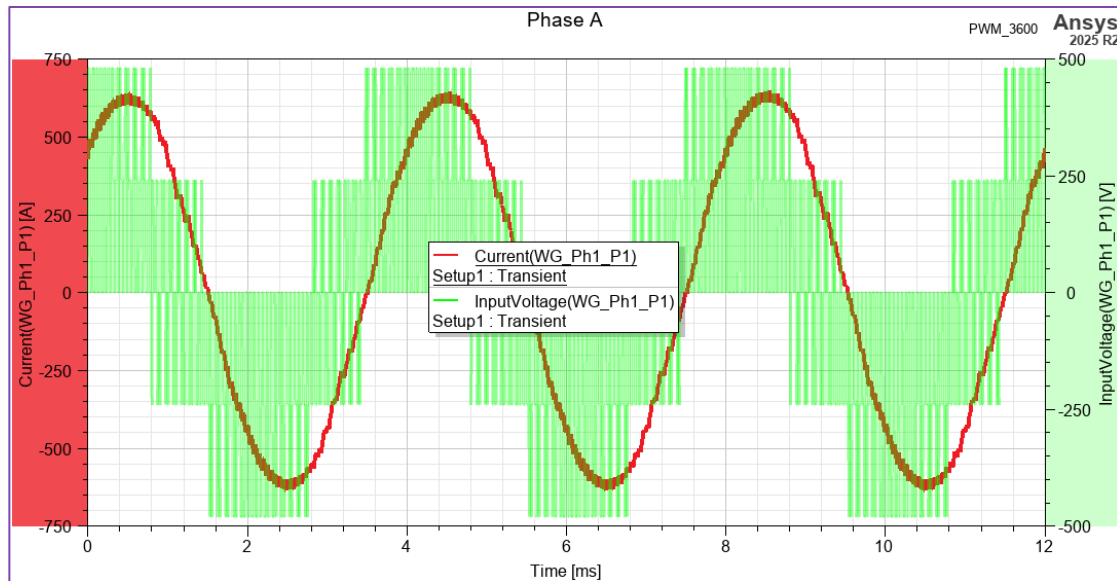
First Step: Motor-CAD Mapping

- Motor-CAD derives the (I_d , I_q) current combination using the MTPA algorithm.
- 10-15 points are selected for the PWM analysis to carry out in Maxwell.

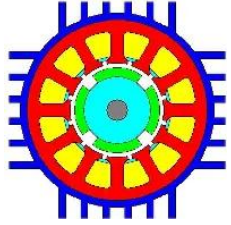


Second Step: Maxwell PWM Analysis

- The selected (Id, Iq, speed) combination are simulated in Maxwell:
 1. Current driven simulation to derive voltage (amplitude and phase), losses.
 2. Voltage driven simulation using the PWM built-in feature: compute the total losses and the additional losses due to PWM.
 3. Repeat the analysis for all the selected points.



Third Step: Automation



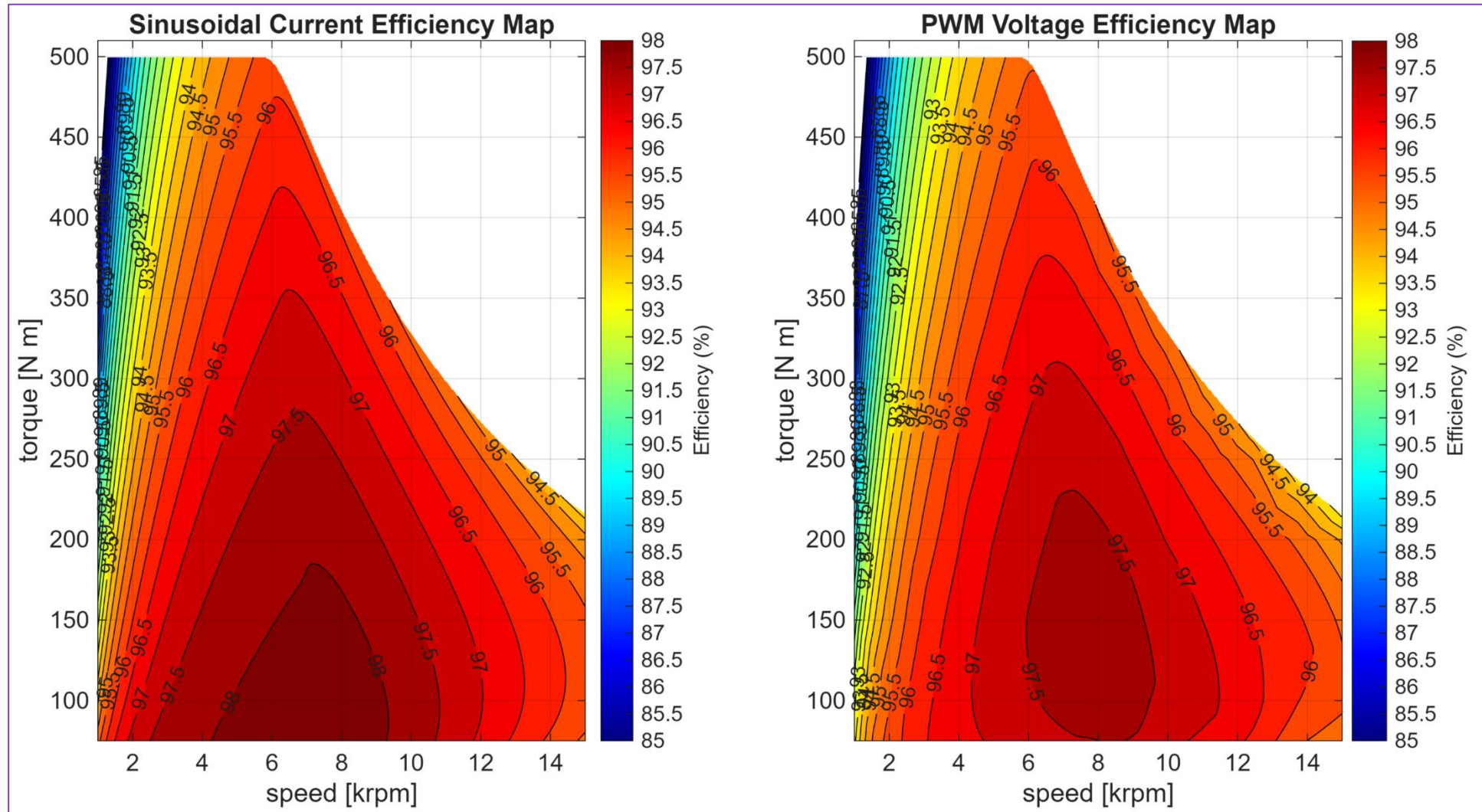
Py/Ansys



- The PWM workflow has been fully automated using `pyaedt` and `pymotorcad`.
- The final files with all the additional losses are produced by the python-based workflow.
- The final step to complete is making use of Motor-CAD Lab to combine the PWM losses map with the existing model to derive the final efficiency map.
 - Polynomial fitting or interpolating function can be defined, but it is an external approach.
 - Implement the matrix interpolation within Motor-CAD to make it easier to the user. An Aha request has been made ([ELE-I-3289 LAB Custom Loss from imported maps](#)).

Final Efficiency Maps

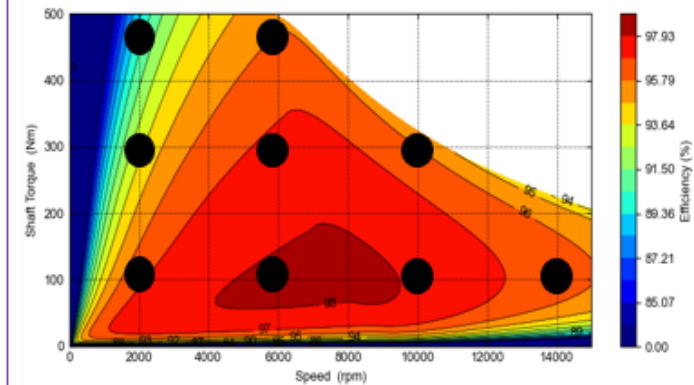
- The last step is combining all the losses to obtain the updated efficiency maps.



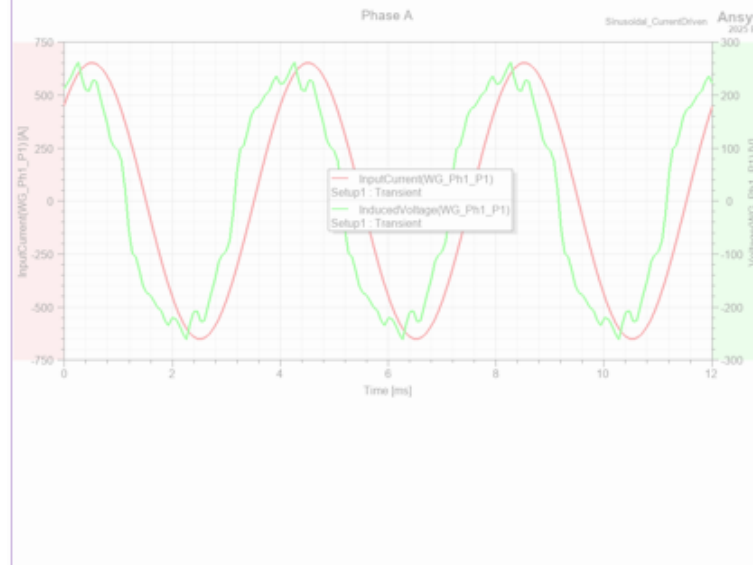
PWM Analysis in Maxwell

Workflow: Motor-CAD Step

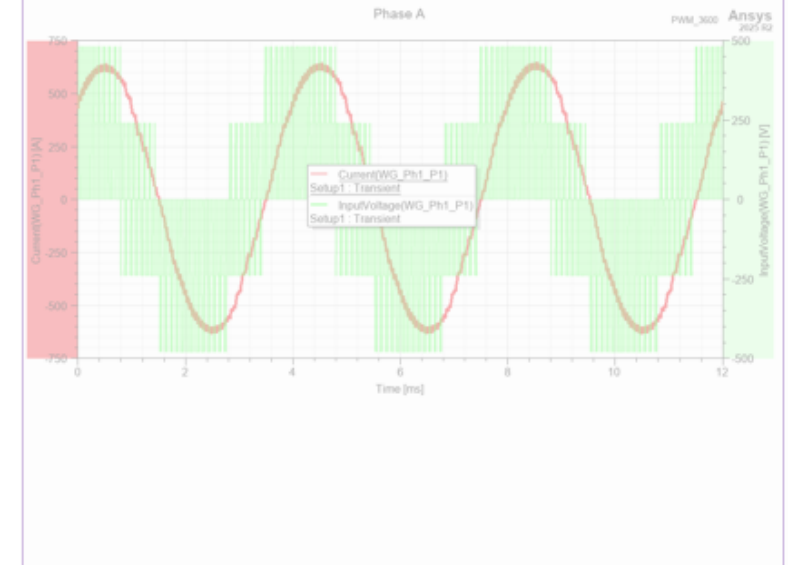
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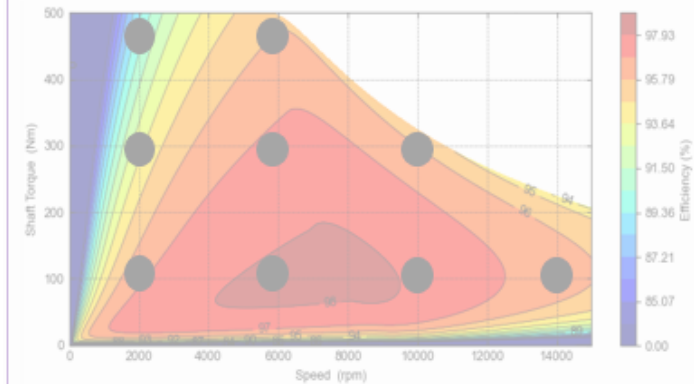


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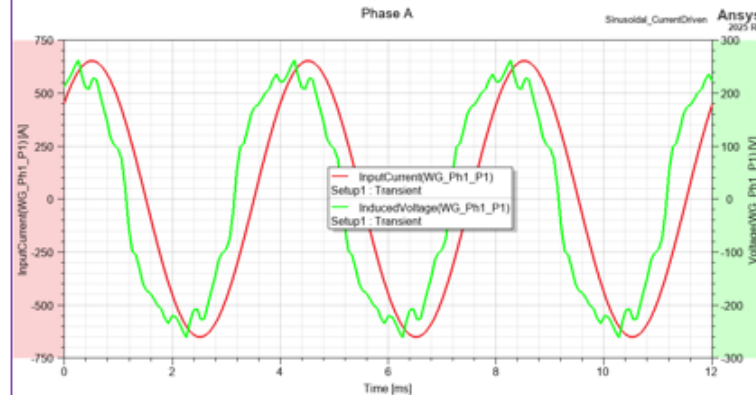


Workflow: Maxwell Current Driven Simulation

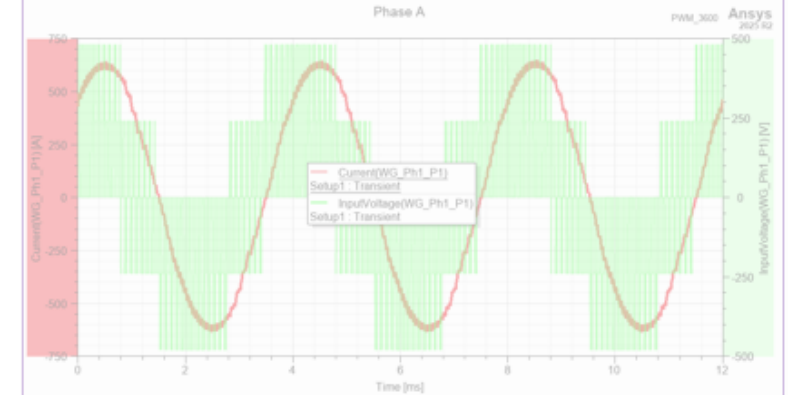
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Maxwell Current Driven – Derive the OP Voltage

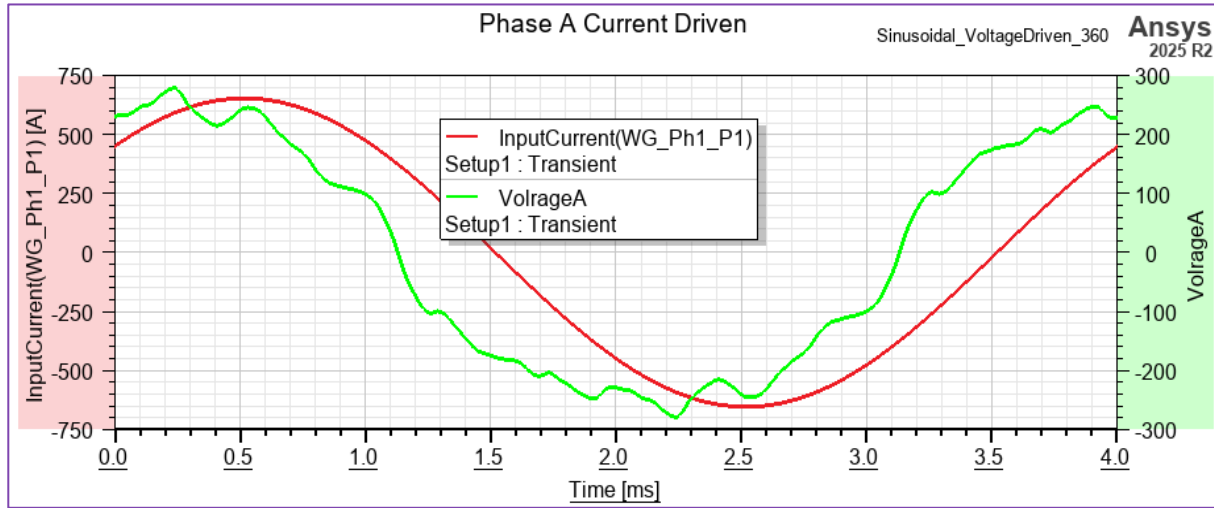
- The current driven simulation is carried out to derive the ideal voltage to apply with the PWM to obtain the same performance as from the (Id-Iq) operating point in the efficiency map.
- The phase voltage is computed adding the resistance and end-winding voltage drop to the induced voltage.

	Time	FFT InputCurrent(WG_Ph1_P1) Imported	FFT VoltageA Imported
1	0.000000	0.000000	0.014679
2	250.000000	650.538239	268.313429
3	500.000000	0.000000	0.029376
4	750.000000	0.000000	26.321505
5	1000.000000	0.000000	0.030028
6	1250.000000	0.000000	10.143702
7	1500.000000	0.000000	0.026746
8	1750.000000	0.000000	7.121358
9	2000.000000	0.000000	0.028441
10	2250.000000	0.000000	12.557573
11	2500.000000	0.000000	0.031012
12	2750.000000	0.000000	12.230096

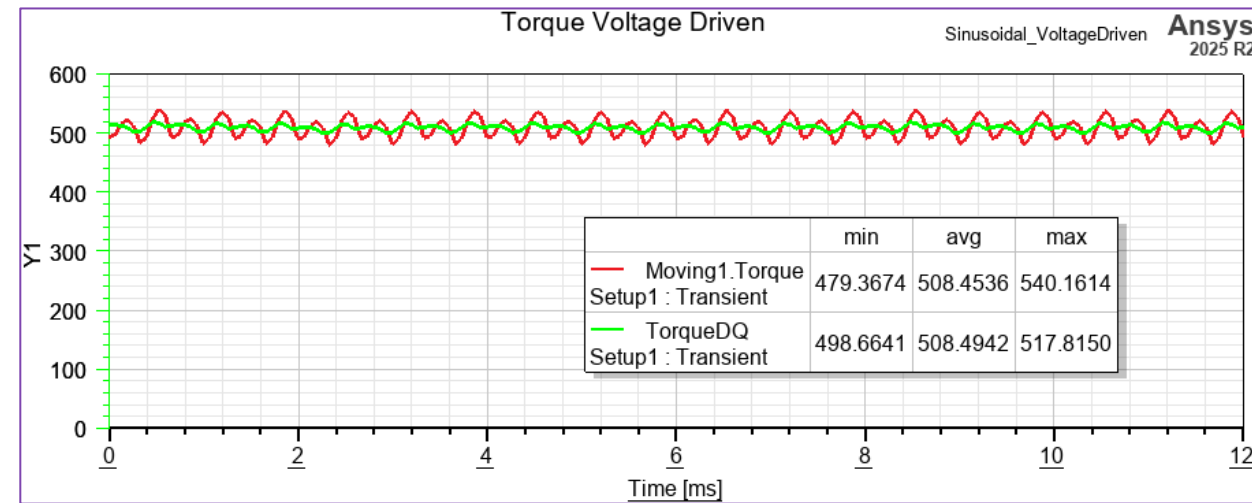
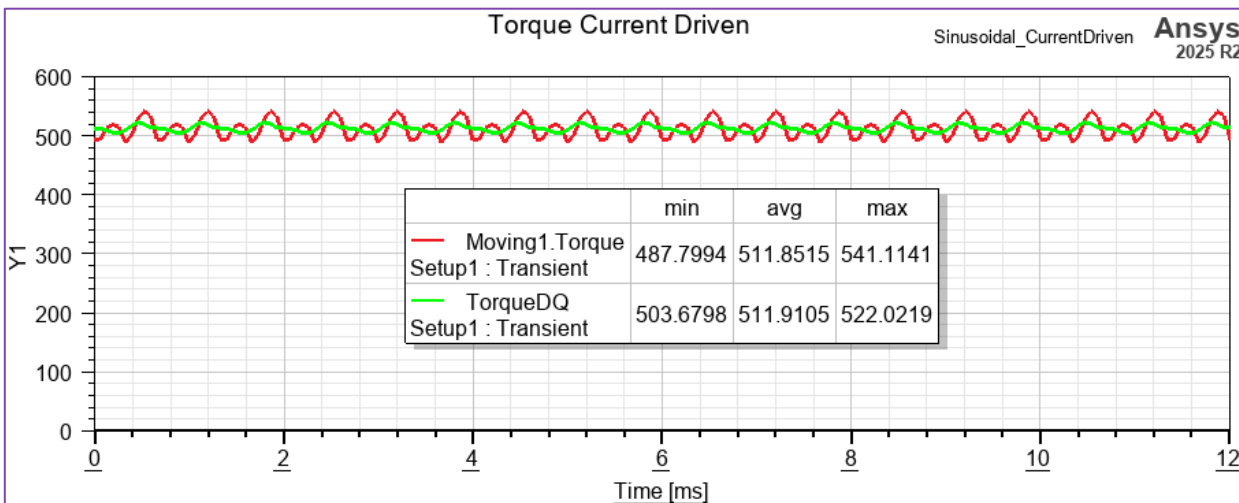
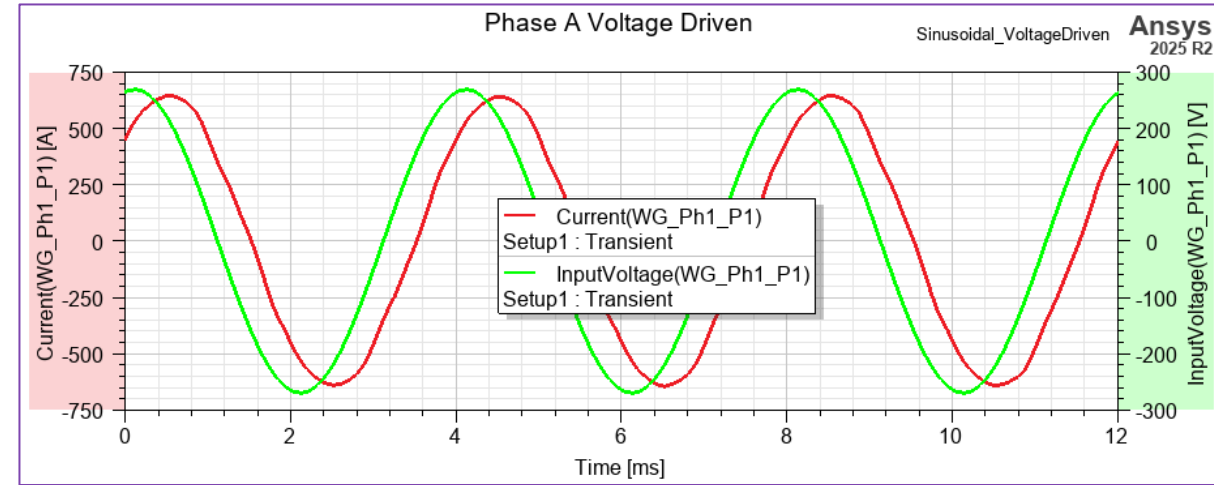
	Time	FFT InputCurrent(WG_Ph1_P1) Imported	FFT VoltageA Imported
1	0.000000	180.000000	0.000000
2	250.000000	-46.670000	-11.784419
3	500.000000	-70.749737	-4.216112
4	750.000000	-105.720019	158.637196
5	1000.000000	-133.191651	-3.075640
6	1250.000000	105.984711	-71.668488
7	1500.000000	-26.703128	-8.420904
8	1750.000000	-170.466070	58.305376
9	2000.000000	-100.635514	-15.870792
10	2250.000000	-88.724687	-134.183162
11	2500.000000	-61.569054	-7.092571
12	2750.000000	-93.536137	110.595832

Current Driven vs. Sinusoidal Voltage – Sanity Check

Sinusoidal Current Driven

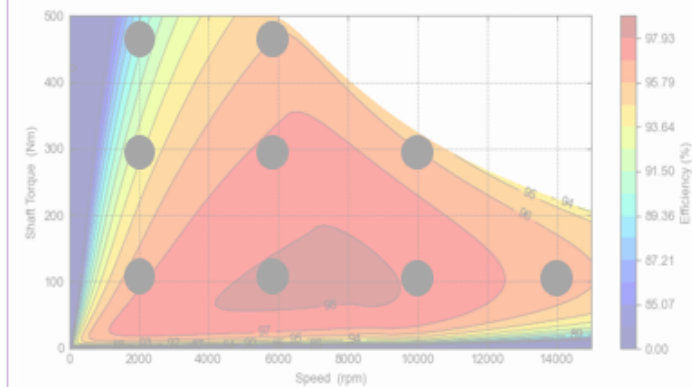


Sinusoidal Voltage Driven

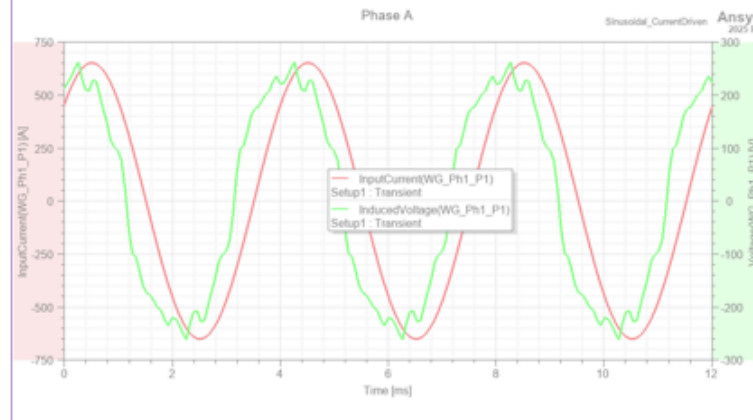


Workflow: Maxwell PWM Voltage Driven Simulation

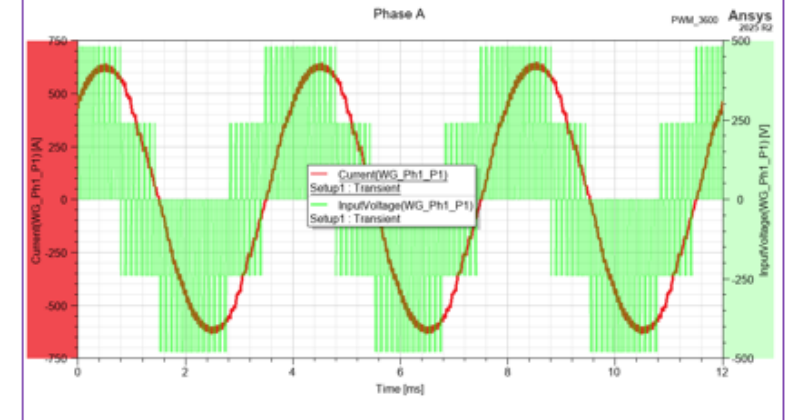
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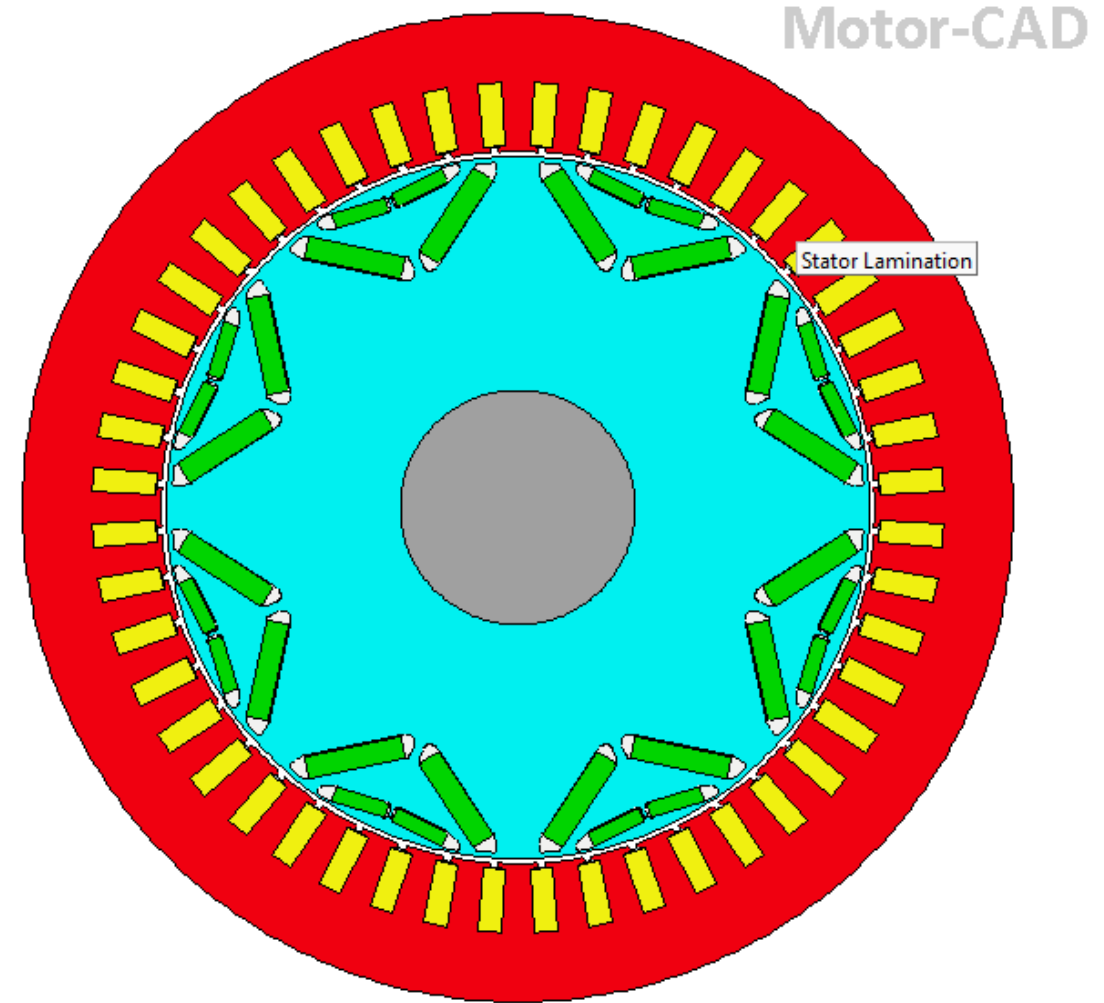


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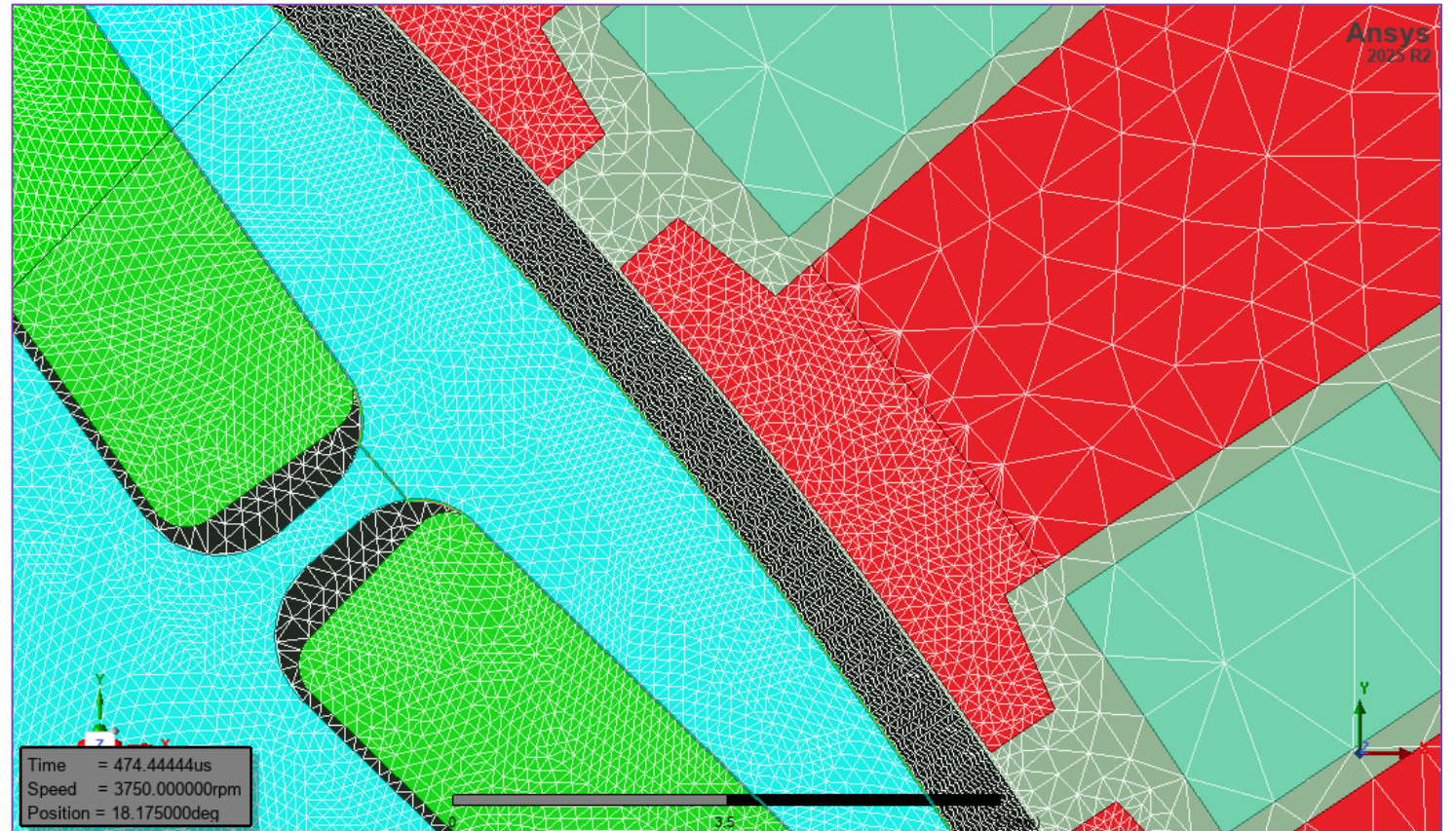
Operating Point Analysis with PWM (1)

- The first step to verify the workflow robustness is the definition of a benchmark case where the best practices for an accurate simulation are applied:
 - Refined mesh in the air-gap, magnets, solid conductors and specific iron regions.
 - Clicking mesh method to avoid interpolations – a step for each air-gap element.
 - No skew
- The 2D analysis is carried out to get results with a reasonable time and it is preferred for an automated method.
- The 2D analysis allows a quick check to determine the effect of the variable time step and mesh operations on the resulting losses.



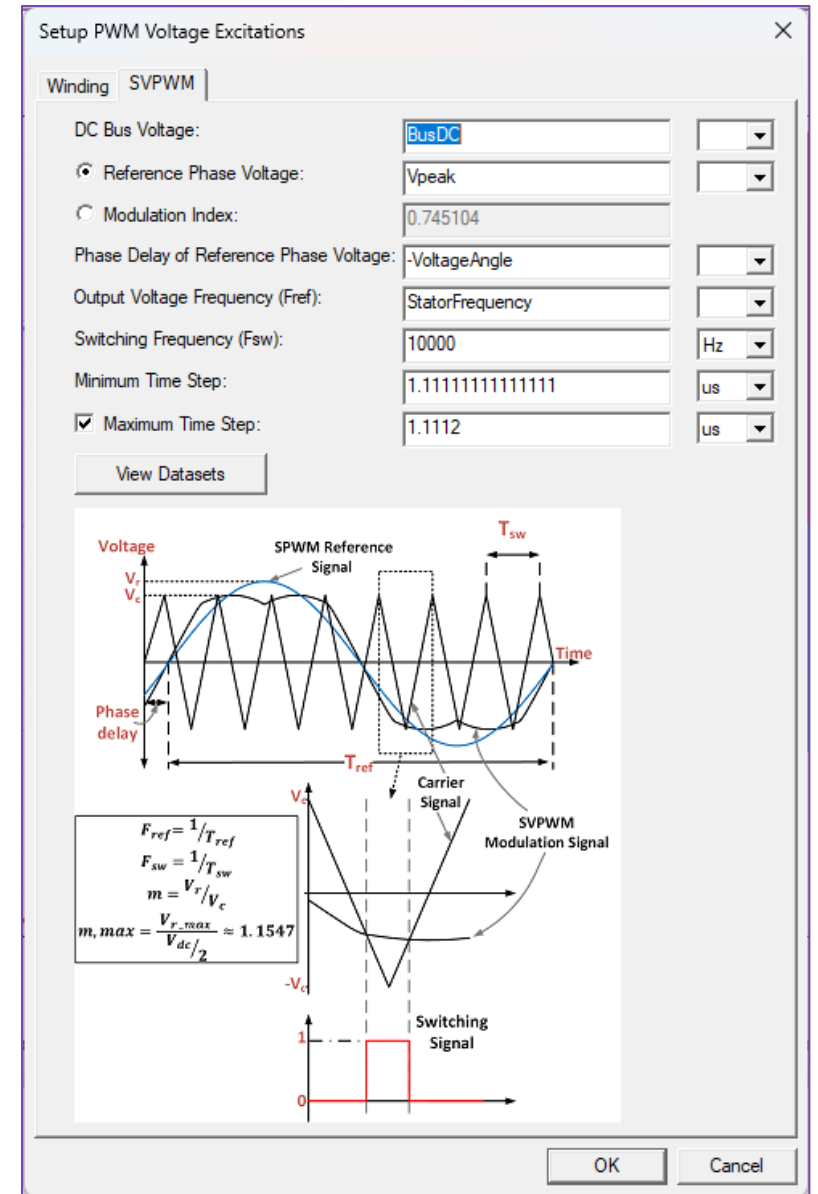
Operating Point Analysis with PWM (2)

- The first considered operating point is the MTPA region at the maximum current:
 - Stator frequency: 250Hz.
 - Stator current: ~500A rms.
 - Speed: 3750 rpm.
 - Air-gap mesh points: 3600.
 - Points per cycle: 3600.
 - Points per switching period: 90.
 - Switching frequency: 10kHz
 - Time-step: 1.11 us.



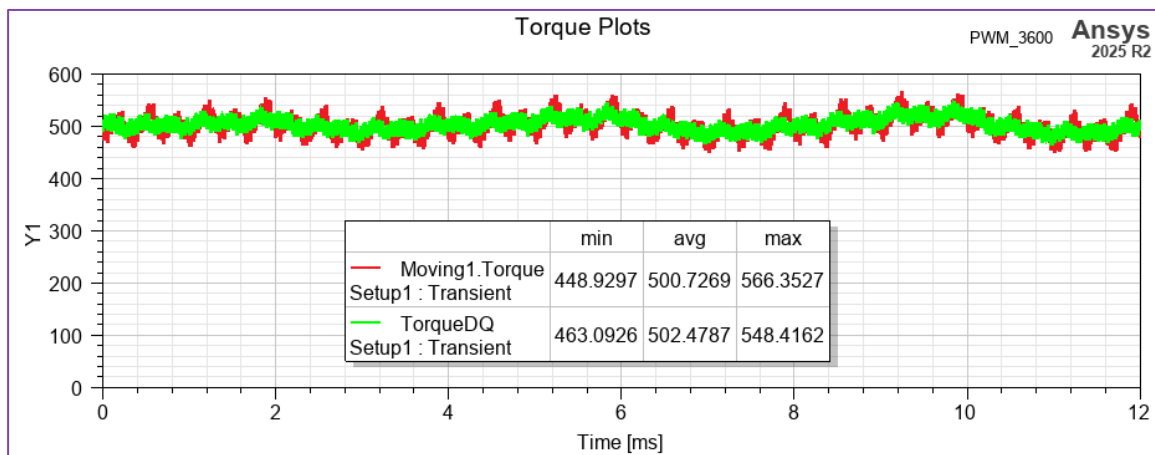
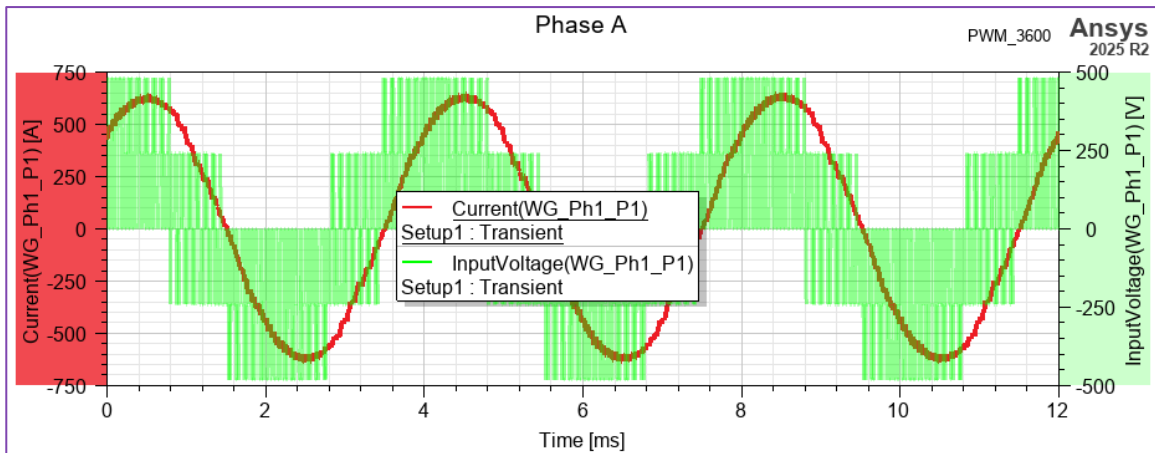
Comparison with Variable Time-Step

- The variable step is applied with the SVPWM feature to reduce simulation time and put less points when the voltage is constant.
- The mesh density is the same.
- Two combination have been tested:
 - Maximum time step equal 3 times the minimum time step (1.11 us).
 - Maximum time step selected by the SVPWM algorithm.
- Main comparison factor are:
 - Simulation time.
 - Losses output deviation.

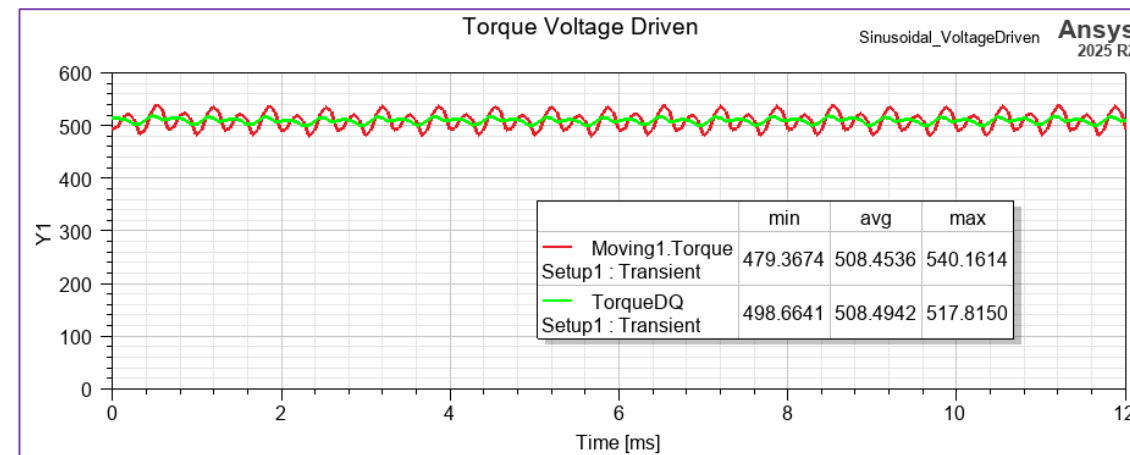
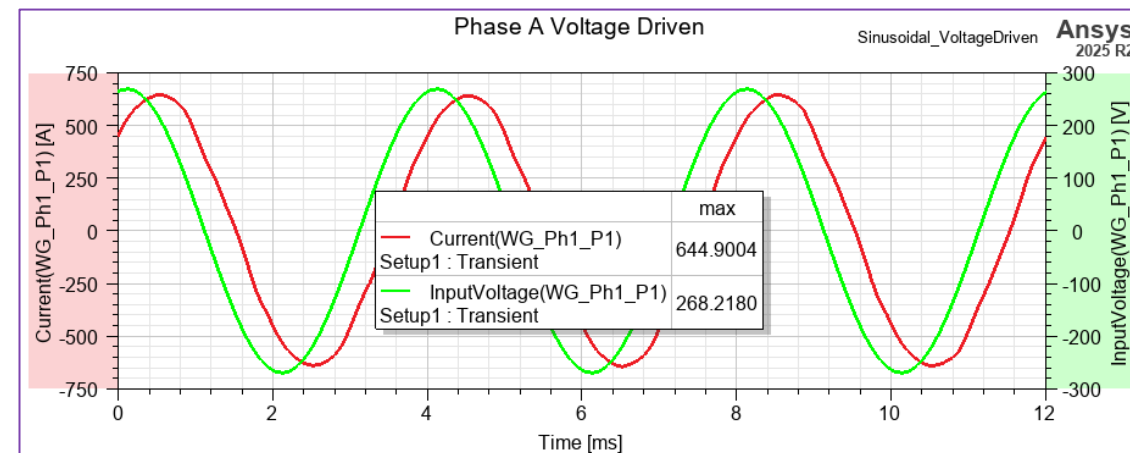


Operating Point Analysis with PWM (3)

PWM Voltage Driven



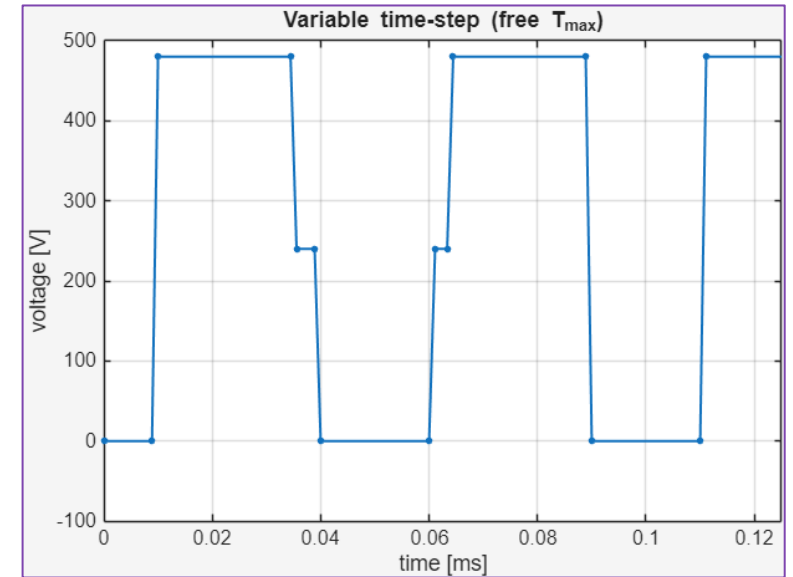
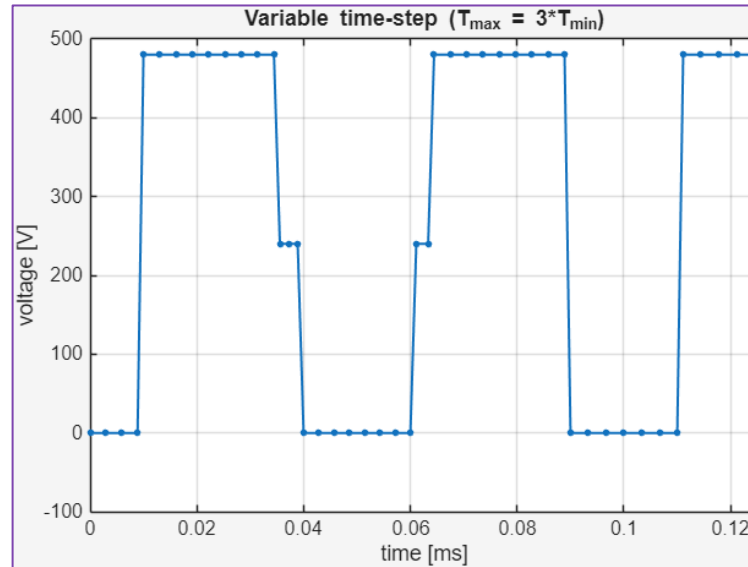
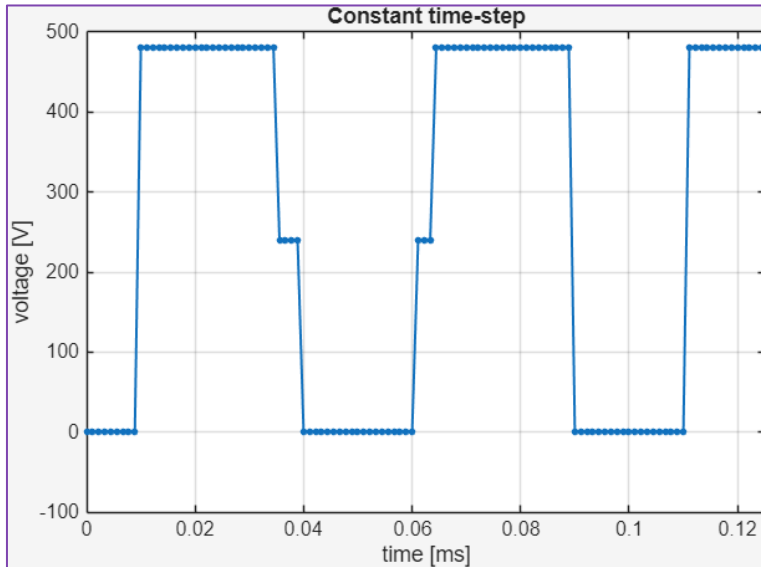
Sinusoidal Voltage Driven



Analysis Using the SVPWM Feature in Ansys Maxwell

Comparison with Variable Time-Step – Simulation Time

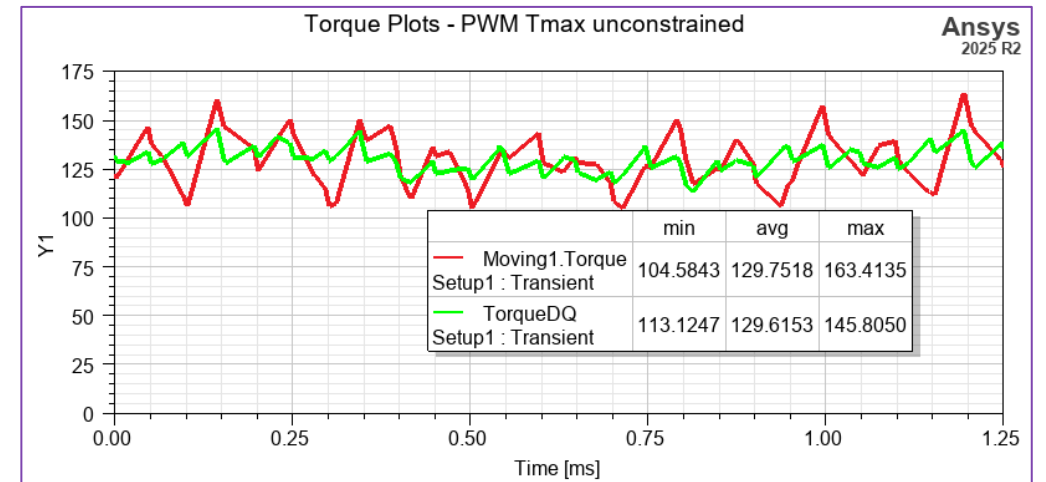
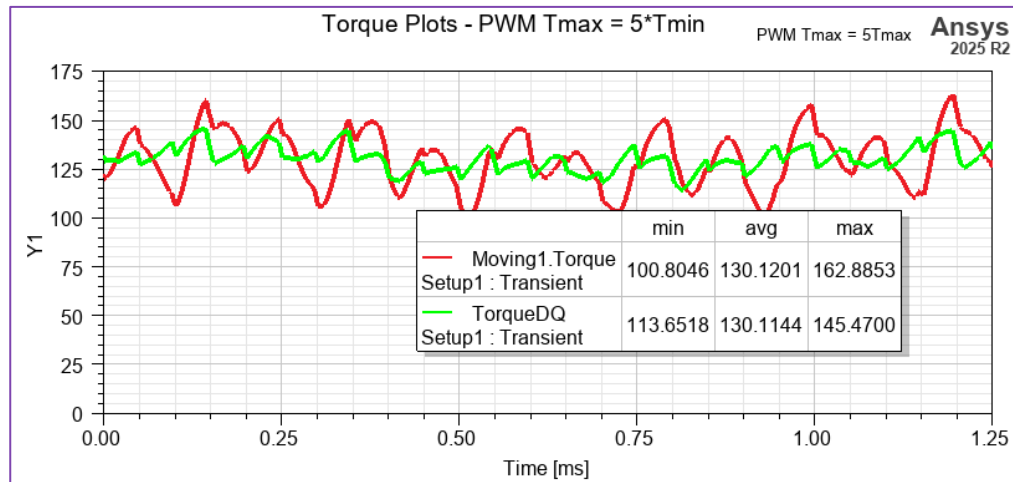
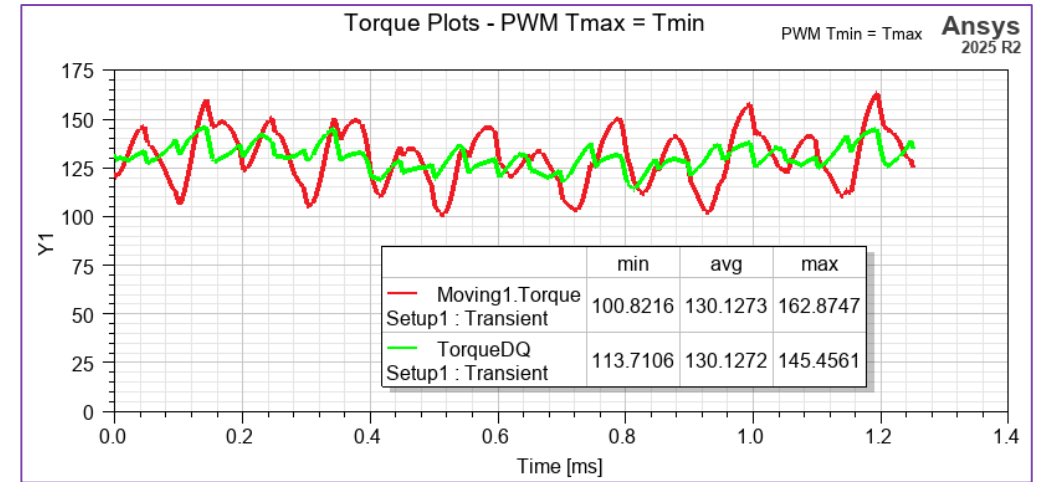
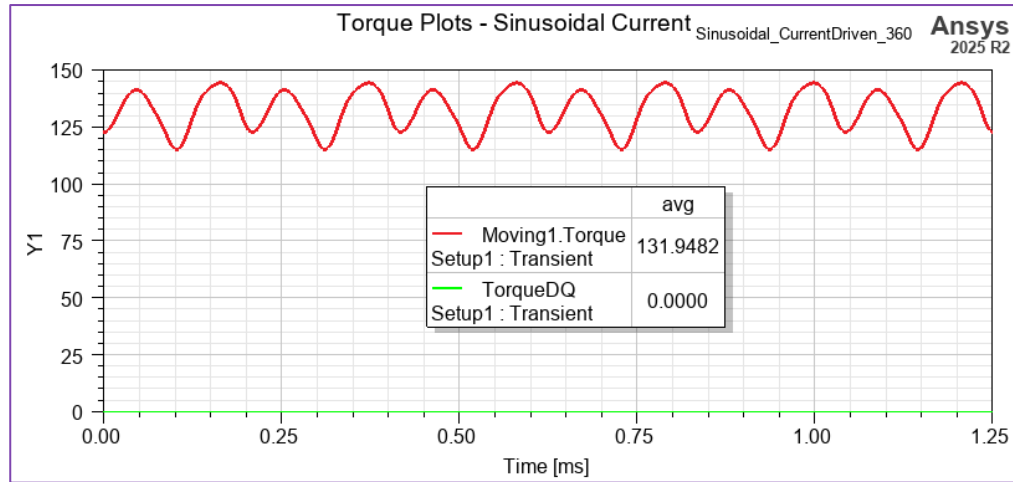
- The simulations have been run for 2 stator fundamental frequency periods:
 - Constant time-step.
 - Variable time-step ($T_{\max} = 5 \cdot T_{\min}$).
 - Variable time-step (free T_{\max}).



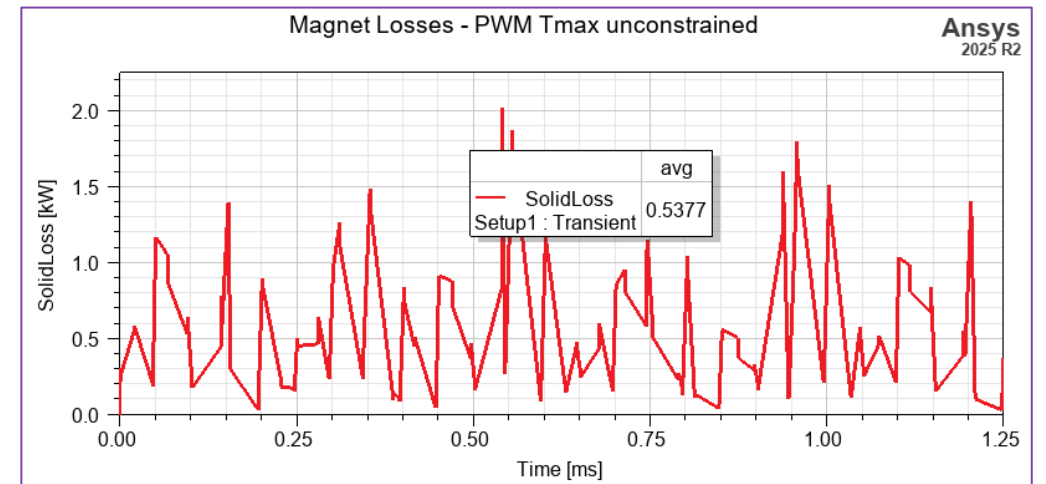
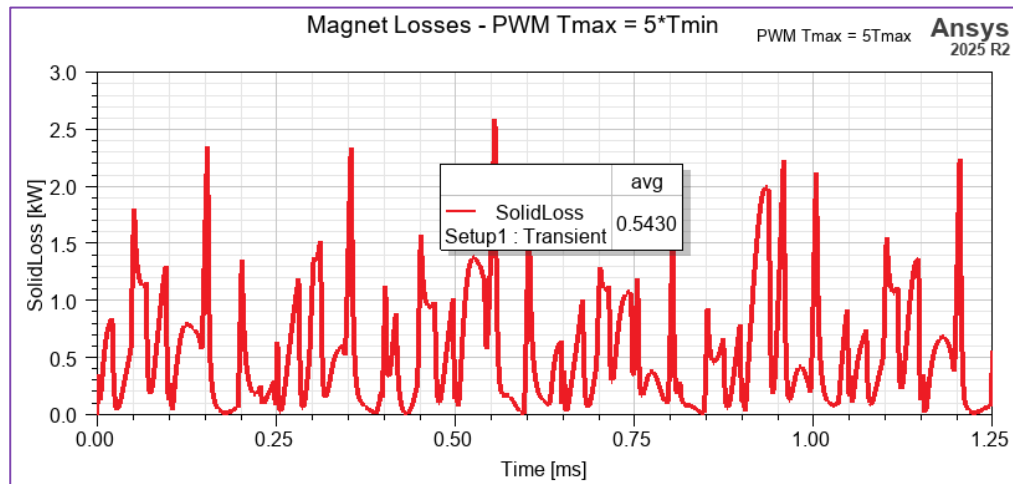
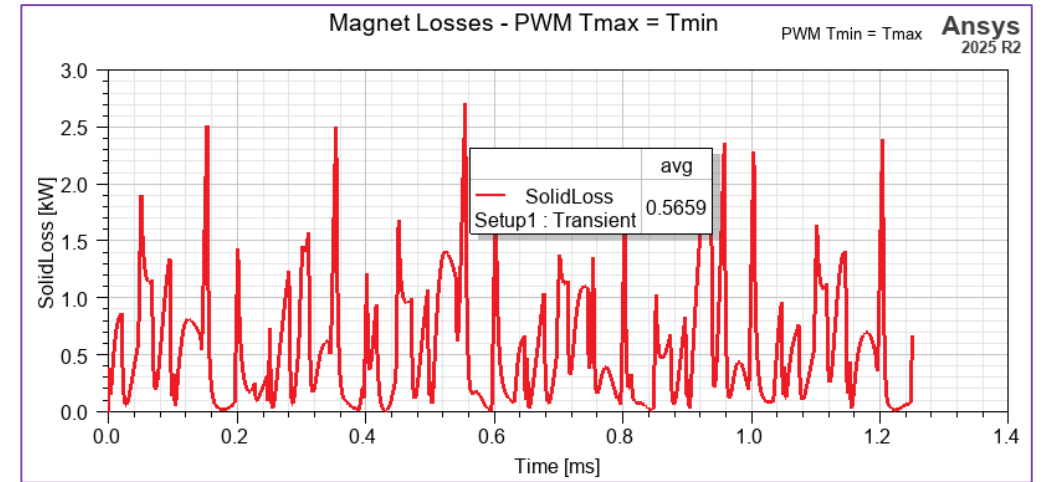
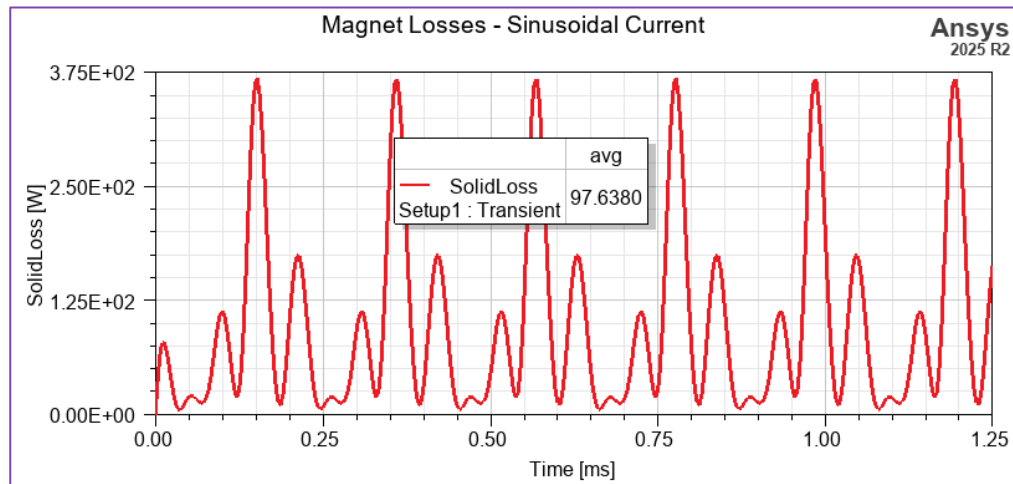
12000 rpm, 130 N m – Simulation Settings

- Sinusoidal simulations:
 - 360 points per cycle.
- Constant time step:
 - 3600 points per cycle of the fundamental.
 - 288 points per period of switching.
 - Time step: $t_s = 0.347\mu\text{s}$.
- Same T_{\min} ; $T_{\max} = 5 * T_{\min}$:
 - 800 points per cycle.
 - $T_{\min} = 0.347 \mu\text{s}$; $T_{\max} = 1.7361 \mu\text{s}$.
- Same T_{\min} ; T_{\max} max possible:
 - 153 points per cycle.
- Bus DC, Modulation Index:
 - $V_{\text{DC}} = 800 \text{ V}$.
 - Modulation Index: $m = 1.05332$.
- No TDM, res = 1e-8.

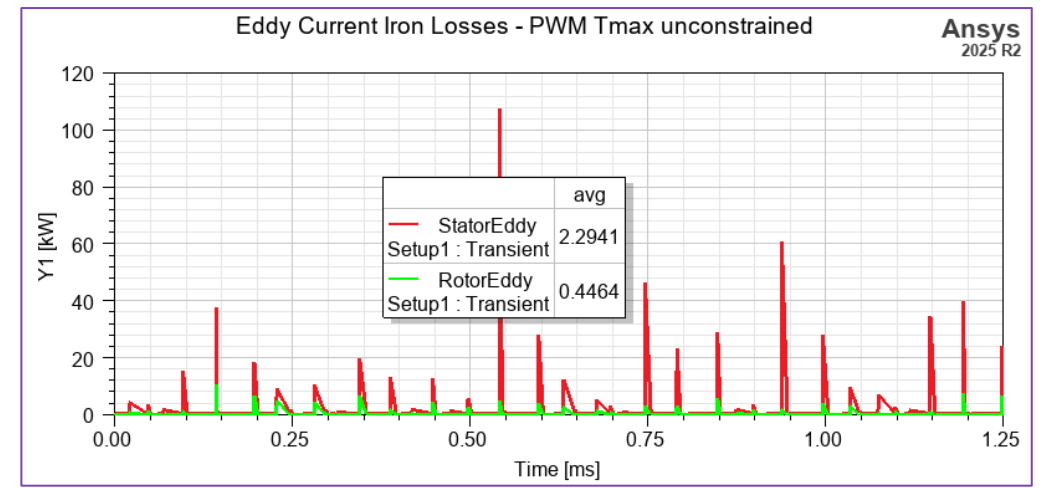
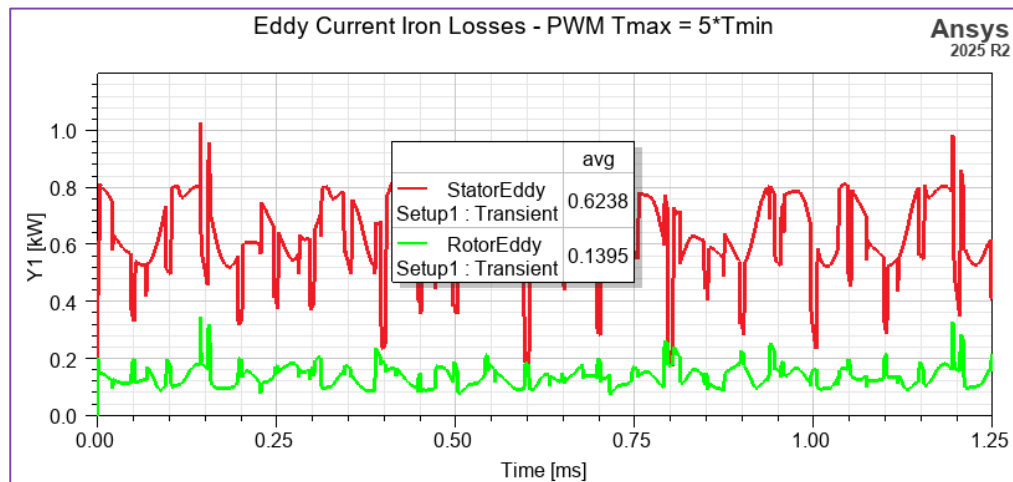
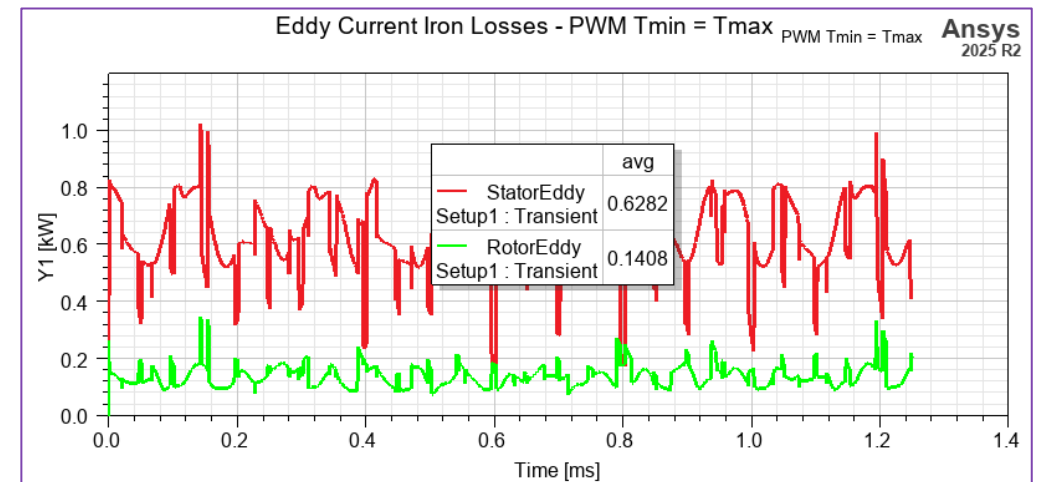
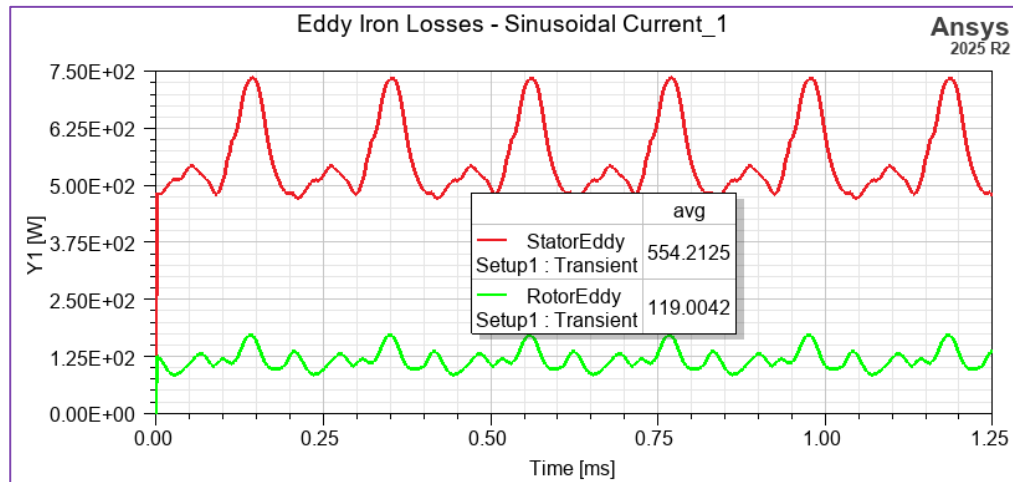
12000 rpm, 130 N m – Torque



12000 rpm, 130 N m – Magnet Losses

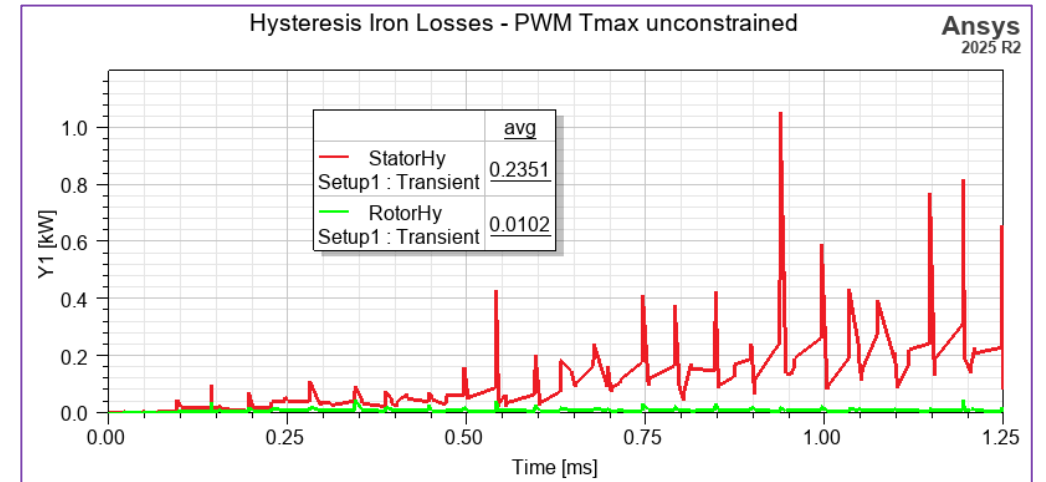
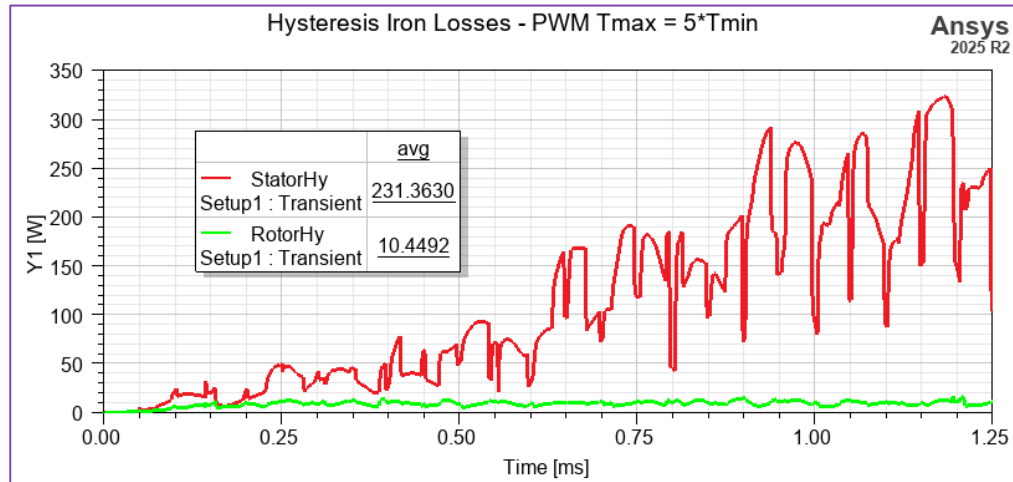
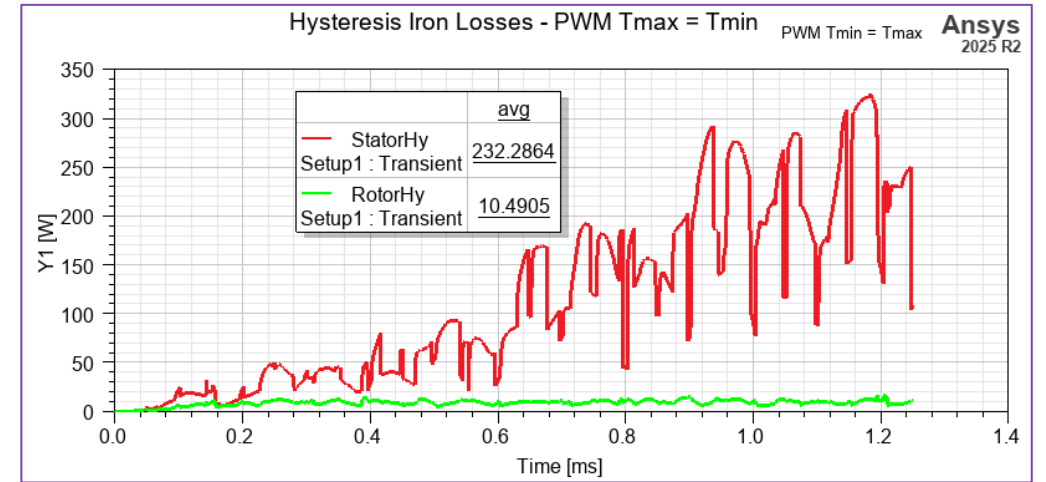
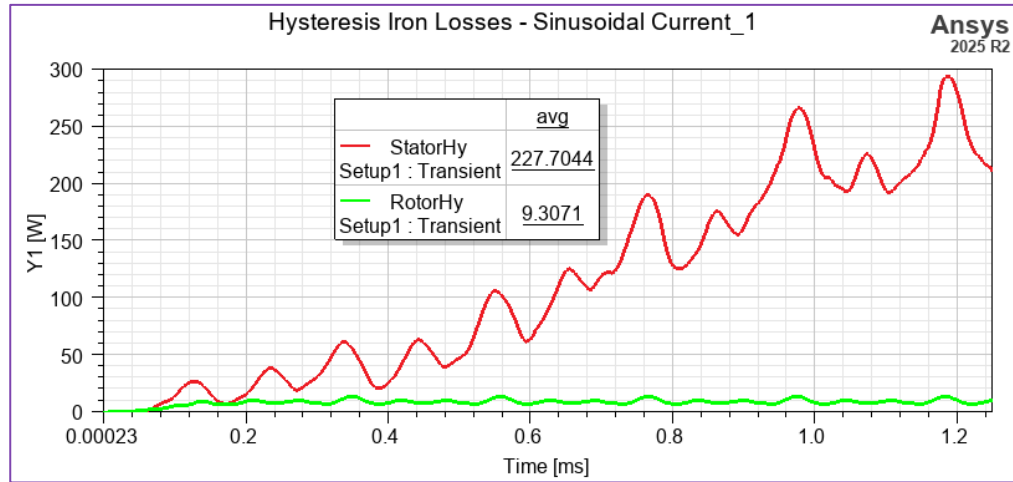


12000 rpm, 130 N m – Eddy Current Iron Losses



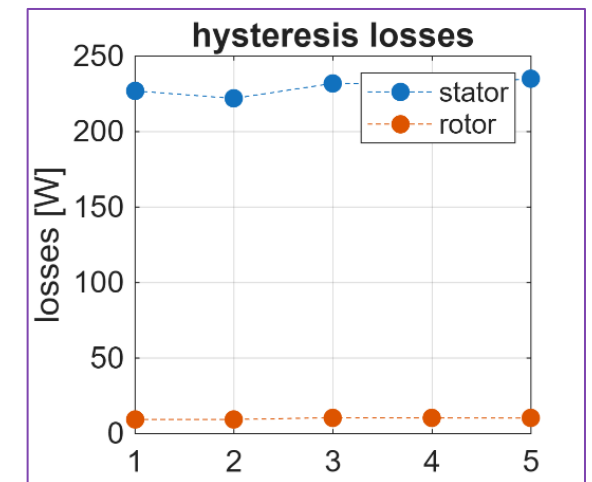
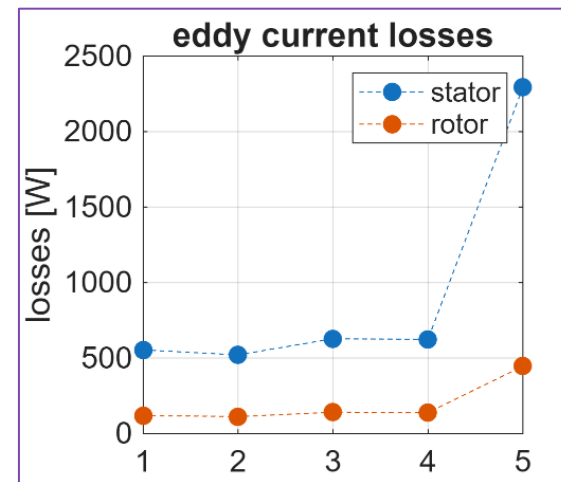
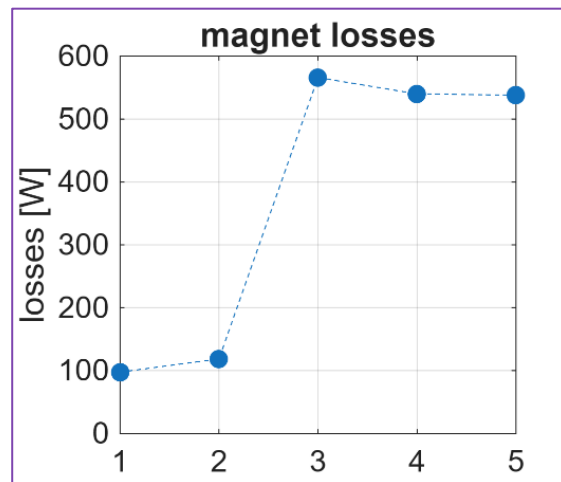
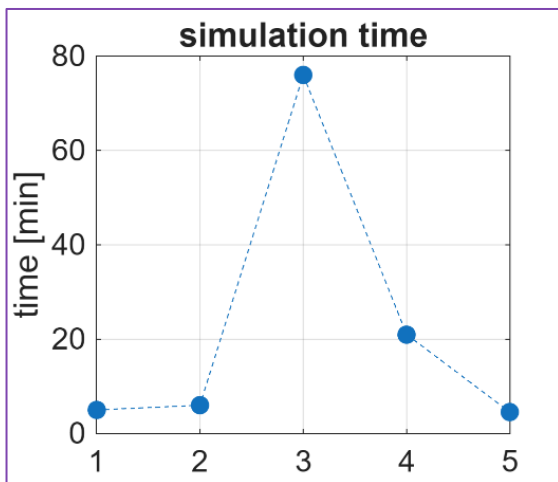
Significant impact of unconstrained Tmax on Eddy Current Iron Losses

12000 rpm, 130 N m – Hysteresis Iron Losses



12000 rpm, 130 N m – Summary

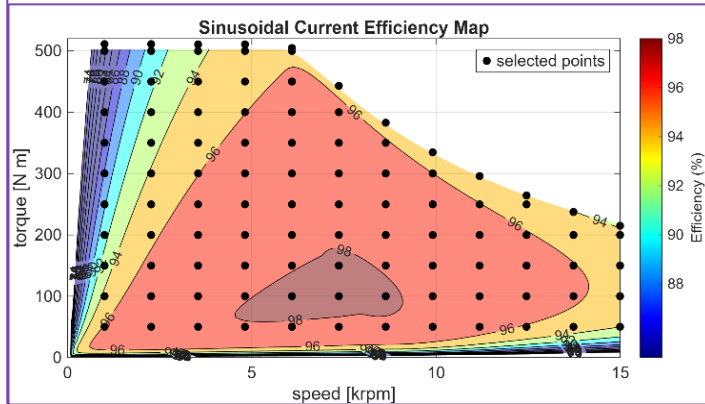
	Simulation	Torque [N m]	Sim. time	Mag Losses [W]	Eddy Losses [W]	Hysteresis Losses [W]
1	Sinusoidal Curr.	131.9	00:04:41	97.6	S:554; R:119	S:227; R:9.3
2	Sinusoidal Volt.	130.4	00:06:01	118.5	S:521; R:112	S:222; R:9.3
3	PWM – $T_{\max} = T_{\min}$	130.1	01:15:45	566	S:628; R:141	S:232; R:10.5
4	PWM – $T_{\max} = 5T_{\min}$	130.1	00:21:30	540	S:624; R:139	S:231; R:10.4
5	PWM - freeeee T_{\max}	129.7	00:04:24	538	S:2294; R:446	S:235; R:10.2



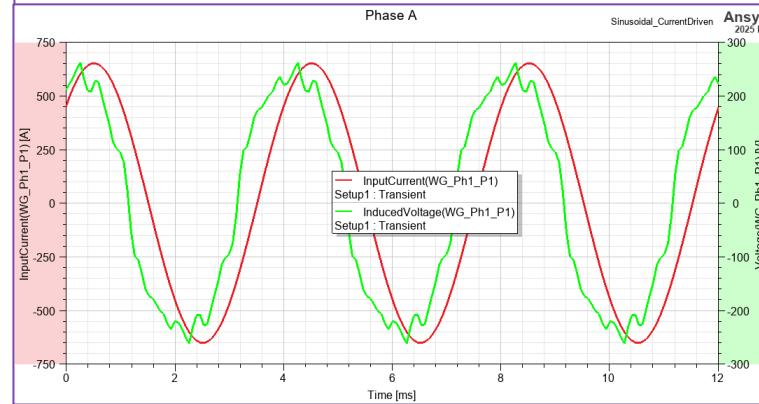
Motor-CAD/Maxwell Automated Workflow with PyAnsys

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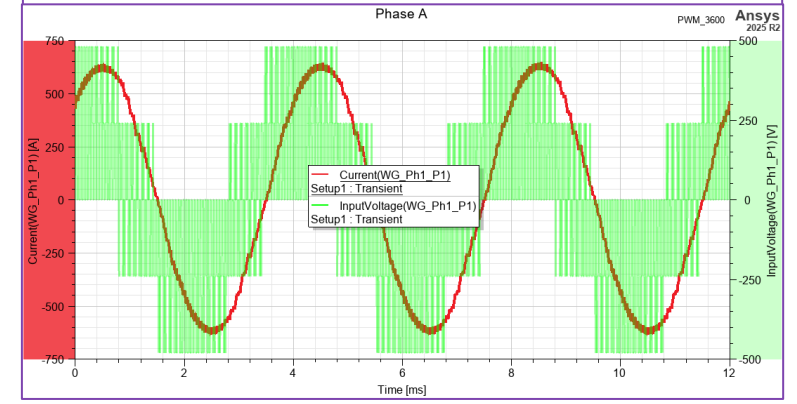
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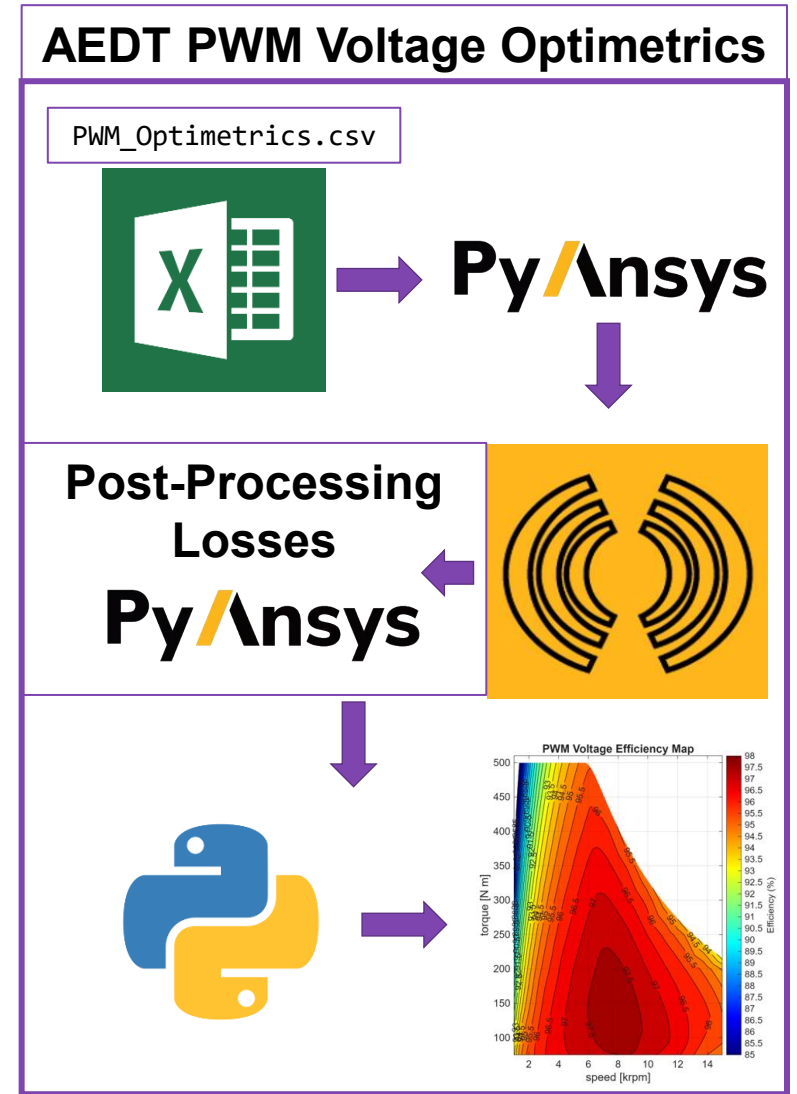
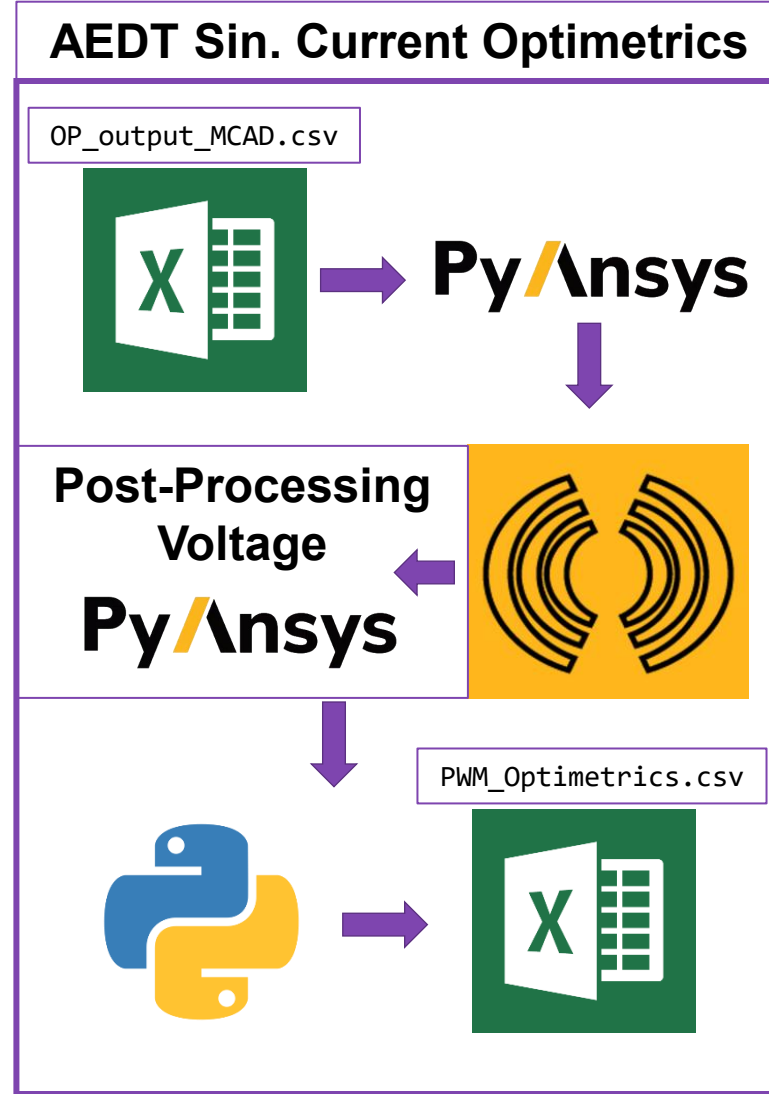
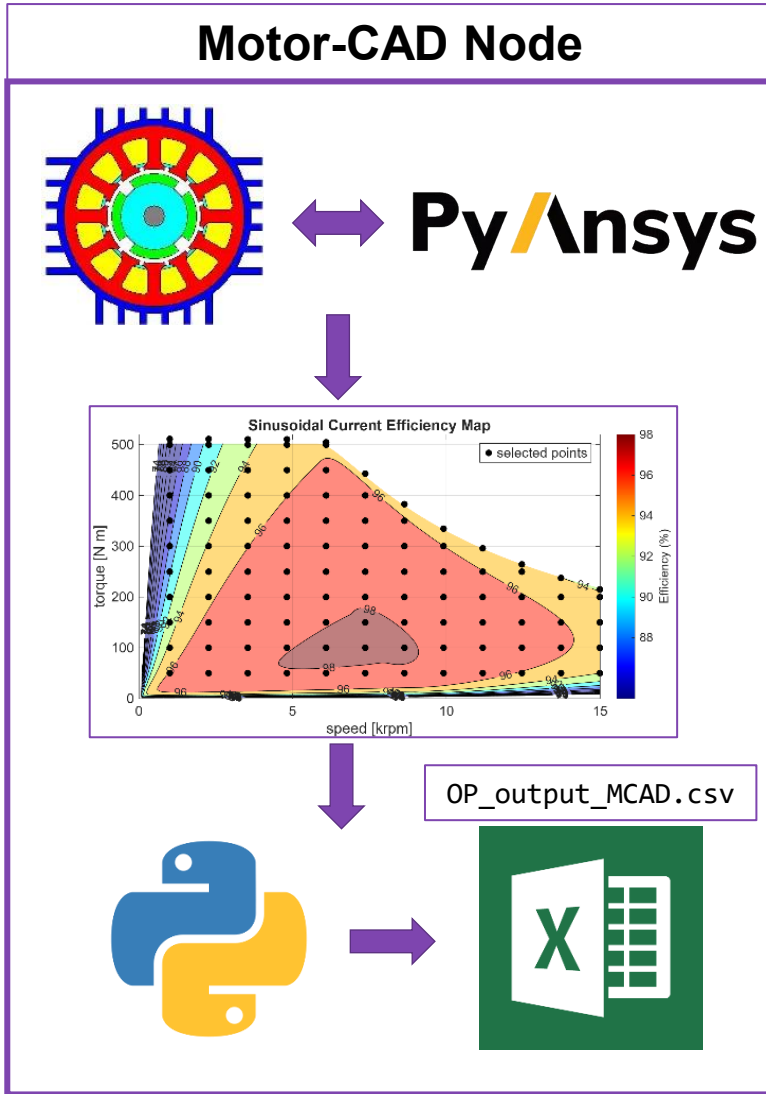
- **Maxwell current driven** simulation with current and phase advance from M-CAD to derive the correct voltage to apply with the PWM generator (phase and amplitude).



- **Maxwell voltage driven with SVPWM** is carried out with amplitude and phase form previous simulation.
- Additional losses due to PWM are calculated

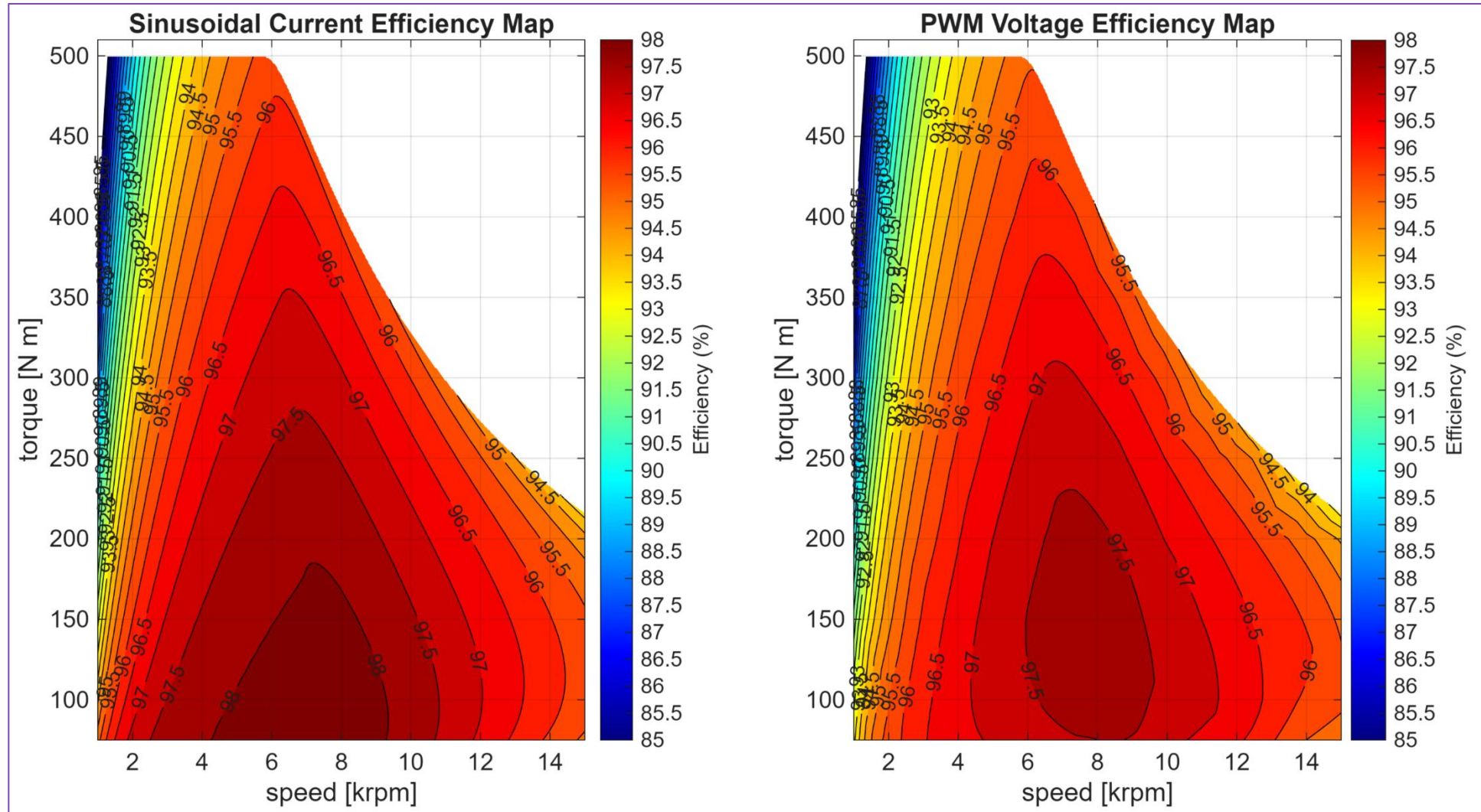


Automated Workflow Description

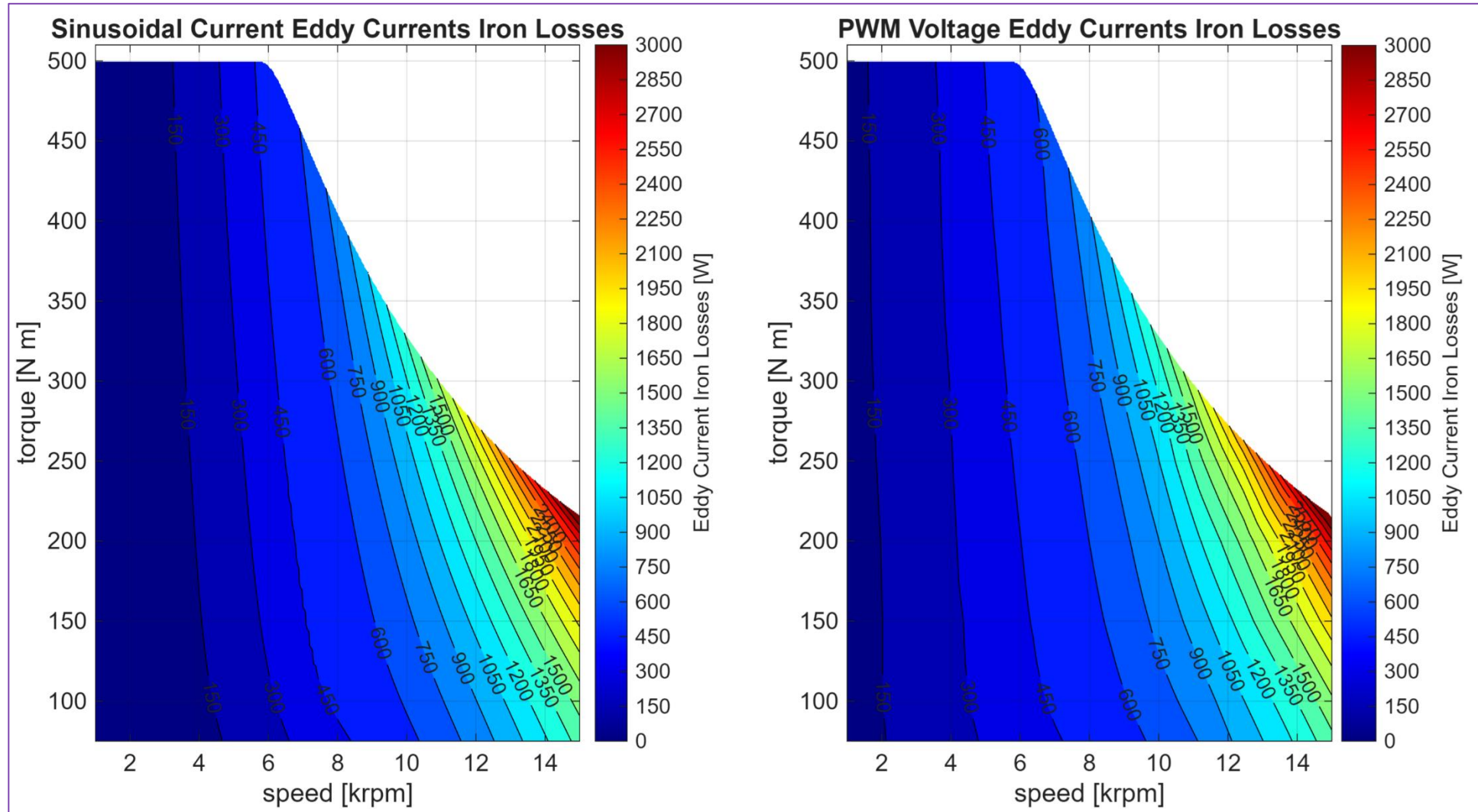


Some Results!!

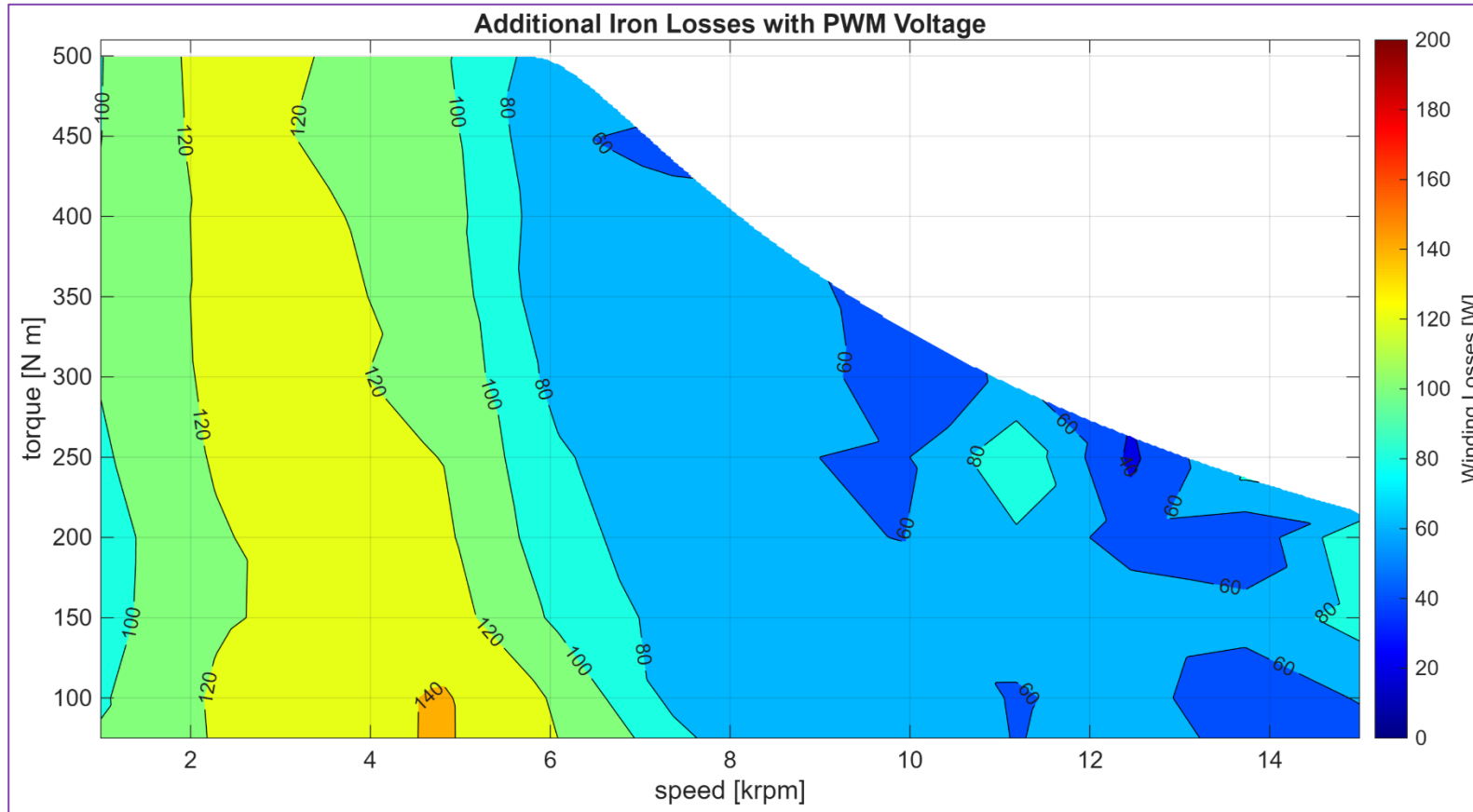
Efficiency Maps Comparison



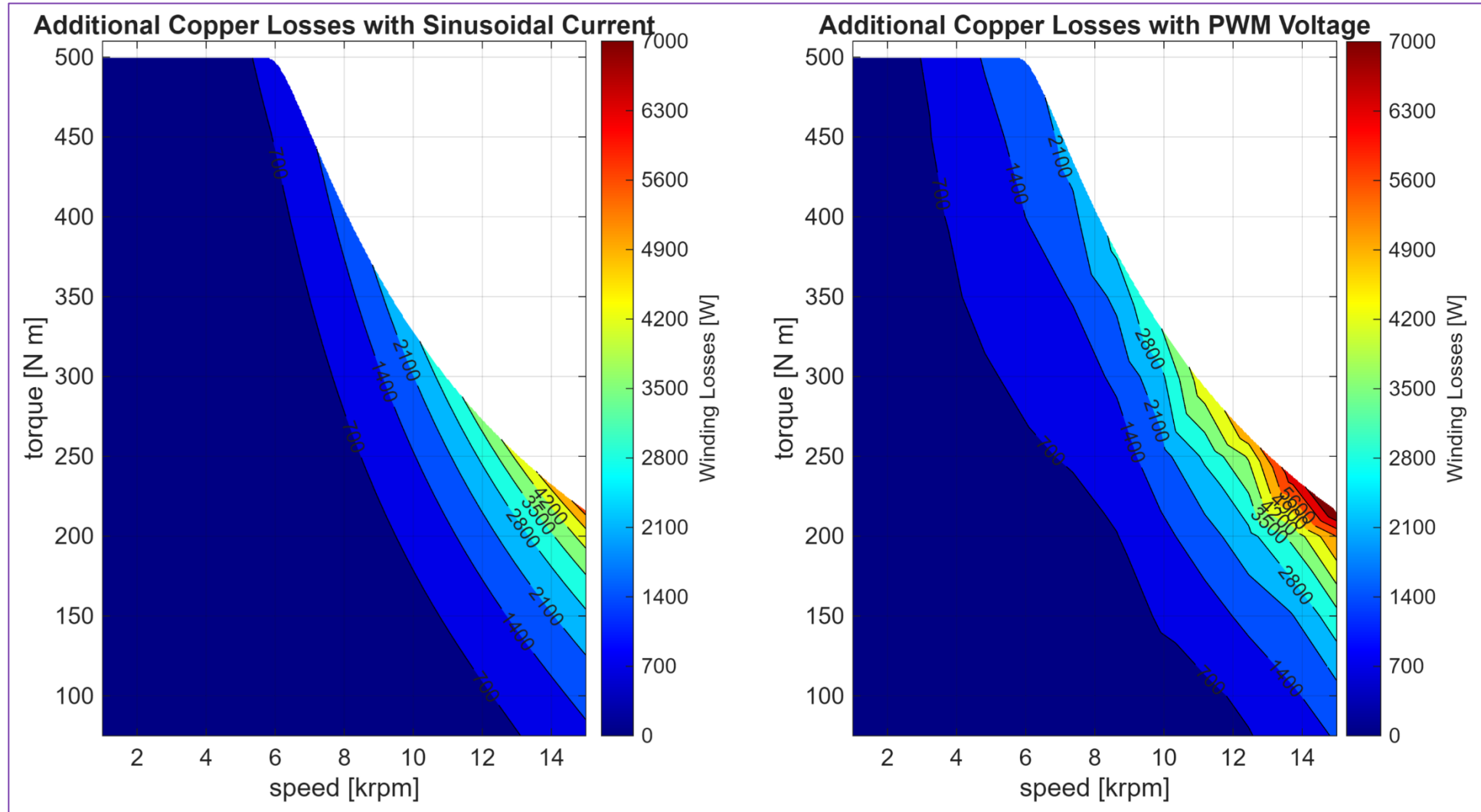
Eddy Currents Iron Losses Comparison



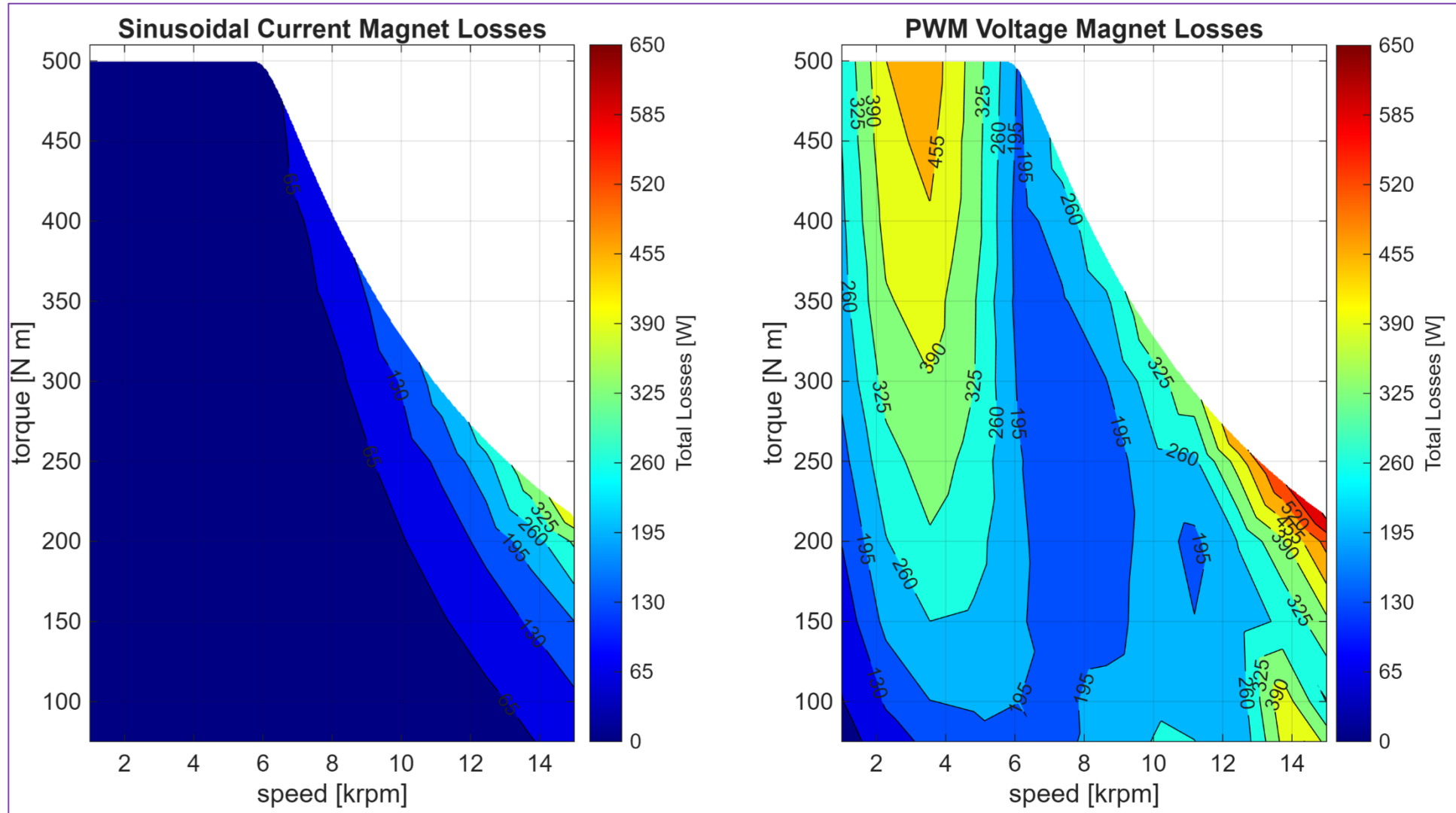
Additional Eddy Currents Iron Losses Map



Additional Copper Losses Maps Comparison



Magnet Losses Maps Comparison



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Thank you