Intensive Course:

Electric Motor Design Using MotorXP and MATLAB From Basics to Advanced

Amazon Lab126

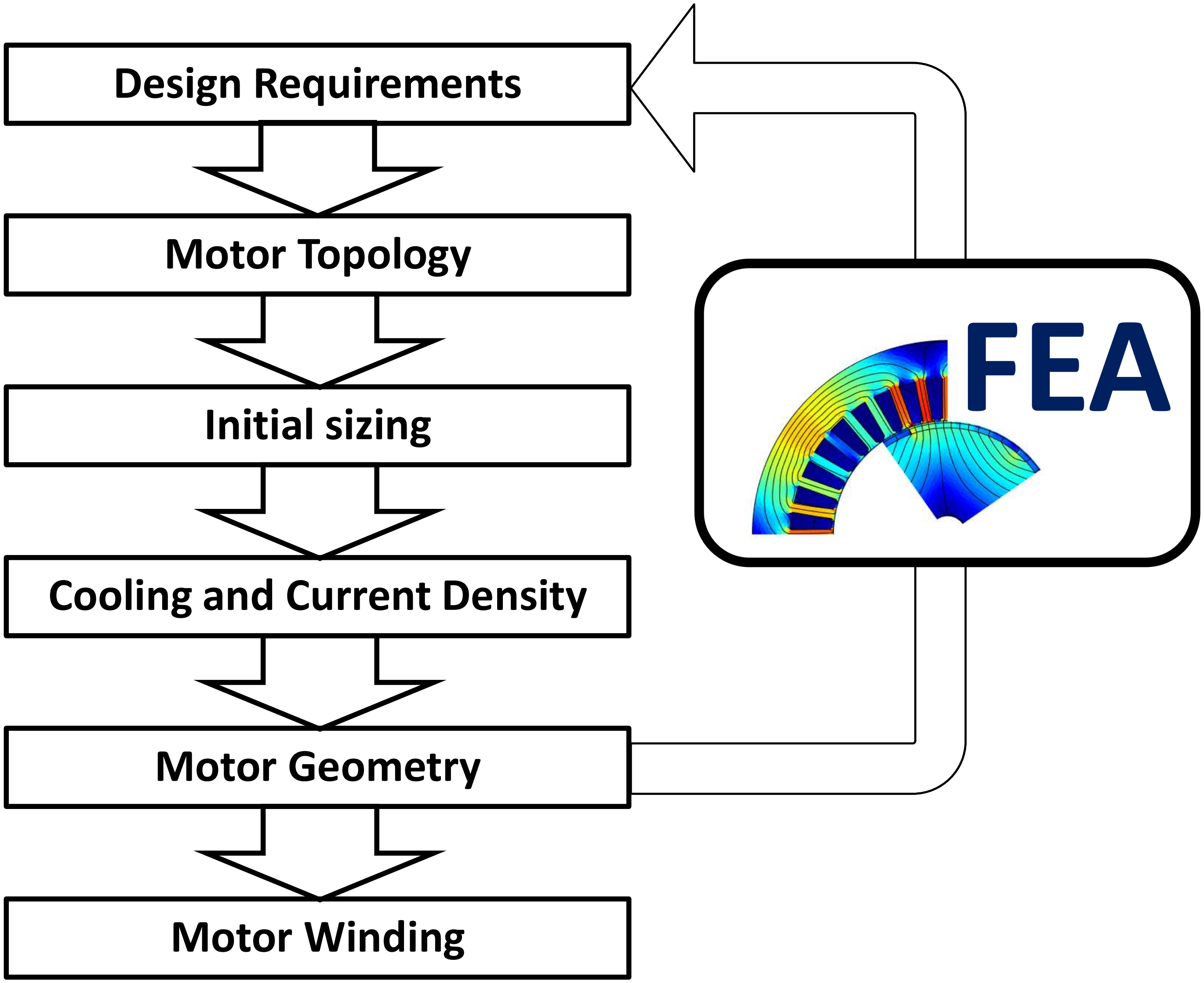
3-4 December 2025

MOTORXP

Agenda: day 1

- Basic design considerations and motor design workflow using MotorXP
- Design of an inrunner PMSM using magnetostatic FEA
- Design of an outrunner PMSM using magnetostatic FEA (independent task)
- Automatic optimization of the inrunner PMSM previously designed
- Optimization results analysis and discussion
- Design of an axial flux PMSM using magnetostatic FEA
- Automatic optimization of the axial flux PMSM previously designed
- Optimization results analysis and discussion

Electric Motor Design Workflow



Electric Motor Design Workflow: Design Requirements

Application details:

EV, robotics, aviation, industrial, etc.

Key Performance Metrics:

- Rated power and torque
- Operating speed range
- Voltage and current limitations

Use the power balance equation to match the electrical and mechanical parameters:

$$\underbrace{3 \cdot I_s \cdot V_s \cdot \cos(\phi) \cdot \eta}_{\text{Electrical power}} = \underbrace{T_e \cdot \omega_m}_{\text{Mechanical power}}$$

- I_s and V_s – stator phase current and voltage
- $\cos(\phi)$ – power factor
- η – motor's efficiency
- T_e – electromagnetic torque
- ω_m – mechanical angular speed of the rotor (rad/s)

Electric Motor Design Workflow: Motor Topology

Rotor type:

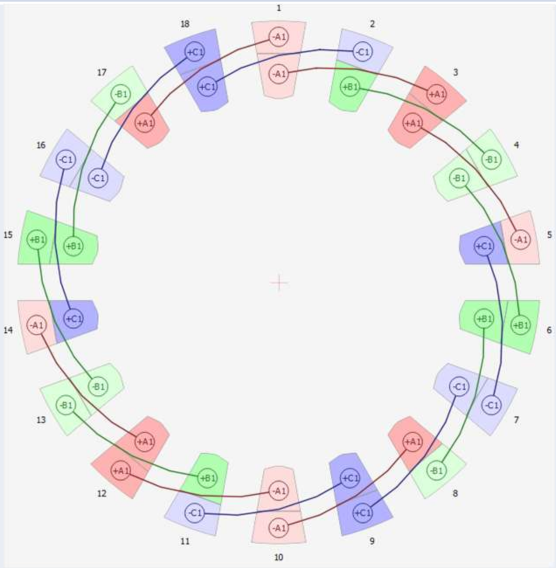
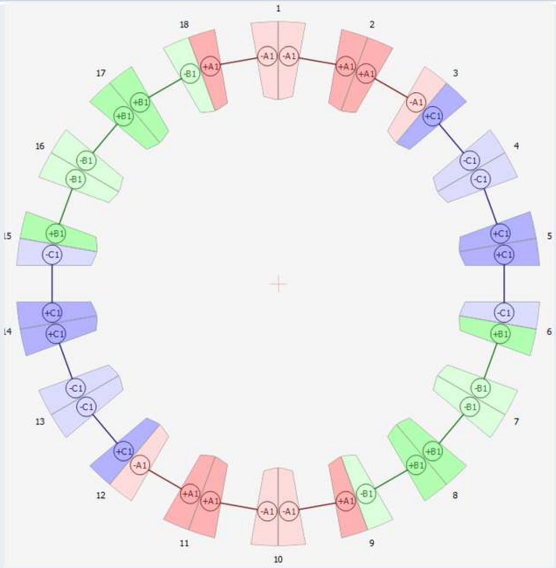
- Inrunner: higher speed, lower torque
- Outrunner: higher torque, lower speed
- Surface-mounted or IPM

Stator Winding Configuration:

- Distributed or concentrated winding (see next slide)
- Slot/pole combination
    - Higher number of poles allows for a more compact design but increases the supply frequency
- Slot fill factor considerations:
    - Higher slot fill factor allows for a smaller winding resistance: rectangular wire windings (also known as “hairpin”) have higher fill factor then round wire windings, but require advanced manufacturing techniques
    - Rectangular wires slot fill factor can be up to 70% or more compared to 30-50% for round wires

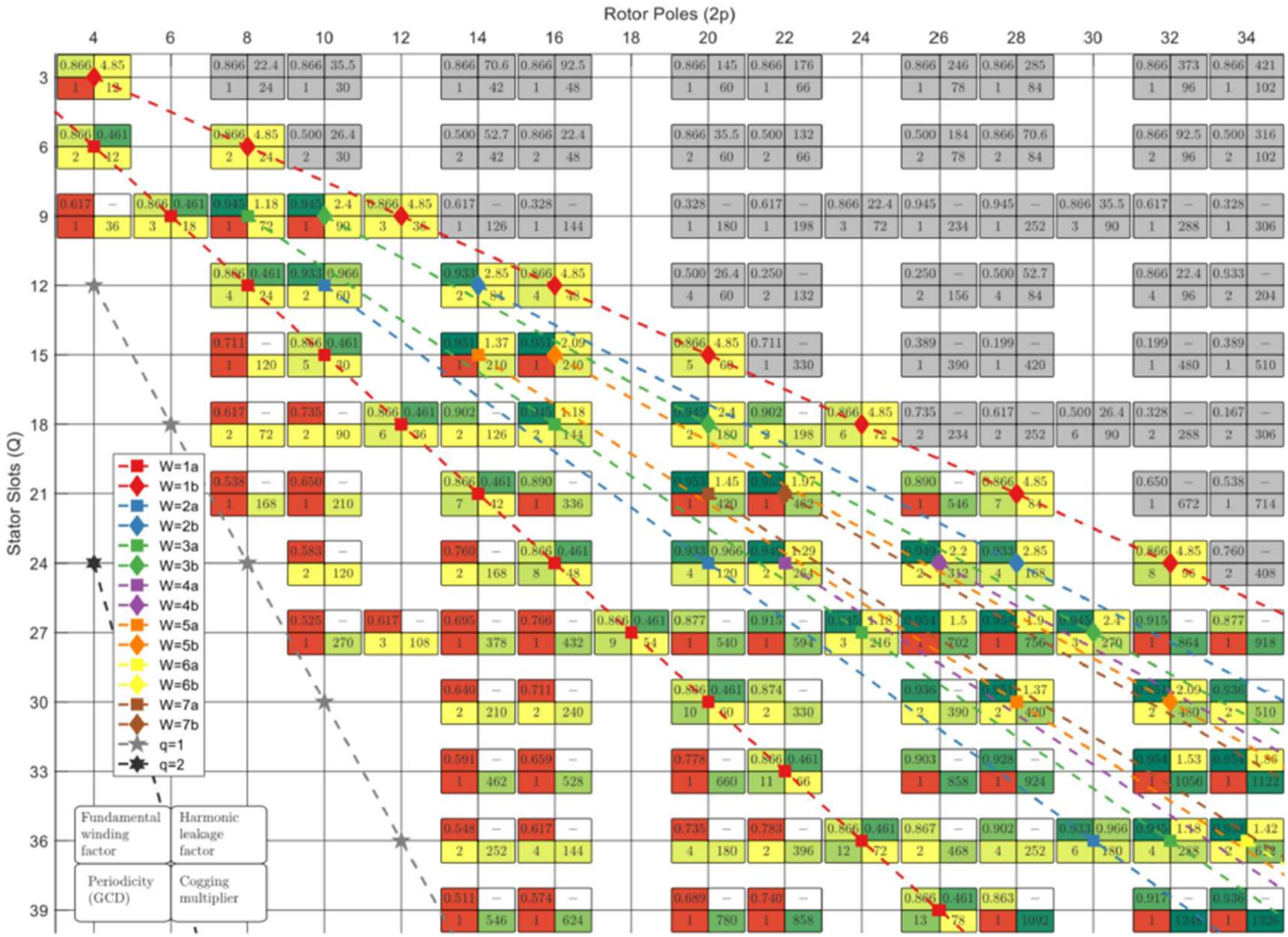
Electric Motor Design Workflow: Motor Topology

Stator Winding Configuration: *Distributed vs. concentrated winding*

Feature	Distributed Winding	Concentrated Winding
Magnetic Field	Smoother, reduces harmonics More sinusoidal back-EMF	Higher harmonics, leading to torque ripple More trapezoidal back-EMF
Manufacturing	Complex	Simple
Power Factor	Higher	Lower
Size	Larger	More compact
Application	Industrial motors, EV traction drives	Robotics, small appliances, cost-sensitive designs
Example		

Electric Motor Design Workflow: Motor Topology

Stator Winding Configuration: *Slot/pole combinations for concentrated windings**



*S. Skoog and A. Acquaviva, "Pole-Slot Selection Considerations for Double Layer Three-phase Tooth-Coil Wound Electrical Machines," *2018 XIII International Conference on Electrical Machines (ICEM)*, Alexandroupoli, Greece, 2018

Electric Motor Design Workflow: Initial Sizing

Outer diameter (D_o) and lamination length (L_l):

- Available space for the motor and dimensional constraints
- Torque requirements:
  - For radial flux motors the torque is proportional to the airgap radius squared - larger outer diameters allow for a larger airgap radius and higher torque; torque is also proportional to lamination length
  - For axial flux motor the torque is proportional to $R_o^3 - R_i^3$, where R_o and R_i are outer and inner radii of the airgap, which makes AFM often preferred for applications requiring high torque density in a compact form factor.
- Rotor strength and mechanical stress: larger outer diameters lead to higher centrifugal forces which can damage the rotor at high rotational speeds
- Lower $\frac{D_o}{L_l}$ ratios for high-speed applications. Higher $\frac{D_o}{L_l}$ ratios for high-torque applications.

Air gap considerations:

- Smaller air gap:
  - Higher efficiency and torque due to reduced flux leakage and magnetic resistance
  - Must account for thermal expansion of the rotor and stator to prevent contact
- Larger air gap:
  - Lower eddy current losses in magnets and lower cogging torque
  - Enhanced airgap airflow for cooling
  - Reduces sensitivity to rotor eccentricity and vibration
- Typical Values:
  - small motors: 0.2–0.5 mm; medium/large motors: 0.5–2 mm

Electric Motor Design Workflow: Cooling and Current Density

Cooling Method	Current Density (A/mm²)	Details
Natural Air Cooling	3–5	For low-power motors or applications with low-duty cycles.
Forced Air Cooling	5–8	Enhanced cooling with fans or blowers.
Water Jacket Cooling	8–15	Effective for high-performance applications (e.g., automotive).
Oil Cooling	10–20	Ideal for high-power-density designs (e.g., motorsport, aerospace).
Spray/Immersion Cooling	20–50	Direct fluid cooling for ultra-high-power motors.

Current density considerations:

- Duty Cycle: Motors with intermittent operation can sustain higher current densities for short periods.
- Insulation Class: Higher thermal-grade insulation (e.g., Class H or F) supports higher operating temperatures and current densities.
- Thermal Management: Advanced cooling systems (heat pipes, thermal interface materials, etc.) improve heat transfer and support higher densities.
- Motor Size: Smaller motors have less thermal mass and may require lower current densities compared to larger motors with more robust cooling.

Electric Motor Design Workflow: Motor Geometry

Geometry considerations for radial flux motor with surface-mounted magnets:

- Magnet Volume Calculation*:

$$MagnetVolume = C_v \cdot \frac{RatedPower}{f_1 \cdot B_r \cdot H_c}$$

  - *RatedPower* – rated output power of the motor
  - f_1 – operational motor frequency
  - B_r – residual flux density of the magnet
  - H_c – coercivity of the magnet
  - C_v – magnet volume coefficient 0.2… 4
- Tooth and slot width:
  - Thicker teeth can reduce saturation and enhance the flux carrying capacity but leave less space for slots
  - Higher slot width allows more space for windings, improving electrical performance (higher current capacity, lower resistance).
- Tooth width and stator back iron depth:
  - For concentrated winding:

$$statorBackIronDepth \leq toothWidth$$

  - For distributed winding:

$$statorBackIronDepth \leq \frac{toothWidth \cdot nSlots}{2 \cdot nPoles}$$

- Stator back iron depth ≈ rotor back iron depth: since they carry the same magnetic flux
- Slot Opening Width:
  - Smaller slot opening width helps to reduce magnet losses and torque ripple caused by slot harmonics
  - Wider slot openings reduce flux leakage
- Adjust geometry based on recommended magnetic flux density levels (next slide).

*C. C. Mi and L. Luo, “Analytical design of permanent magnet traction drive motors,” 2005 IEEE Vehicle Power and Propulsion Conference, Chicago, IL, 2005

Electric Motor Design Workflow: Motor Geometry

Recommended magnetic flux density levels:

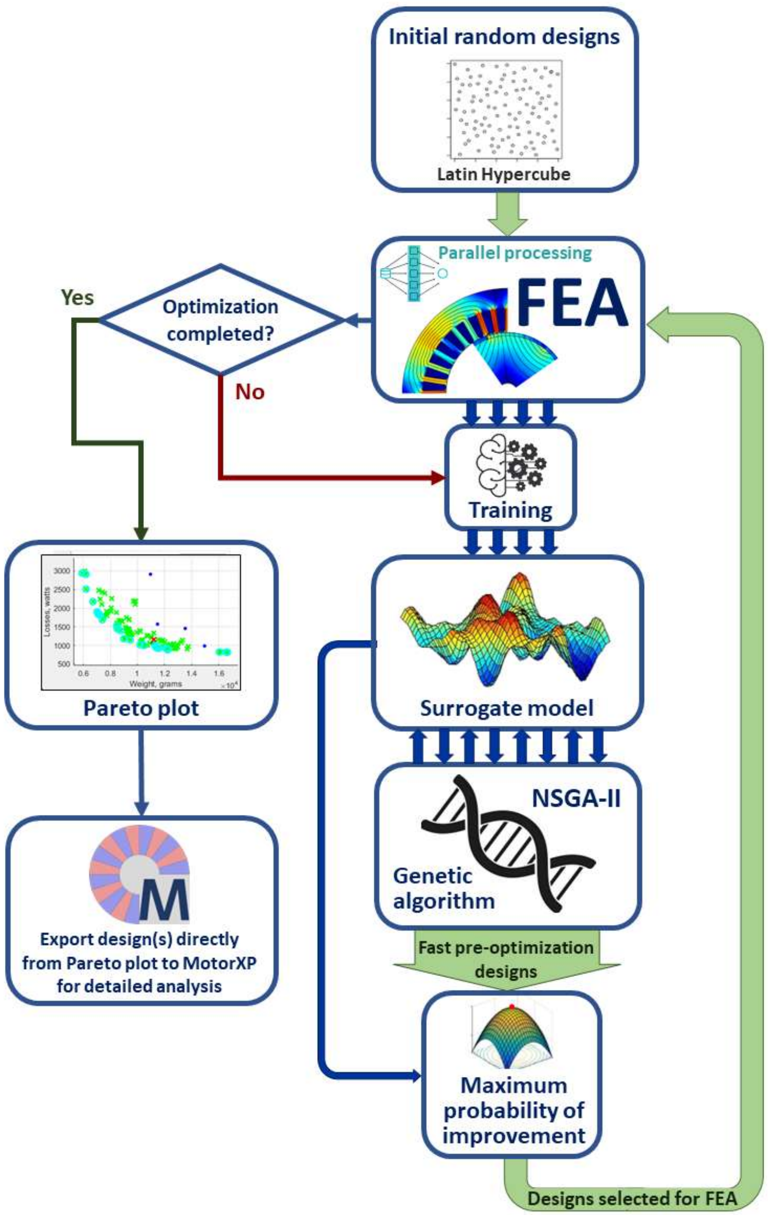
Motor part	Flux density
Air Gap	0.8–1.2 T
Stator Tooth	1.5–1.8 T
Stator Back Iron	1.2–1.5 T
Rotor Back Iron	0.8–1.2 T

Electric Motor Design Workflow: Case Study

Motor specifications and requirements:

- Outer diameter: 350 mm
- Motor length: ≤ 60 mm
- Air gap: 1.5–2.5 mm
- Rated (base) speed: 1600 RPM
- Rated power: 50 kW
- Maximum speed: 4000 RPM
- Current density: 10–11 A/mm^2
- Iron core material: M-19 29Ga, stacking factor ~0.95
- Magnet material: N45UH
- Slot fill factor: ~0.35
- Winding type: concentrated, 18 slots / 16 poles
- Estimated winding temperature: 50°C
- Estimated magnet temperature: 50°C
- Vdc: 650 V, space vector PWM

Motor Design Optimization Algorithm in MotorXP



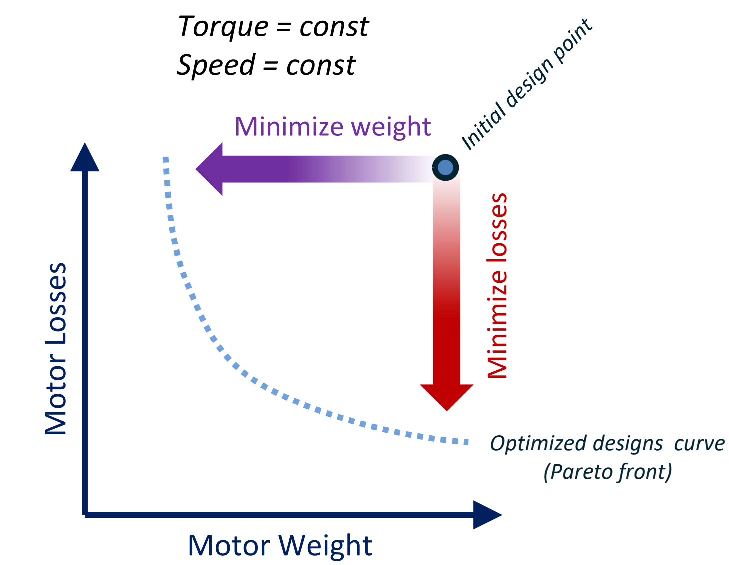
First, several initial designs, randomly distributed across the design space, are generated and processed using FEA. These designs are used for the initial training of the surrogate model.

FEA is used to calculate optimization objectives for each design.
Parallel processing enables the evaluation of several designs simultaneously.

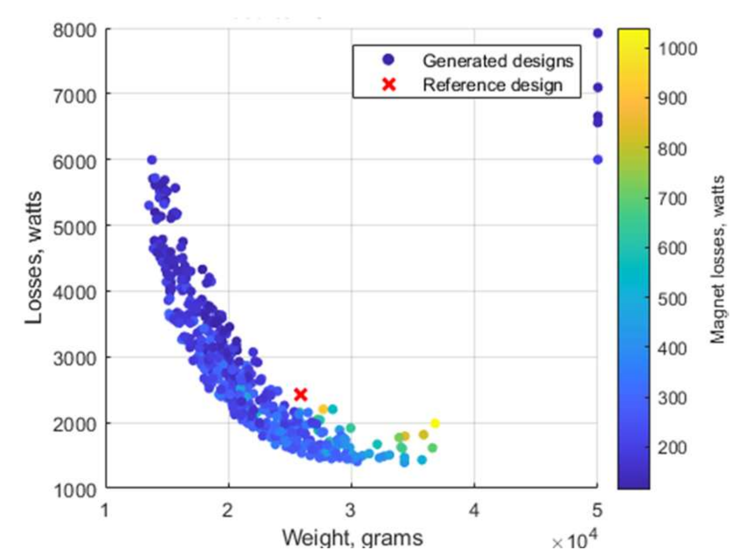
FEA results are utilized to train the surrogate model on how the optimization objectives correlate with the optimization variables. With each iteration of the optimization algorithm, the surrogate model continuously improves as new FEA results are incorporated into the training process.

Because the surrogate model operates much faster than FEA, the genetic algorithm can evaluate thousands of designs within seconds.

Based on the “maximum probability of improvement” criteria, only several “most promising” designs, among those generated by the genetic algorithm, are chosen for further processing with FEA.

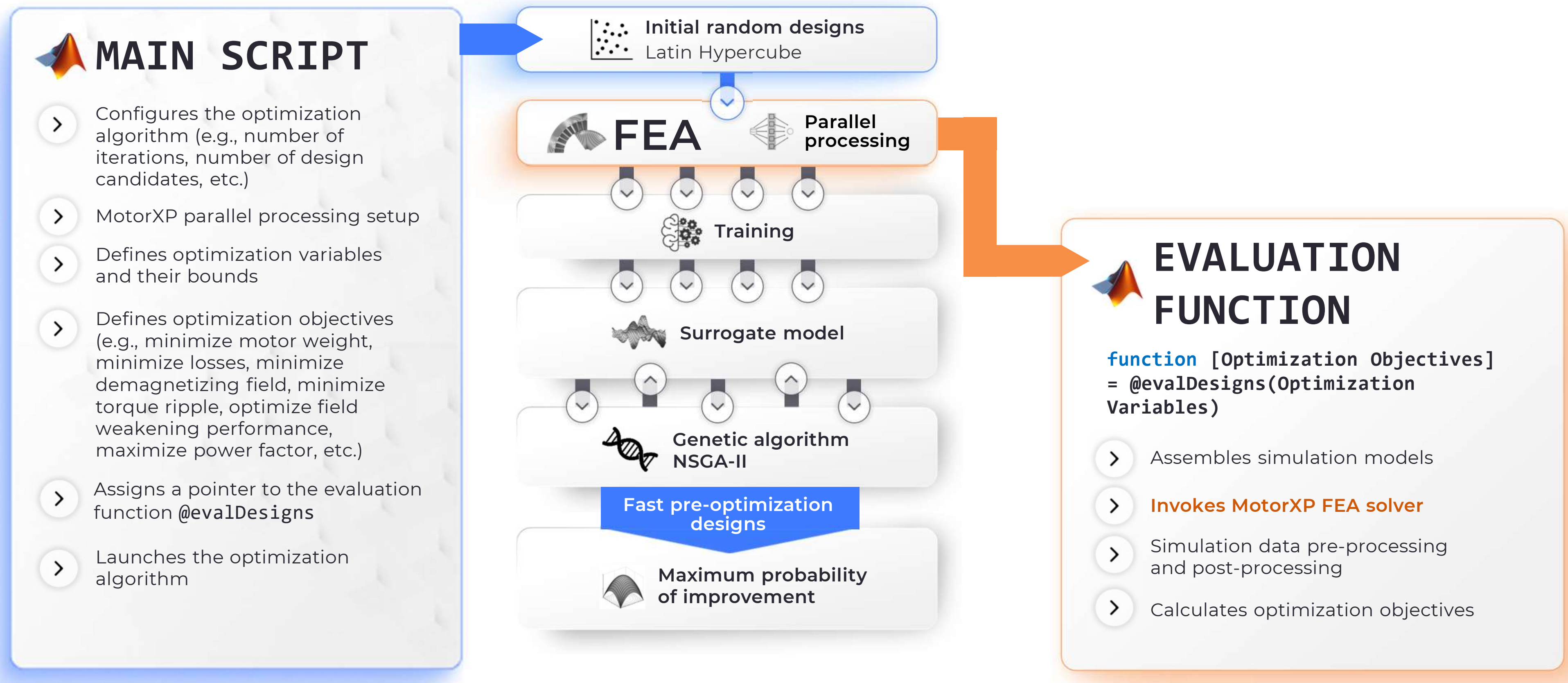


Optimization principle for two objectives

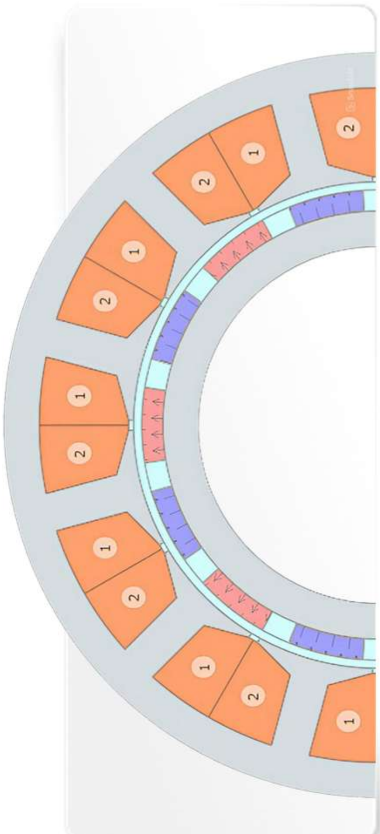


Example of Pareto plot for three optimization objectives

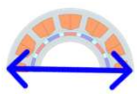
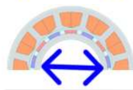
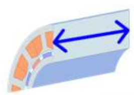
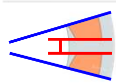
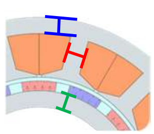
Motor Design Optimization: implementation using MATLAB



Automatic Design Workflow Example



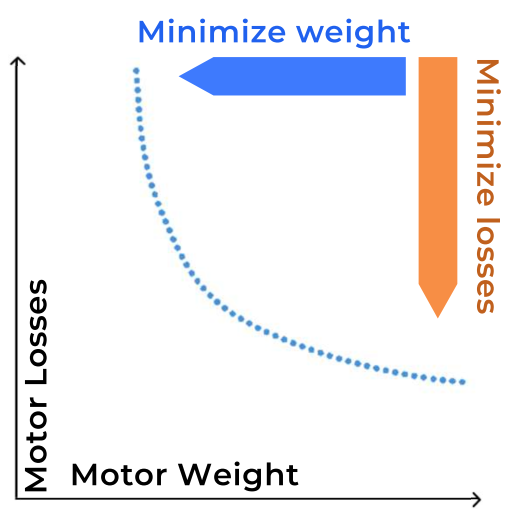
RADIAL FLUX SURFACE-MOUNTED PMSM

	DESIGN VARIABLE	DEFAULT VALUES Min		DEFAULT VALUES Max
	Outer diameter	Defined by user as a range or as a fixed value		
	Inner diameter	Defined by user as a range or as a fixed value		
	Lamination length	Defined by user as a range or as a fixed value		
	Air gap	Defined by user as a range or as a fixed value		
	Magnet weight (volume)	Defined by user as a range, as a fixed value or calculated automatically		
	Tooth width span	0.2		0.8
	Stator back iron / Tooth width	0.3		1
	Rotor back iron / Stator back iron	0.8		1.2
	Magnet angle (elect. degrees)	110		180

For more info:
https://motorxp.com/ai-powered-electric-motor-design/

Optimized designs curve (Pareto front)

Torque = const
Speed = const



Agenda: day 2

- Motor Winding Design
- Field-Weakening Operation
- Design Considerations for Interior Permanent Magnet Motors (IPM)
- Dynamic D-Q Analysis and Inverter Losses Calculation
- Introduction to Custom Geometry Template Development
- Dynamic FEA
- Q&A Session

Electric Motor Design Workflow: Motor Winding

Selection of number of turns and parallel paths:

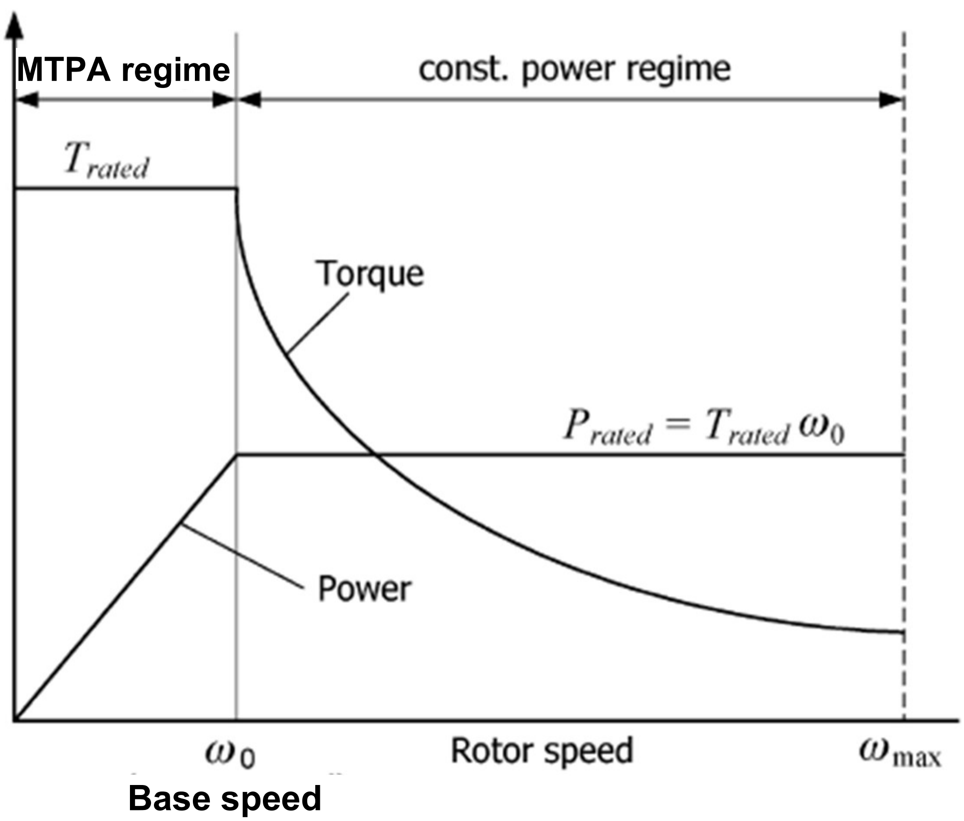
$$I_s = I_s(1) \cdot N_{pp}/W$$
$$V_s = V_s(1) \cdot W/N_{pp}$$

- I_s and V_s – stator RMS phase current and RMS phase voltage
- $I_s(1)$ and $V_s(1)$ – stator RMS phase current and RMS phase voltage for one turn and one parallel path
- N_{pp} – number of parallel paths
- W – number of turns
- *Vdc* – DC voltage of the inverter

Maximum inverter voltage levels for different modulation types:

Connection	Modulation type	Maximum phase voltage (RMS)
Star	Sinusoidal PWM, Hysteresis PWM	$\frac{Vdc}{2 \cdot \sqrt{2}} \approx 0.3536 \cdot Vdc$
Star	Space Vector PWM	$\frac{Vdc}{\sqrt{6}} \approx 0.4082 \cdot Vdc$
Delta	Sinusoidal PWM, Hysteresis PWM	$\frac{Vdc \cdot \sqrt{3}}{2 \cdot \sqrt{2}} \approx 0.6124 \cdot Vdc$
Delta	Space Vector PWM	$\frac{Vdc}{\sqrt{2}} \approx 0.7071 \cdot Vdc$

Field-Weakening Operation



Constant output power condition (optimal flux weakening condition)*:

$$\begin{cases} I_{ch} = \Psi_{md}/L_d \\ I_{rated} \approx I_{ch} \end{cases}$$

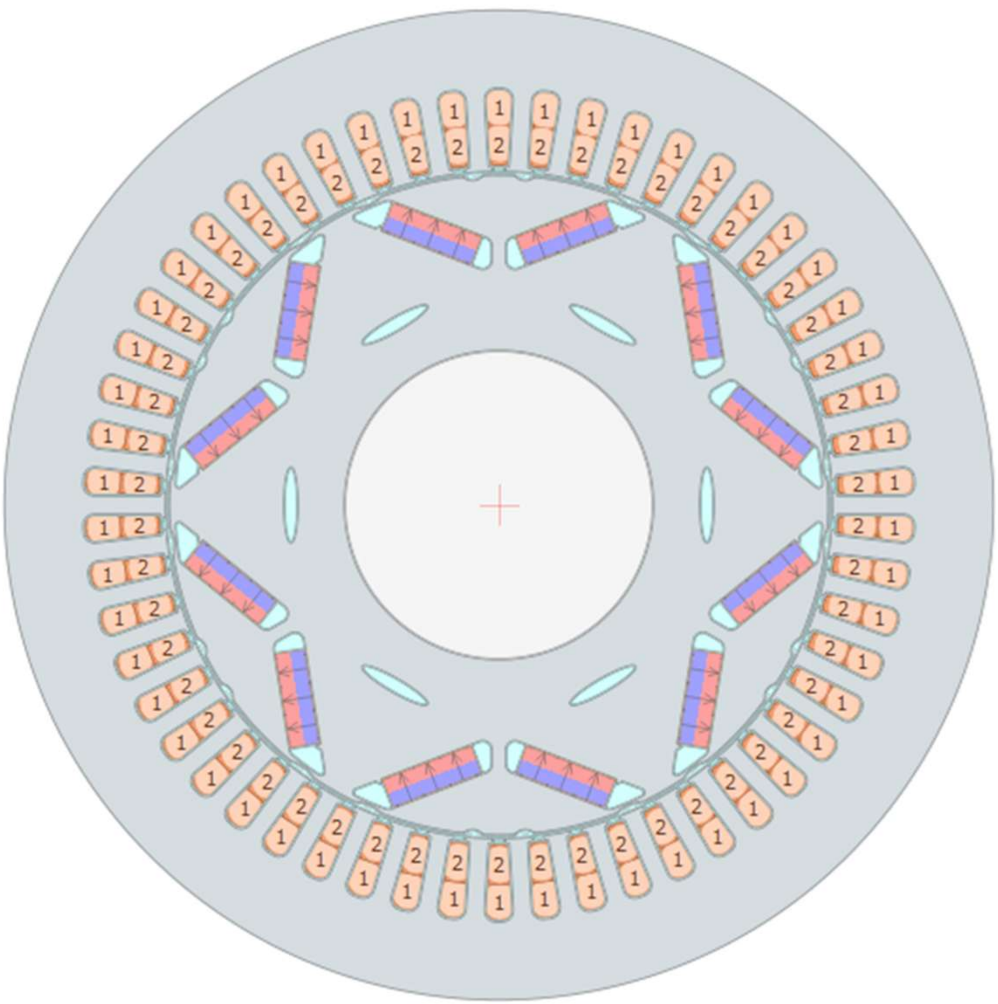
- I_{rated} – rated current of the motor
- I_{ch} – characteristic current
- ψ_{md} – d-axis magnet flux linkage
- L_d – d-axis inductance

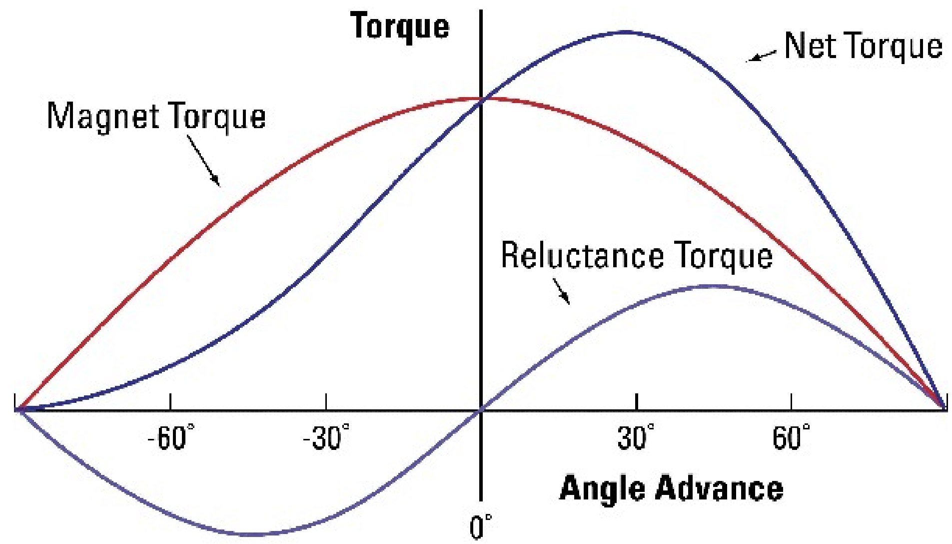
Why Utilize Field-Weakening?

*Kuptsov, V.; Fajri, P.; Trzynadlowski, A.; Zhang, G.; Magdaleno-Adame, S. Electromagnetic Analysis and Design Methodology for Permanent Magnet Motors Using MotorAnalysis-PM Software. Machines 2019, 7, 75.

Interior permanent magnet (IPM) motors

Why Are IPM Motors More Efficient in Field-Weakening Operations?





Torque of IPM motor:

$$T_{em} = \frac{3}{2} p \left[\underbrace{\Psi_{md} I_{qs}}_{\text{Magnet torque}} \underbrace{-(L_q - L_d) I_{qs} I_{ds}}_{\text{Reluctance torque}} \right], \quad L_q > L_d$$

- I_d and I_q – d-axis and q-axis currents of the motor
- L_d and L_q – d-axis and q-axis inductances
- ψ_{md} – d-axis magnet flux linkage
- L_d – number of pole pairs

Dynamic D-Q Analysis

Examples of usage:

- Analysis of the motor performance using actual current and voltage waveforms (including PWM effects)
- Optimal selection of the PWM sampling frequency
  - A higher PWM frequency reduces current ripple, improving efficiency and torque smoothness, but may lead to higher inverter switching losses.
- Optimal selection of inverter transistors
- Evaluation of inverter losses (conduction and switching), voltage drops and overall efficiency

Dynamic Finite Element Analysis

Examples of usage:

- Simulation of custom electrical circuits connected to the motor
- Simulation of custom control algorithms and PWM strategies
- Rotor eccentricities
- Generating mode with different types of load (R, L, C, rectifier, etc.)
- Circulating currents between parallel paths or in the delta-connected windings.
- Iron losses associated with PWM ripples

Dynamic Finite Element Analysis: using electrical circuits

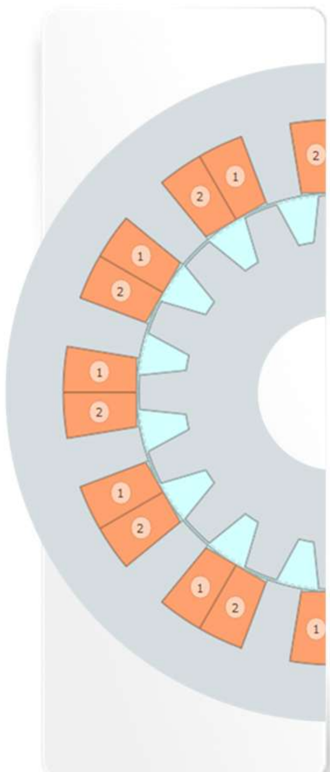
MOTOR – POWER ELECTRONICS – CONTROL CO-SIMULATION

Transient finite element motor model coupled with electrical circuit

Component Type	Electric Circuit Component	Control Behavior
Passive components	Resistor Capacitor Inductor	These components do not have control options
Active components	Electric switch	Controlled at each simulation step (ON/OFF)
	Diode	Automatically changes state based on current direction
Power sources	Voltage source Current source	Output is controlled at each simulation step, allowing for different waveform profiles
Motor Winding Coils	Coil	Provides coupling between the electrical circuit and the motor's finite element model

Dynamic Finite Element Analysis Example

Switched reluctance motor: Electrical circuit (Asymmetric Half-Bridge Converter)

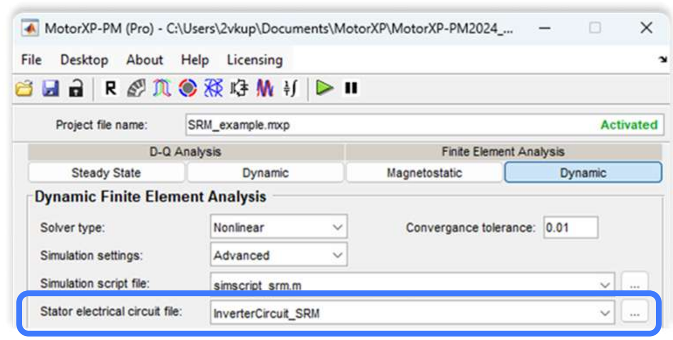


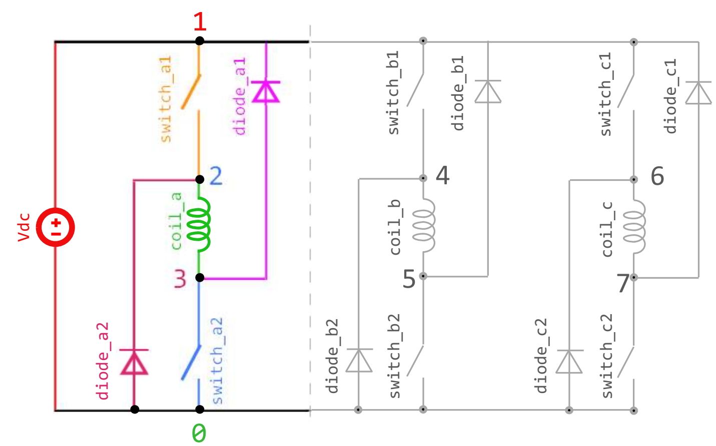
Stator electrical circuit file: InverterCircuit_SRM

MotorXP\InverterCircuit_SRM.m

EDITOR PUBLISH VIEW

```
.........................
Schematic = CircuitCreateSchematic();

Branch = CircuitCreateBranch(0,1);
Branch = CircuitAddE(Branch,'Vdc','CircuitControl.vdc');
Schematic = CircuitAddBranch(Schematic,Branch);

% Phase A
Branch = CircuitCreateBranch(1,2);
Branch = CircuitAddSwitch(Branch,'switch_a1',...
         'CircuitControl.switch_a1',Roff,Ron);
Schematic = CircuitAddBranch(Schematic,Branch);

Branch = CircuitCreateBranch(3,1);
Branch = CircuitAddDiode(Branch,'diode_a1',Roff,Ron,1);
Schematic = CircuitAddBranch(Schematic,Branch);

Branch = CircuitCreateBranch(2,3);
Branch = CircuitAddCoil(Branch,'coil_a','a',...
Schematic = CircuitAddBranch(Schematic,Branch);

Branch = CircuitCreateBranch(3,0);
Branch = CircuitAddSwitch(Branch,'switch_a2',...
         'CircuitControl.switch_a2',Roff,Ron);
Schematic = CircuitAddBranch(Schematic,Branch);

Branch = CircuitCreateBranch(0,2);
Branch = CircuitAddDiode(Branch,'diode_a2',Roff,Ron,1);
Schematic = CircuitAddBranch(Schematic,Branch);
.........................
```





Dynamic Finite Element Analysis Example

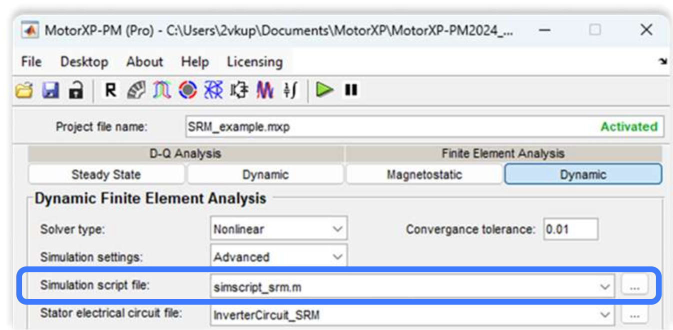
Switched reluctance motor: Control

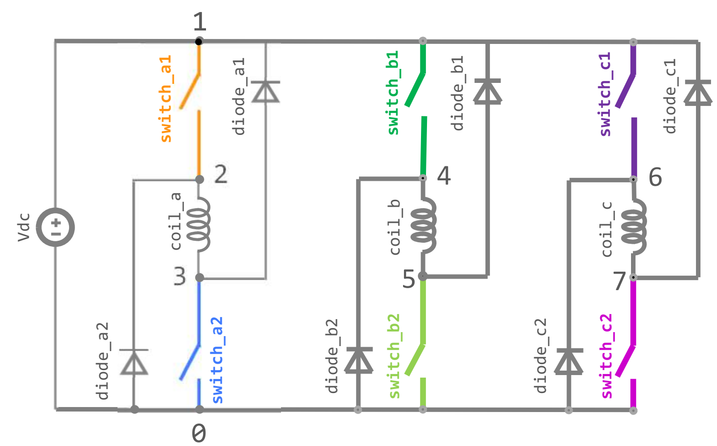
Simulation script file: simscript_srm.m

MotorXP\simscript_srm.m

EDITOR PUBLISH VIEW

```
.........................
% Switching phases depending on the rotor position - theta_deg
if (theta_deg >= 0 && theta_deg < 30) || (theta_deg >= 90 && theta_deg < 120)...
 || (theta_deg >= 180 && theta_deg < 210) || (theta_deg >= 270 && theta_deg < 300)
      % Turn on phase A
      CircuitControl.switch_a1 = 1;
      CircuitControl.switch_a2 = 1;
      CircuitControl.switch_b1 = 0;
      CircuitControl.switch_b2 = 0;
      CircuitControl.switch_c1 = 0;
      CircuitControl.switch_c2 = 0;
elseif (theta_deg >= 30 && theta_deg < 60) || (theta_deg >= 120 && theta_deg < 150)...
 || (theta_deg >= 210 && theta_deg < 240) || (theta_deg >= 300 && theta_deg < 330)
      % Turn on phase B
      CircuitControl.switch_a1 = 0;
      CircuitControl.switch_a2 = 0;
      CircuitControl.switch_b1 = 1;
      CircuitControl.switch_b2 = 1;
      CircuitControl.switch_c1 = 0;
      CircuitControl.switch_c2 = 0;
elseif (theta_deg >= 60 && theta_deg < 90) || (theta_deg >= 150 && theta_deg < 180)...
 || (theta_deg >= 240 && theta_deg < 270) || (theta_deg >= 330 && theta_deg < 360)
      % Turn on phase C
      CircuitControl.switch_a1 = 0;
      CircuitControl.switch_a2 = 0;
      CircuitControl.switch_b1 = 0;
      CircuitControl.switch_b2 = 0;
      CircuitControl.switch_c1 = 1;
      CircuitControl.switch_c2 = 1;
end
.........................
```





Dynamic Finite Element Analysis Example

Switched reluctance motor: Simulation results