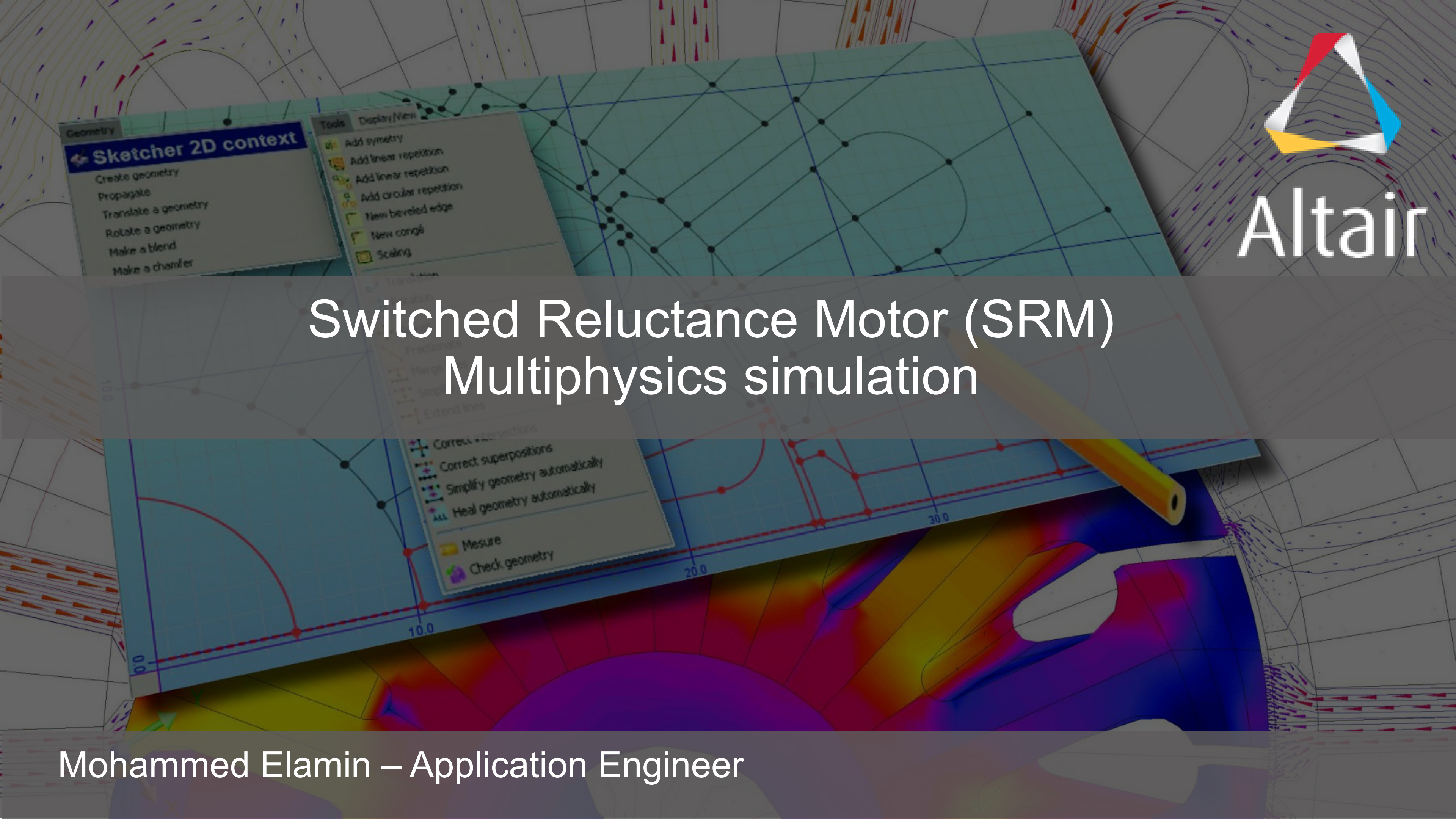


Switched Reluctance Motor (SRM) Multiphysics simulation

Mohammed Elamin – Application Engineer

CONTENTS

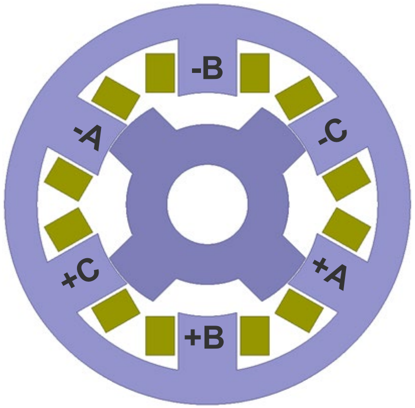
- SRM Operation.
- Case study.
- Electromagnetic simulation of SRM:
  - ➢ Static simulation.
  - ➢ Transient simulation.
- System and control:
  - ➢ Different modeling approaches.
  - ➢ Open loop control and comparison.
  - ➢ Closed loop (Speed) control.
- Mechanical Vibroacoustic:
  - ➢ Noise and vibration in SRM.
  - ➢ Magnetic force analysis.
  - ➢ frequency response and modal analysis

SRM OPERATION

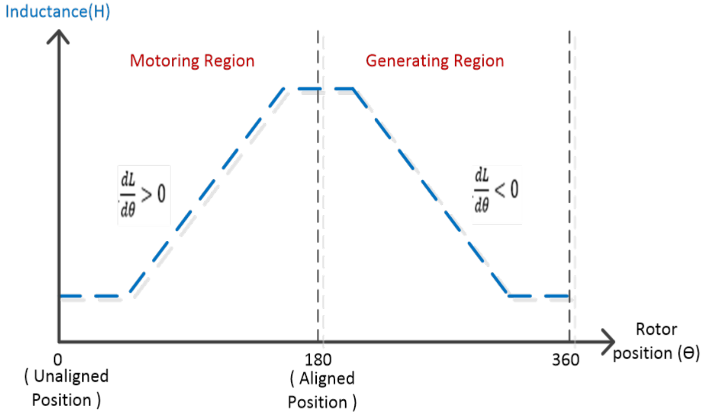
- SRM has double salient structure.
- Electromagnetic torque generation depends on minimizing the reluctance of the flux path.
- Electromagnetic torque:

$$T = \left[\frac{\partial W_c}{\partial \theta}\right]_{i=const} \qquad T = \frac{1}{2} i^2 \frac{dL}{d\theta}$$

- Ideal inductance profile (ignoring saturation and fringing effect)
- Aligned and unaligned position
- Motoring and generating regions



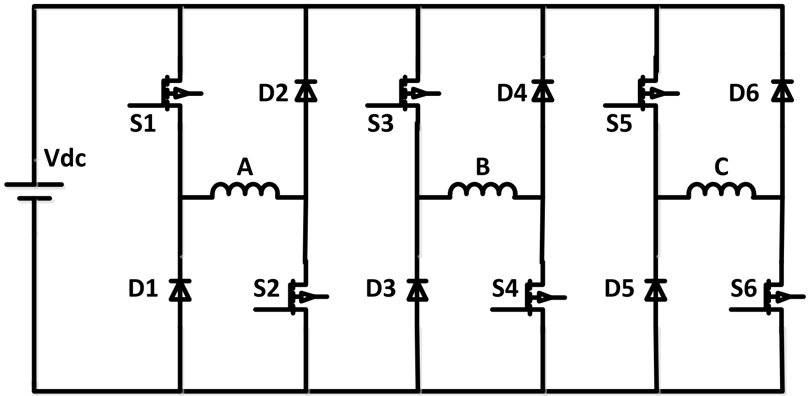
SRM Structure



Ideal inductance profile

SRM OPERATIONS

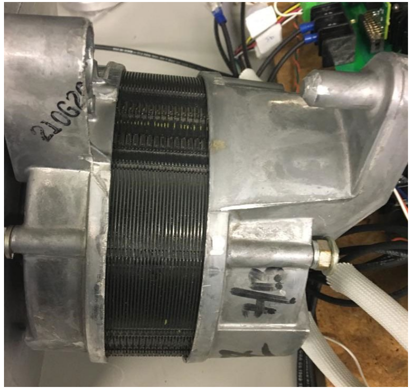
- SRM requires electronically commutated excitation
- AHB is the most used power converter to drive SRMs
- Magnetization, demagnetization, and free-wheeling
- Control parameters: turn-on angle, turn-off angle, and the reference current.



Asymmetric half bridge (AHB) converter

CASE STUDY

Application	Washer machine
Number of phases	3
Number of stator/rotor poles	12/8
Stator Outer Radius	69.76 mm
Stator Inner Radius	41.935 mm
Shaft Radius	8.54 mm
Air gap	0.445 mm
Stack Length	46.92 mm
Number of turns per pole	150
Number of parallel path	2
Phase resistance	2 Ohm
Core material	M19_29G



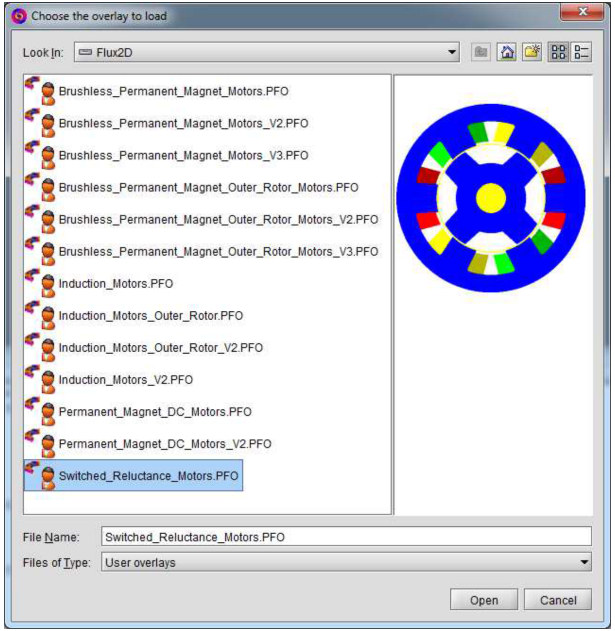
- Ref – (Abd Elmutalab, Mohamad. "EXTENDING THE SPEED RANGE OF A SWITCHED RELUCTANCE MOTOR USING A FAST DEMAGNETIZING TECHNIQUE." Electronic Thesis or Dissertation. University of Akron, 2016)

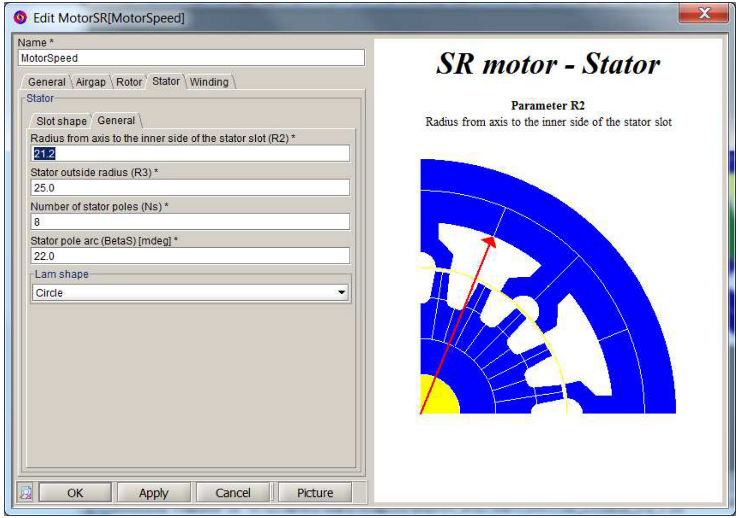
ELECTROMAGNETIC

MOTOR OVERLAY

- Automatic build of motor geometry (periodicity & boundary condition, mesh and some parts of the physics).

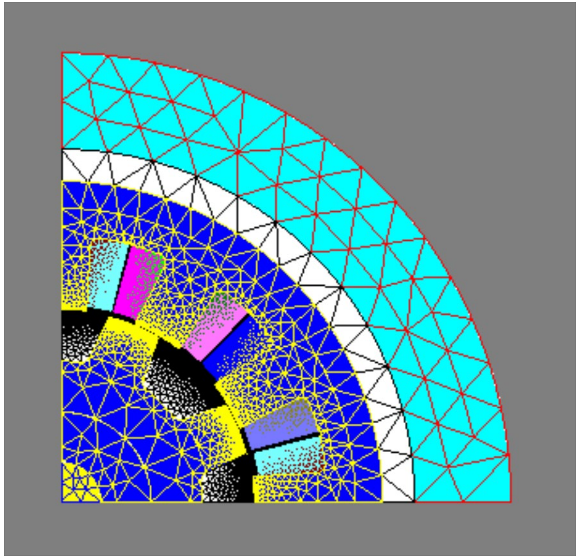
- Define the different parameters: General, airgap, stator, rotor and winding.



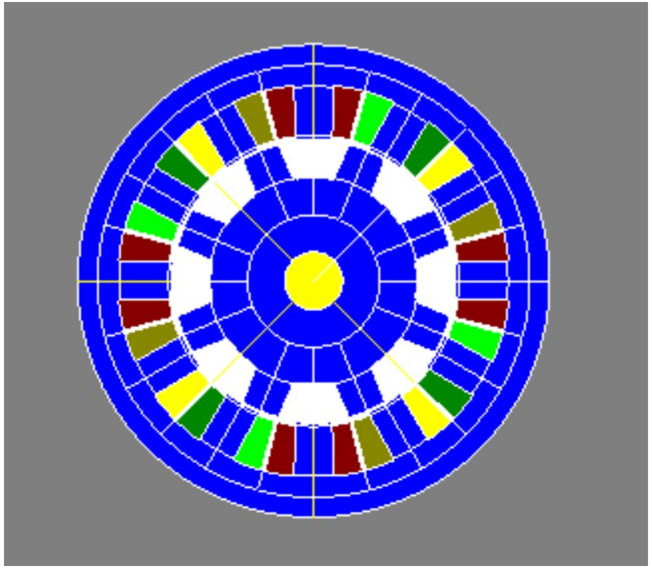


FLUX PROJECT

- Final geometry built by the overlay (predacity and mesh automatically created)

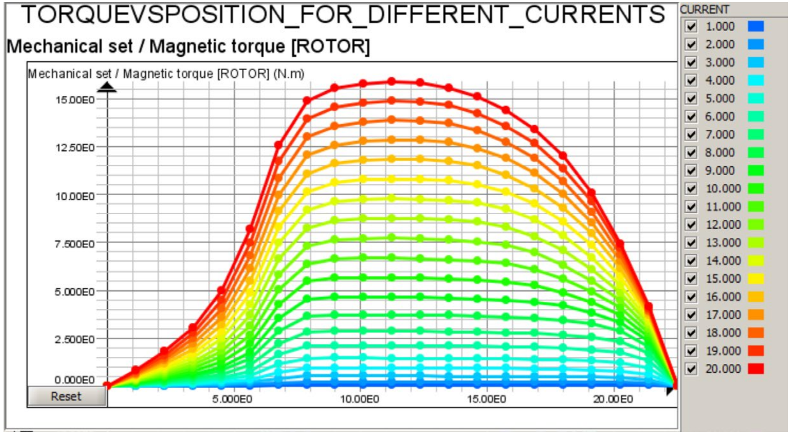


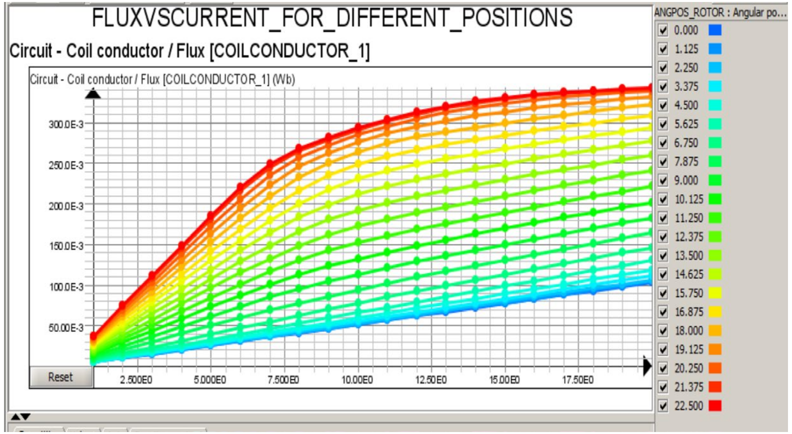
- Full geometry of the motor.



STATIC CHARACTERISTIC

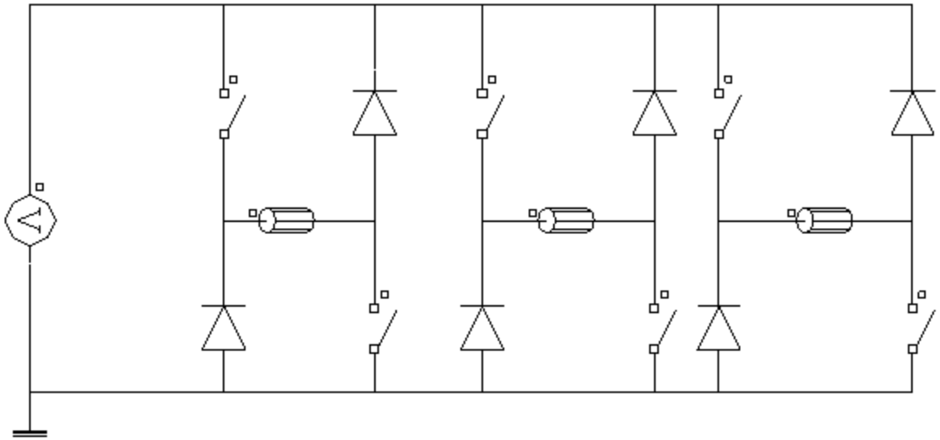
- Can be fully determined by the static torque and flux linkage for different current levels and rotor positions.
- Only one phase is excited with constant current.
- Simulation done for half electric cycle, the entire cycle can be extrapolated (symmetric)
- Similarly a static curves for the forces can be developed as well.

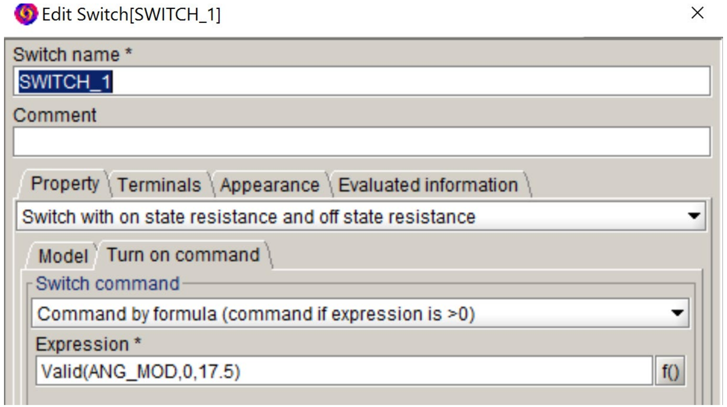




TRANSIENT SIMULATION

- AHB Converter can be defined inside Flux.
- Control the switching timing.
- Simulate both chopping and single pulse mode
- Chopping Mode is possible by using user defined function (groovy function) to define the hysteresis control
- Kinematics coupling (constant speed or coupled load)

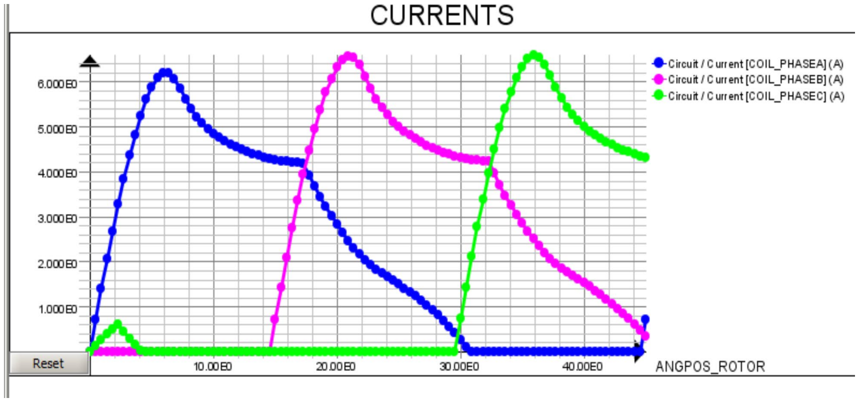


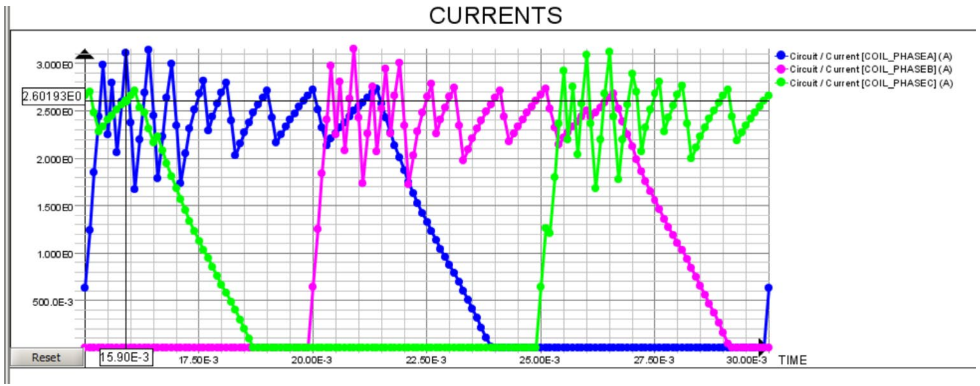


TRANSIENT SIMULATION

- Single pulse mode used in high speed, current is limited by BEMF.

- Chopping mode for low speed, current is limited by the controller using hysterias control (Soft or hard switching)





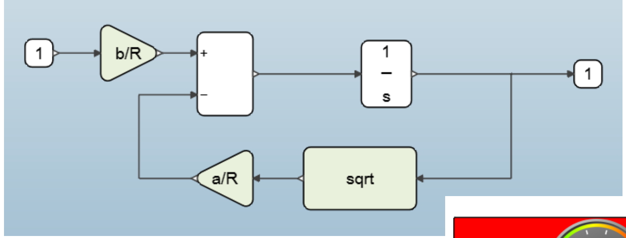
Speed: 1000 rpm
Turn on angle: 0 deg
Turn off angle : 140 deg

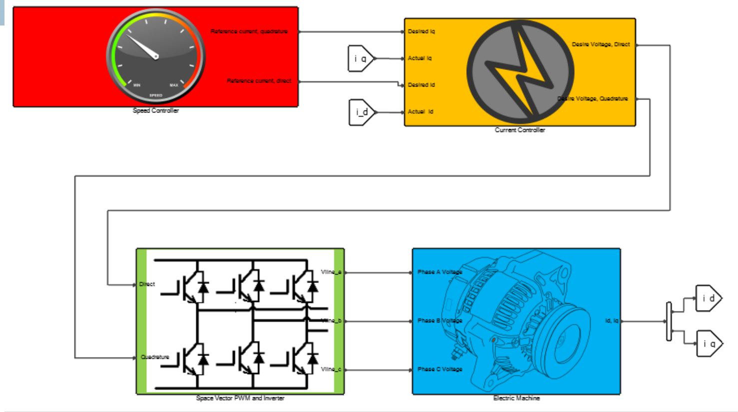
- Speed: 500 rpm
- Turn on angle: 0 deg
- Turn off angle : 140 deg
- Ref current: 2.5 A
- Hysteresis band : 0.2 A

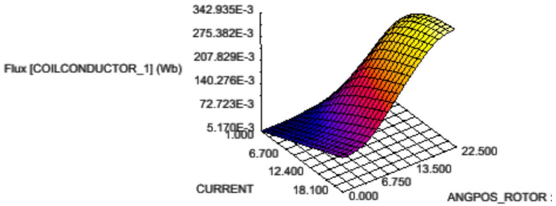
SYSTEM AND CONTROL

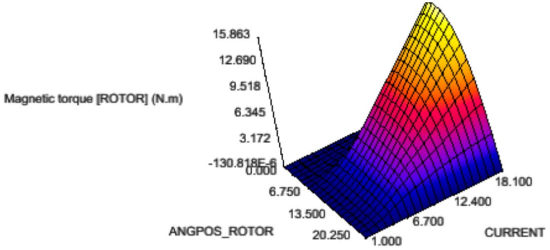
WHY ACTIVATE ?

- Easy and intuitive to use, The user can set up the model using blocks (either logical or physical).
- Model the whole system including (controller, inverter, external disturbances, ….)
- The possibility to use analytical or look up tables (LUTs) model. This can reduce the simulation time and allow faster study to the effect of the different system parameters.



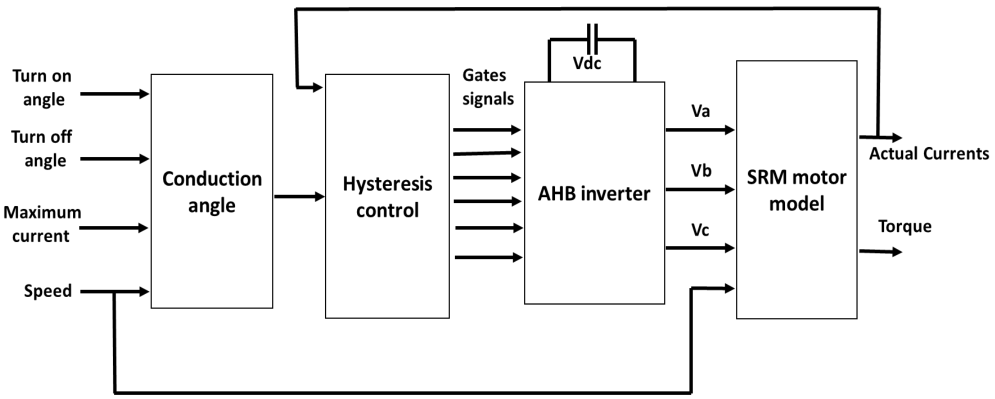






WHAT IS POSSIBLE?

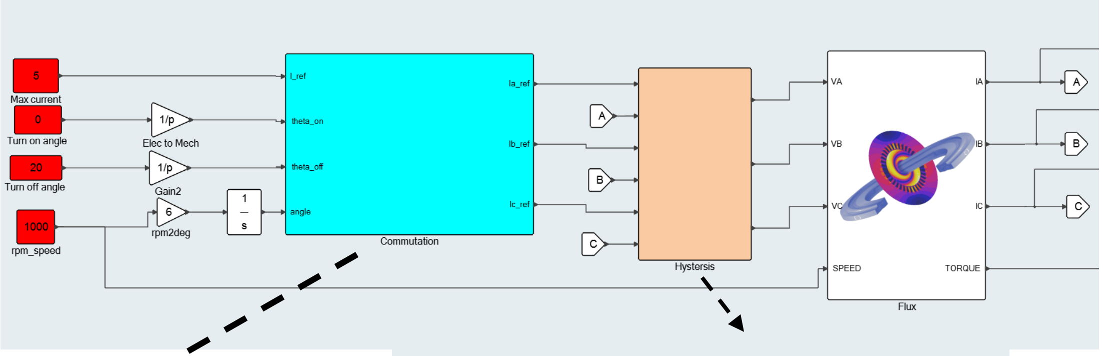
- System level:
  - Open loop control.
  - Closed loop control.
- SRM motor model
  - Flux model (co-simulation block).
  - Look up tables model(LUTs generated from static simulation in Flux).
- Inverter model
  - Only inverter logic.
  - Physical representation with switches and diodes (Modelica library).

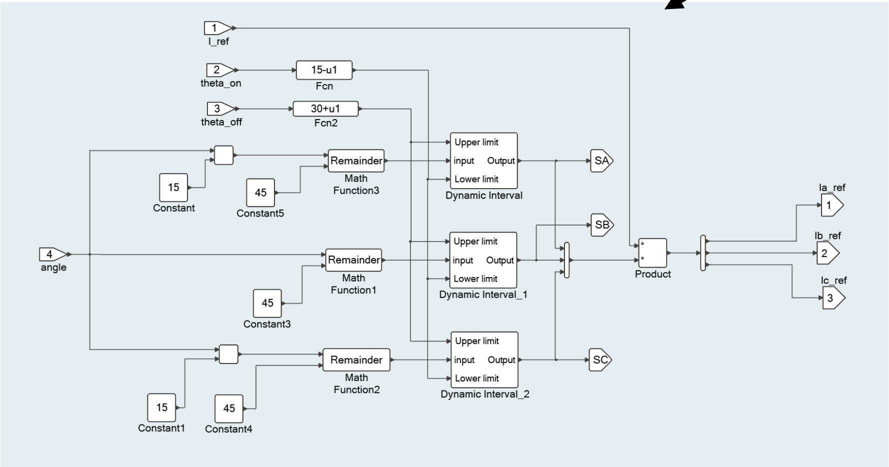


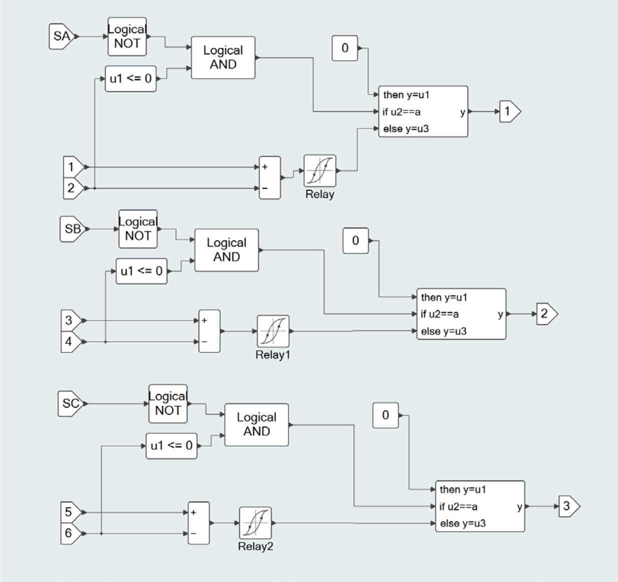
Block diagram of SRM Open loop control

OPEN LOOP CONTROL – INVERTER LOGIC

- The Commutation block defines the reference current of each phase based on the ref Max current, Turn on angle, Turn off angle and Speed.
- The Hysteresis block defines the logic of SRM inverter and provide the voltages at the phases terminals.

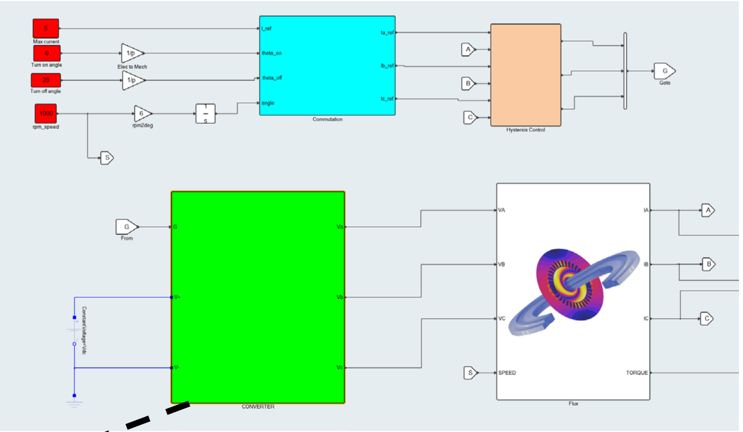


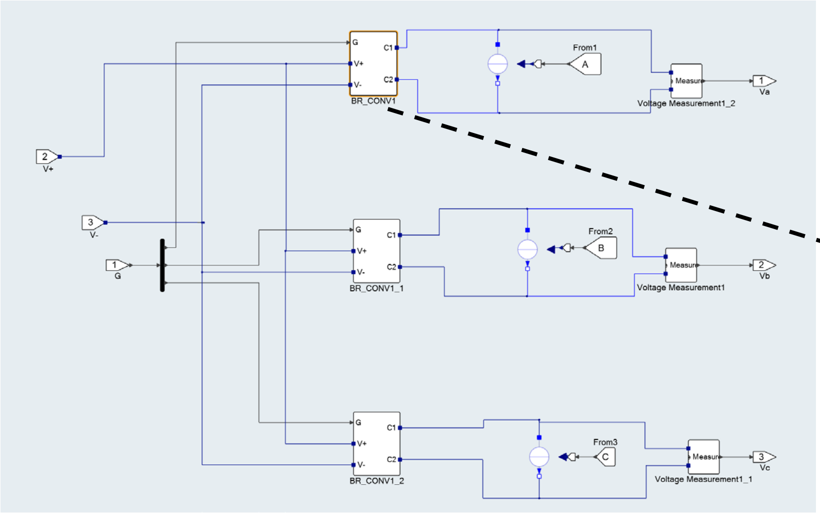




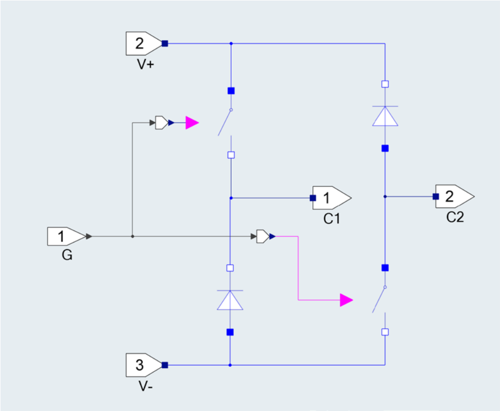
OPEN LOOP CONTROL – PHYSICAL INVERTER

- The Hysteresis block generate the switching commands.
- The convert block has the physical representation of the inverter using Modelica library.





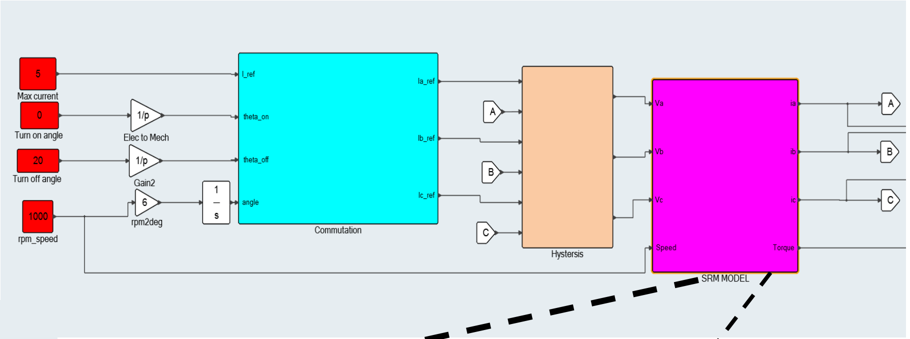
Converter

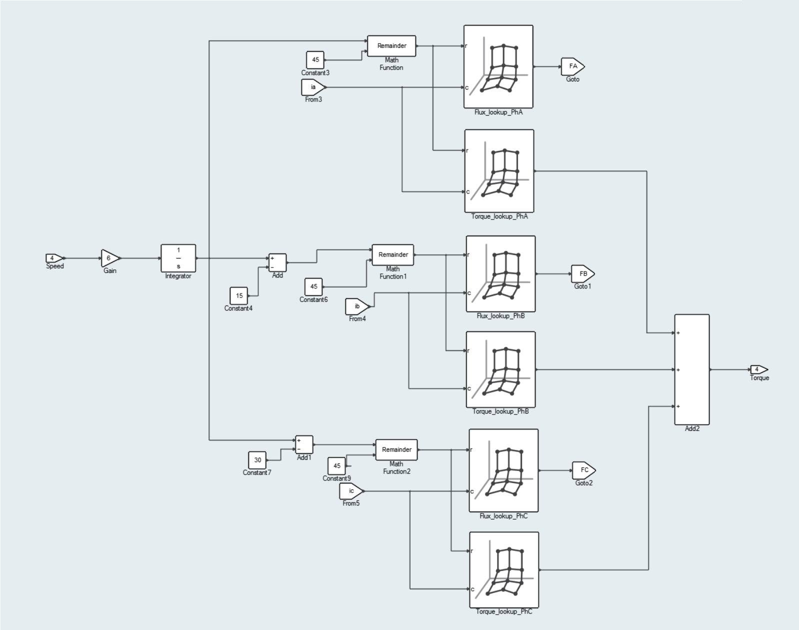


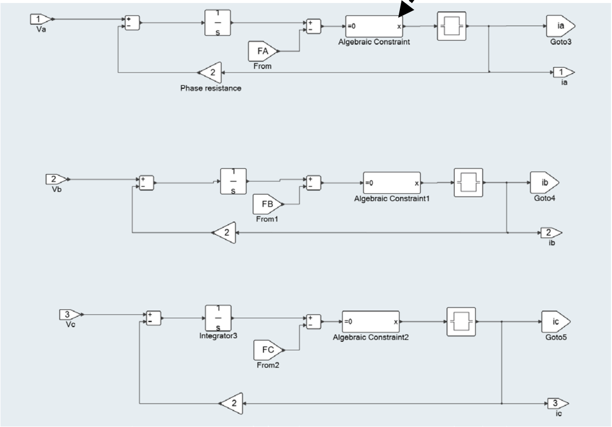
Single Leg

OPEN LOOP CONTROL – SRM MOTOR MODEL

- The simulation time and resource can be reduced significantly by using LUTs based model.
- Torque and Flux linkage characteristics curves obtained from the static analysis will be use.





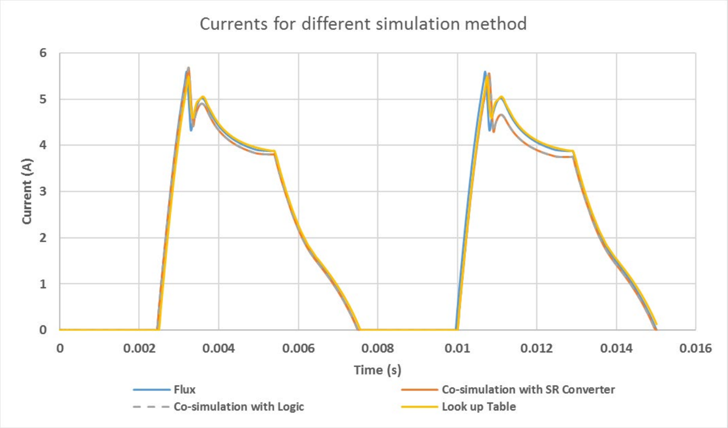


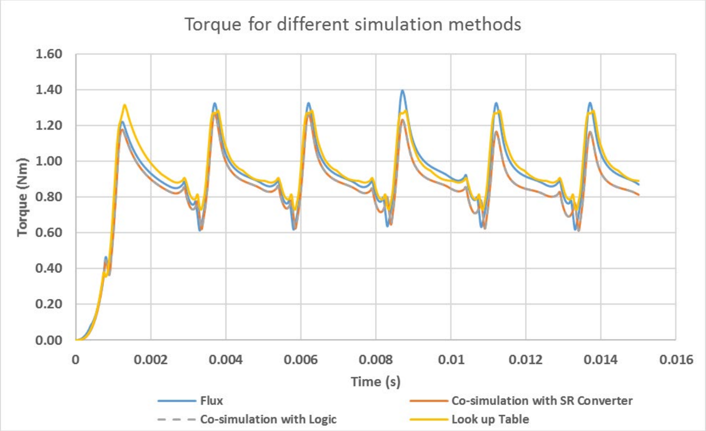
- Terminal voltage : $V = R.i + \frac{d\lambda}{dt}$

RESULTS COMPARISON

- Test Point.
  - Speed: 1000 rpm
  - Turn on angle: 0 deg
  - Turn off angle : 140 deg
  - Ref current : 5 A

- Simulation time:
  - Flux : 591 sec
  - co-simulation methods : 706 sec.
  - LUTs based model : 0.015 s.

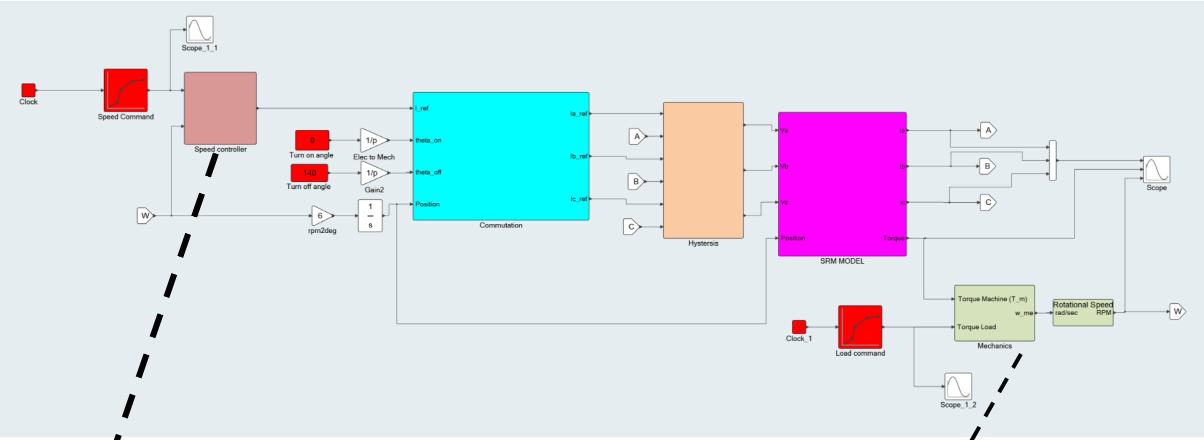


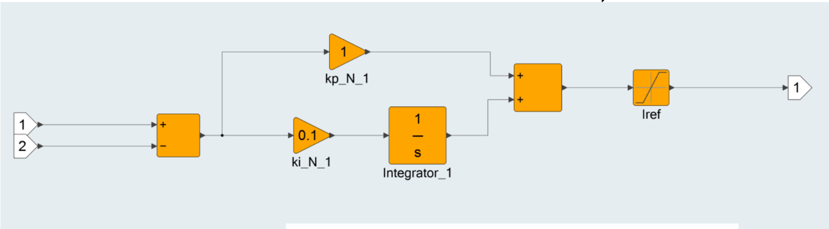


- All methods have similar results .
- Average Torque of Flux method 0.934 N.m compared to 0.92 Nm from Actual test Data (less than 2% error). Ref. Abd Elmutalab, Mohamad. "EXTENDING THE SPEED RANGE OF A SWITCHED RELUCTANCE MOTOR USING A FAST DEMAGNETIZING TECHNIQUE." Electronic Thesis or Dissertation. University of Akron, 2016.

SPEED CONTROL SET-UP

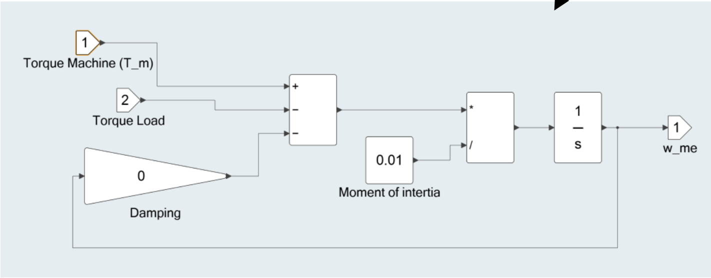
- Additional blocks:
  - Speed PI controller.
  - The mechanical coupling.
  - Speed and load commands.





Speed Controller

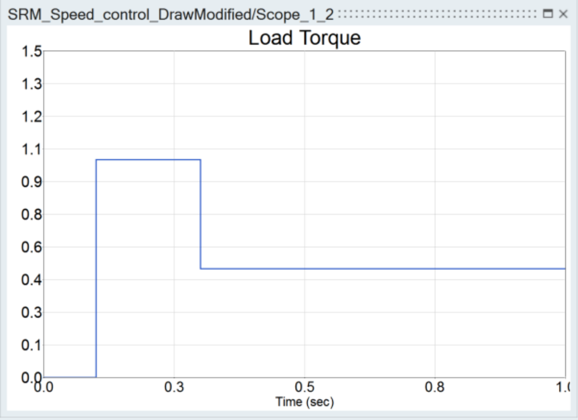
$$u(t) = K_{\mathrm{p}} e(t) + K_{\mathrm{i}} \int_0^t e(t')\, dt'$$

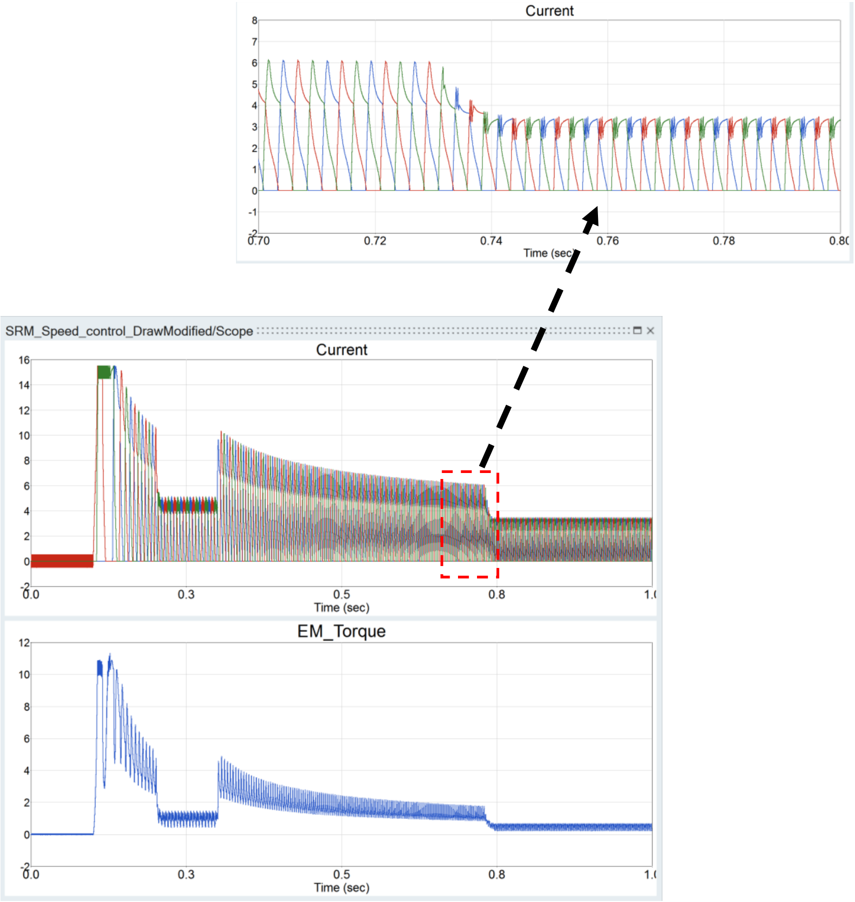


Mechanics

$$T_e - T_{load} - T_{friction} = J \frac{d\omega_m}{dt}$$

SPEED CONTROL - RESULTS



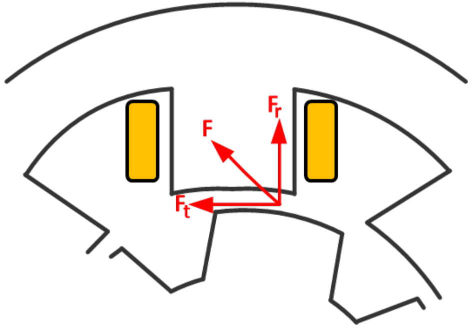


MECHANICAL VIBRATION ANALYSIS

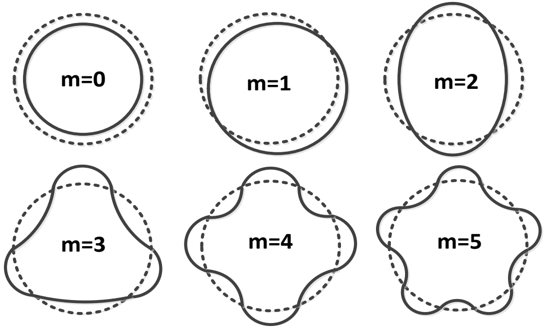
VIBRATION AND NOISE IN SRM

- Sources of the acoustic noise:
  - Mechanical
  - Aerodynamic
  - Electromagnetic
- Due to its saliency structure and phase commutation the variation of the radial force is very high in SRMs.
- The magnetic force $\boldsymbol{F}$ consists of two components: the tangential component $\boldsymbol{F_t}$ and the radial component $\boldsymbol{F_r}$.

- Vibration and noise arise at the natural frequencies.
- The deformation caused by the resonance will often form along the circumference of the stator surface
- The vibration of the outer surface generate airborne acoustic noise



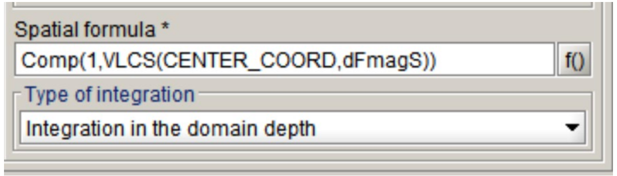
Magnetic force in the air-gap

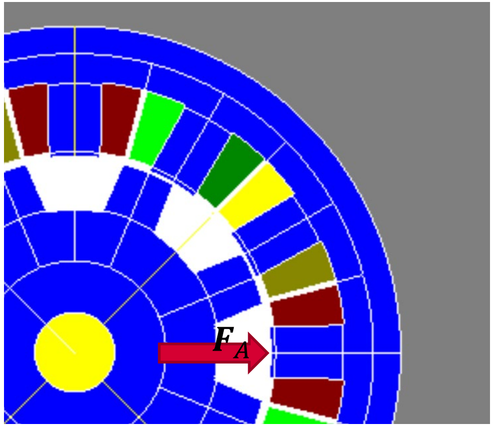


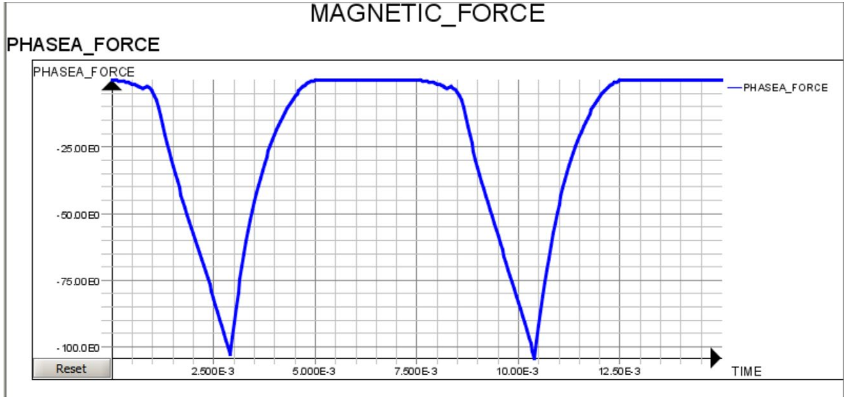
Circumferential mode shapes

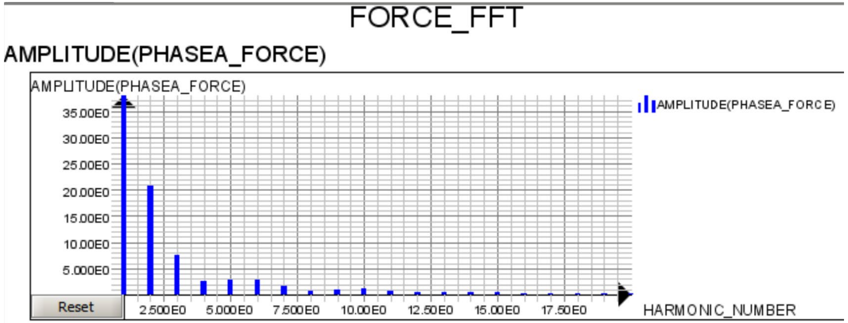
MAGNETIC FORCE - ANALYSIS

- Create sensor to calculate the radial and tangential forces on the stator teeth.
- Analysis the harmonic spectrum of the force.



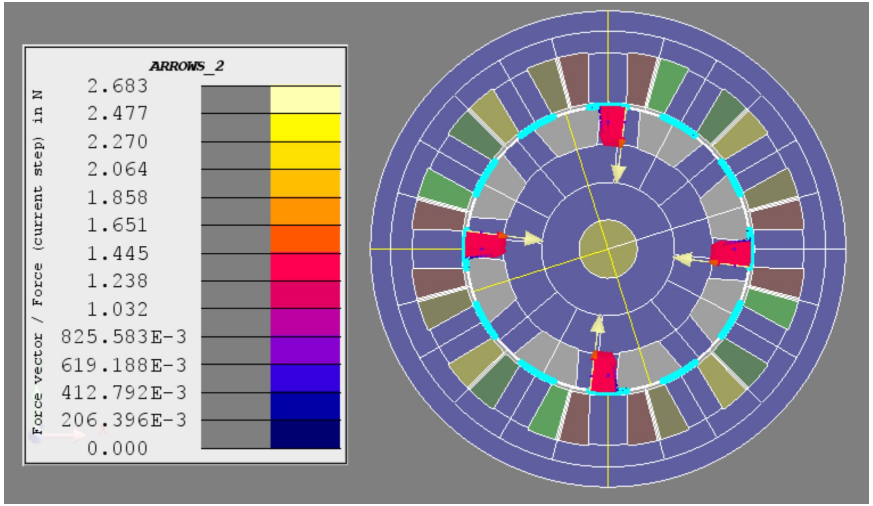




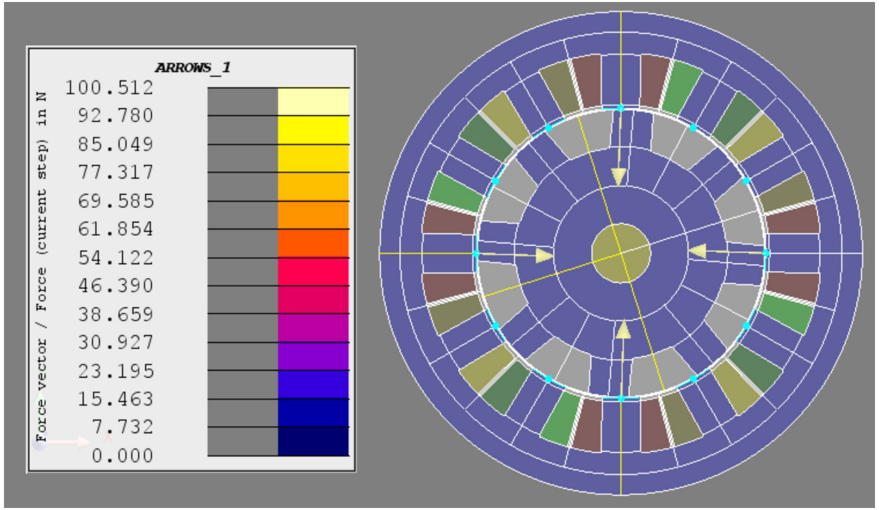


MECHANICAL ANALYSIS CONTEXT

- Create different types of support for the forces calculation.
- Possibility to calculate the magnetic force the support and visualize the forces.



Forces at nodes

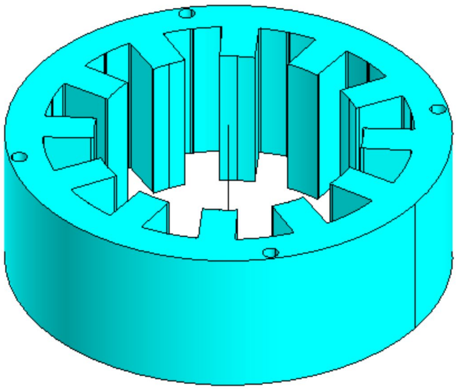


Global forces

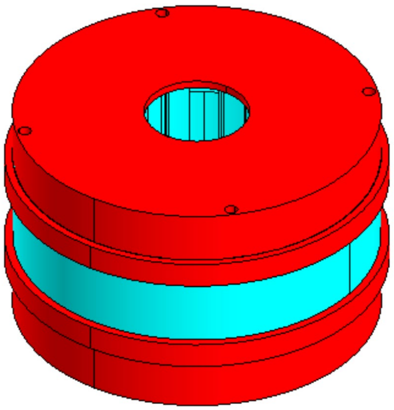
At 2.9 ms where force is maximum at Phase A

MODEL

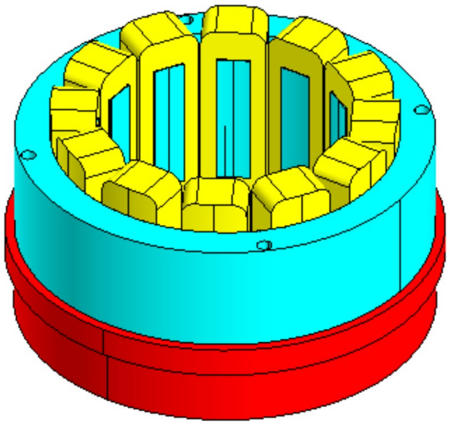
- No CAD model was available.
- Approximated Model created in Flux.



Stator



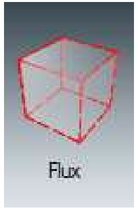
End Caps

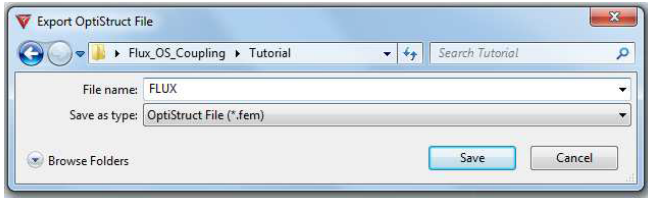


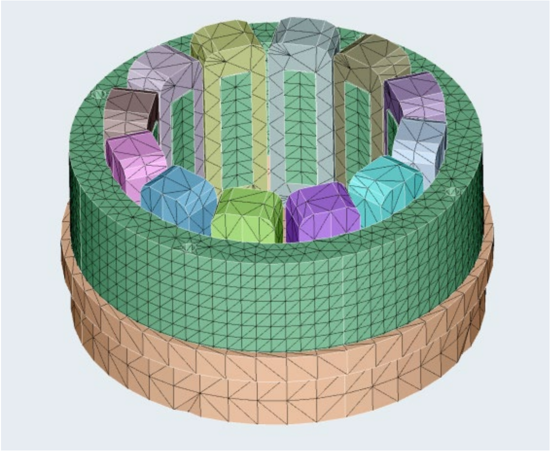
Windings

MESH

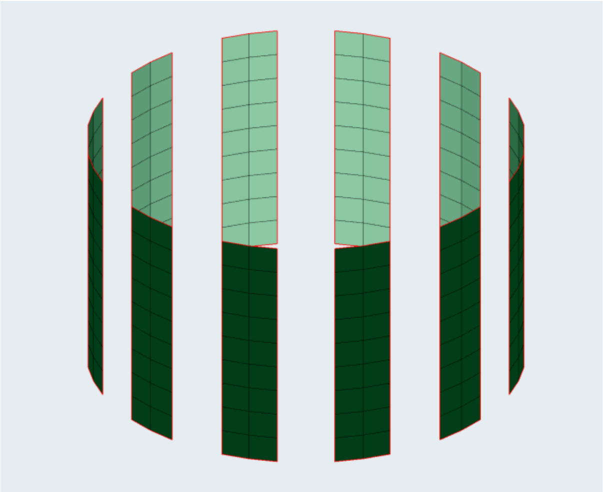
- Simlab will be used to create the mesh for the mechanical model.
- Possibility to control and apply different local mesh control, defeature the geometry
- Export the mesh of the stator teeth to be used in Flux.







Mechanical Mesh

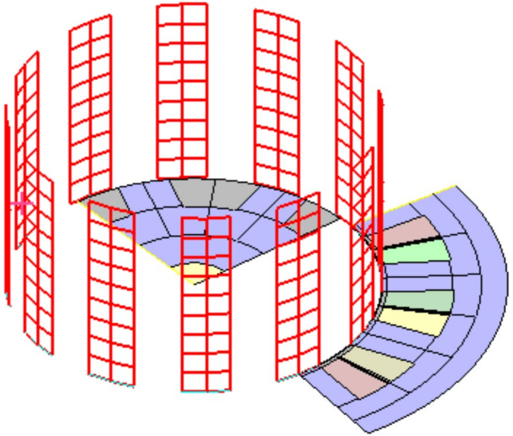


Quadrangular mesh in the stator teeth

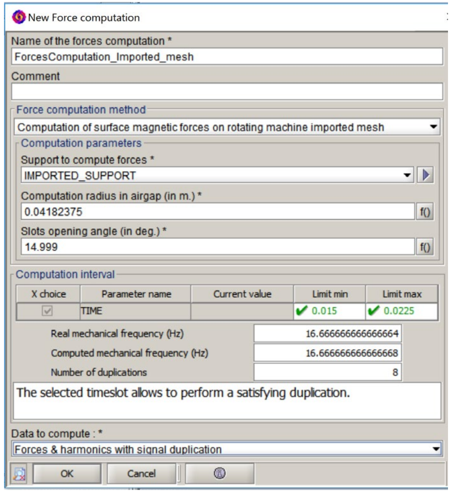
FORCE CALCULATION AND EXPORT

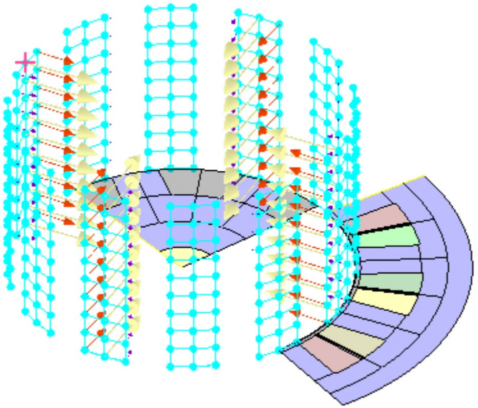
- Import of the mechanical mesh in the stator teeth.
- The force and harmonics computed on the imported support.

- The forces can be extrapolated considering the periodicity and the axial length.
- Export of the computed force (several formats are available)



Imported mesh support





Computed Force at one instant

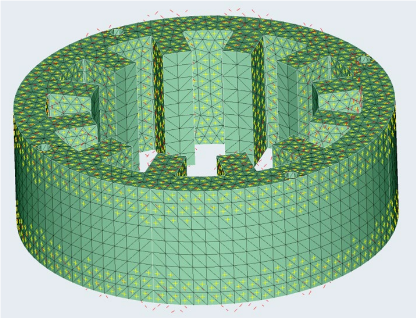
SETTINGS

- Create materials and properties.
- Define 1D Bolts (automatically define different RBE and rigid bars)

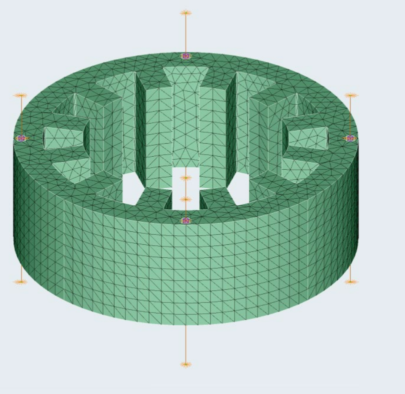
- Define contacts between stator/end caps, stator/winding. (TIE types in Optistruct)
- Define fixed constraints in the top end cap.

Material	Part	Young Modulus (Gpa)	Poisson ratio	Mass density (Kg/m^3)
Steel	Stator	210	0.3	7800
Aluminum	End caps	70	0.33	2700
Copper	Winding	128	0.33	8960

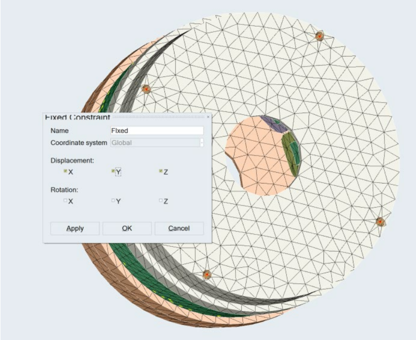
Contacts



RBE and Rigid bars



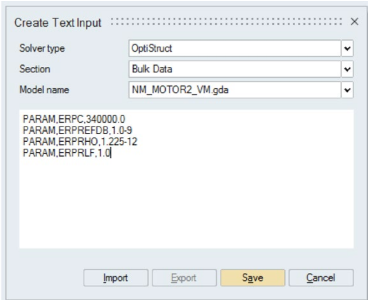
Fixed constraints

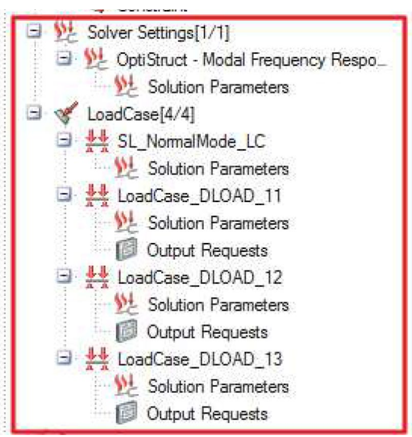


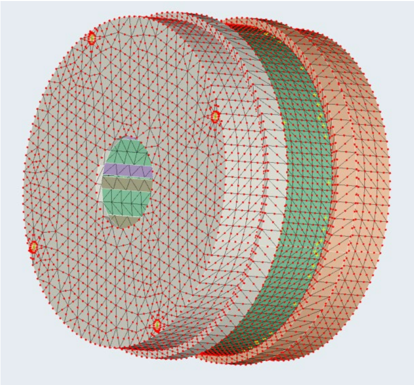
SETTINGS

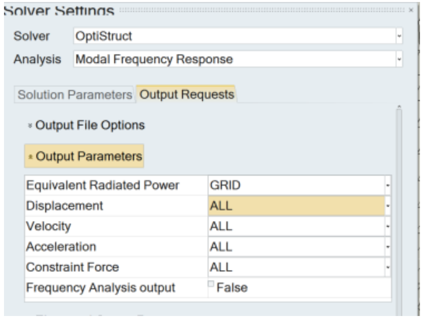
- Import force loads from Flux. Four load cases will be generated.
- Set the constraint and the setting for each load case:
    - Method to extract normal modes : AMES
    - Maximum frequency set to 8516.7 Hz (maximum frequency exported from Flux)
    - Eigen values extracted from the normal mode analysis will be used for other load cases.

- a new set of nodes in all outer surfaces to calculate equivalent radiated power (ERP).
- Define air properties for ERP calculation
- Request outputs of ERP, deformation, velocity and acceleration.





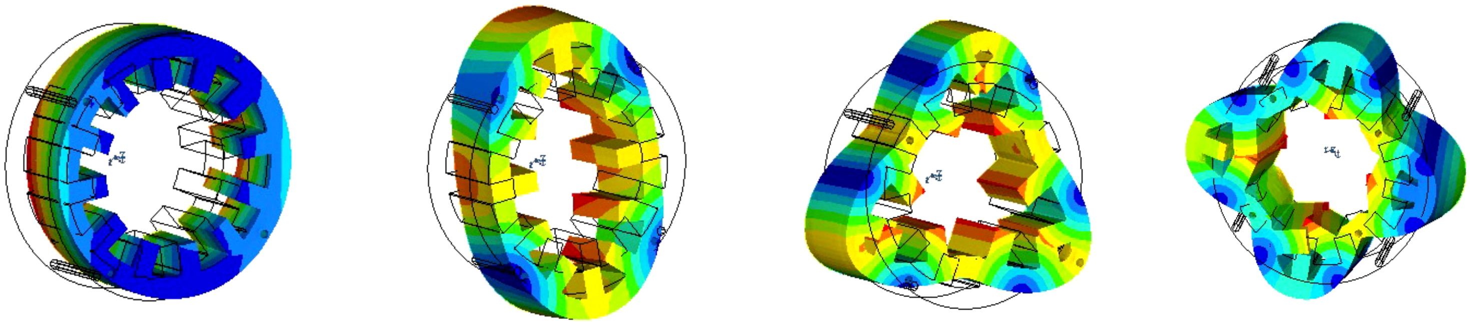




MECHANICAL MODEL - RESULTS

- Results available in H3D format and can be viewed/post-processed using HyperView / HyperGraph.

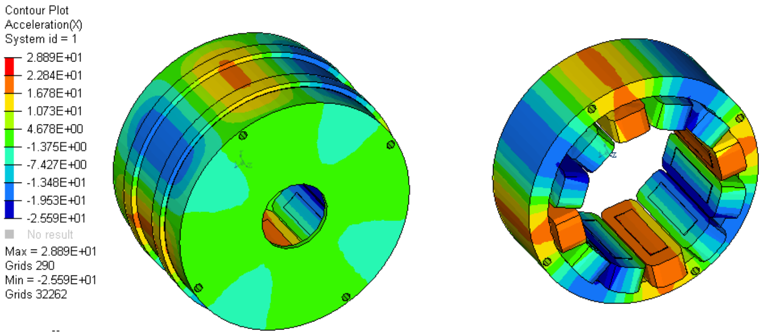
- Modal analysis allow to determine the frequencies associate to the mode shapes of the structure.
- According to the literature, mode shapes with m equal 2 and 4 are the most dominant for SRM.



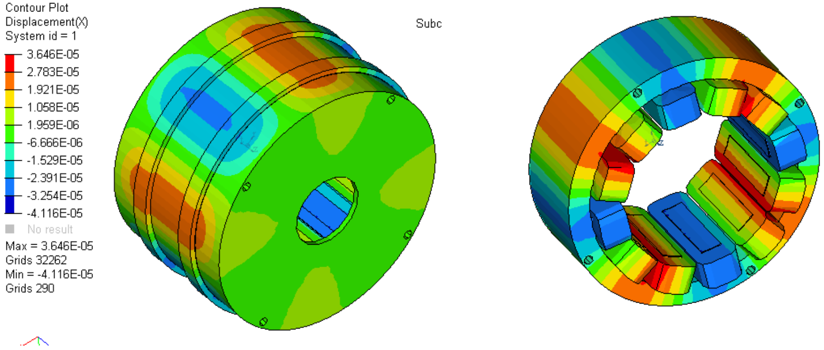
m-number	1	2	3	4
Frequency	1578 Hz 1584 Hz	2588 Hz 2615 Hz	4486 Hz	6832 Hz 6983 Hz

MECHANICAL - RESULTS

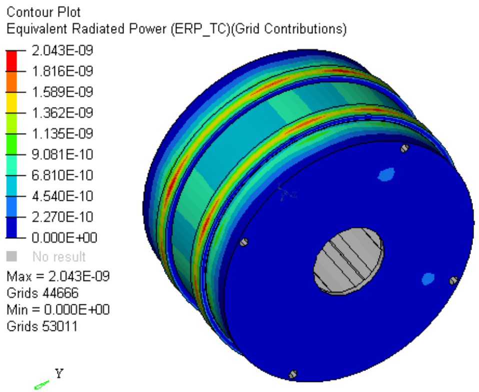
- Contour plot of deformation, velocity, acceleration at specific frequency.
- Contour viewed in the radial direction (cylindrical coordinate system)



Acceleration (mm/s^2)



Displacement (mm)

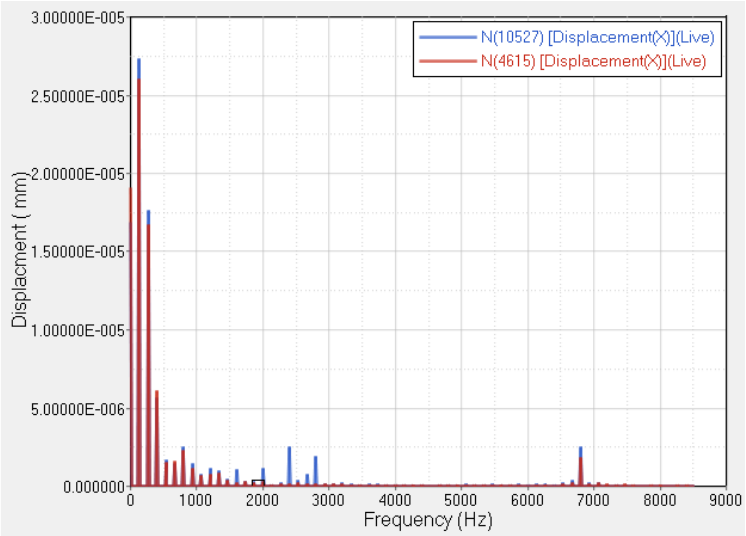


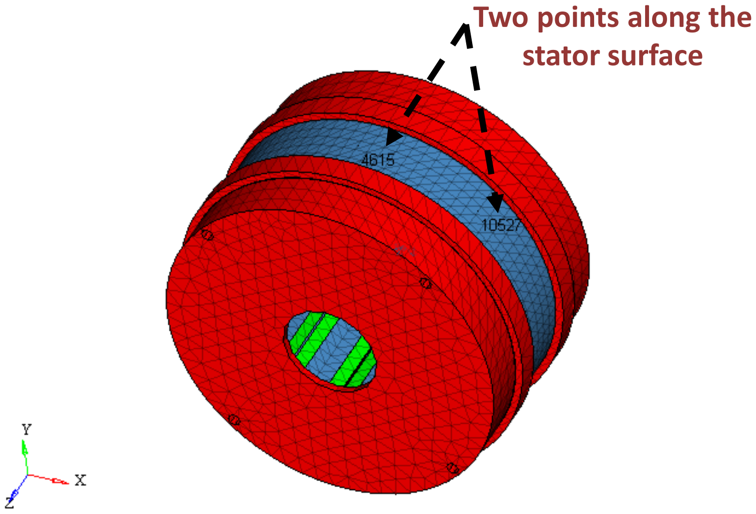
ERP (W)

Results at 133.333 Hz

MECHANICAL MODEL- RESULTS

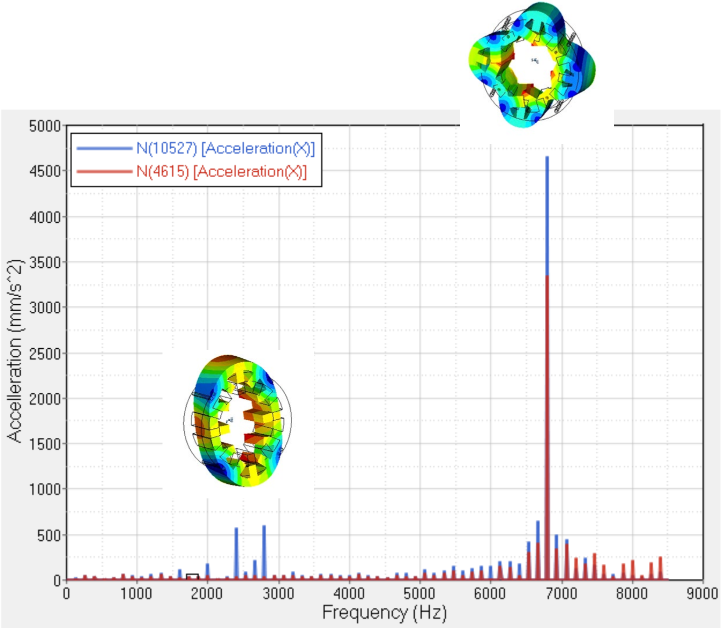
- Plot of deformation over the frequency range.

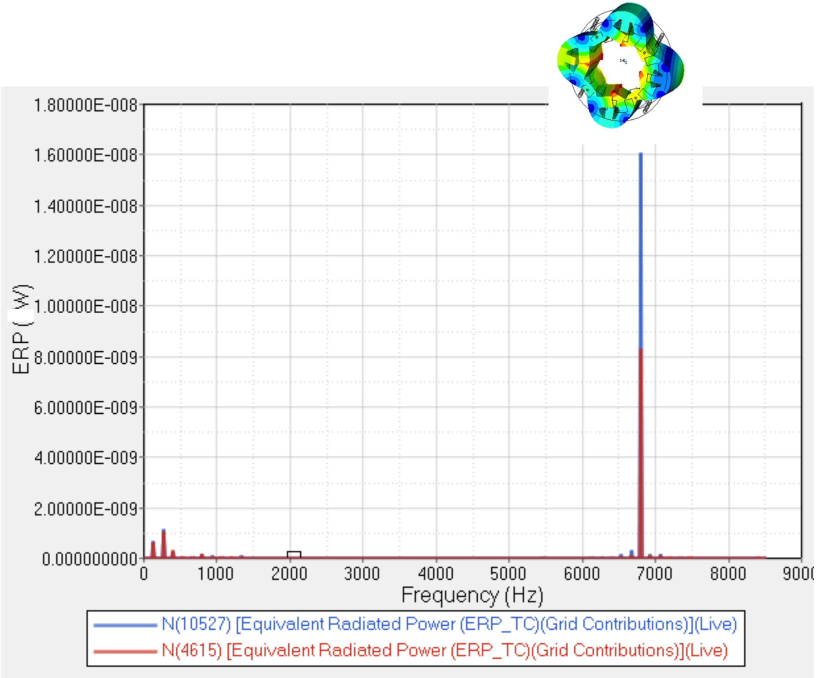




MECHANICAL MODEL - RESULTS

- plots of acceleration and ERP over the frequency range.





- The peak of acceleration and ERP happens at the frequency 6800 Hz (near the mode shape with m= 4.)

WORKFLOW

Step 1: Simlab

- Mesh the model
- Export the mesh on the stator teeth

Step2 :Flux

- Import the mechanical mesh
- Compute the forces on the mesh nodes
- Export the different harmonics of the force.

Step 3: Simlab

- Import (Load) the forces from Flux
- Create the model settings(Materials, constraints and contacts)
- Set the solving setting

Step 4: Optistruct

- Solve frequency response analysis

Step 5: HyperView/Graph

- Post-processing of the results:
  - Mode shapes
  - Deformation
  - Acceleration
  - ERP

CONCLUSION

- More demand for multi-physics simulation in the market today.
- Flux can consider both the FEA domain and also the power electronics and control.
- Activate can help with building the control system (blocks based instead of scripts).
- Activate can help to build simplified model of the motor (LUTs or analytical).
- Coupling (work flow) between Flux and Simlab/Optistruct is possible to perform Vibracoustic ananlysis.

Thank You