Design principle of WFSM for Electric Vehicle based non-linear magnetic equivalent circuit

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Background

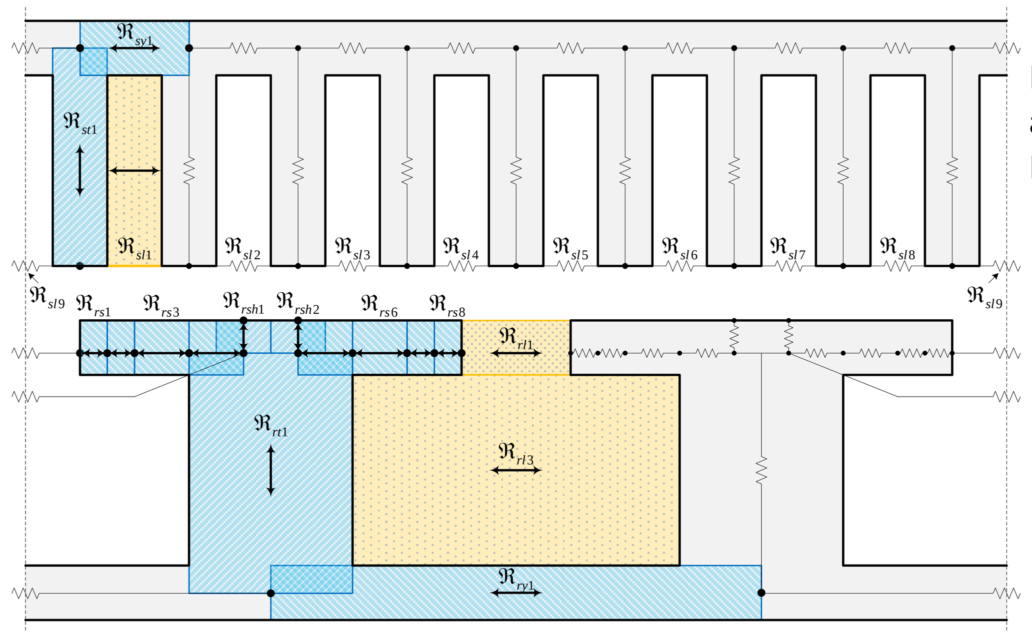
Because main flux path is sensitive to the magnetic saturation, Wound Field Synchronous Motor (WFSM) has to be designed considering magnetic saturation, especially for the applications requiring high torque density such as EV. Thus Magnetic Equivalent Circuit (MEC) should be constructed considering the nonlinearity of the electrical steel sheet.

Objectives

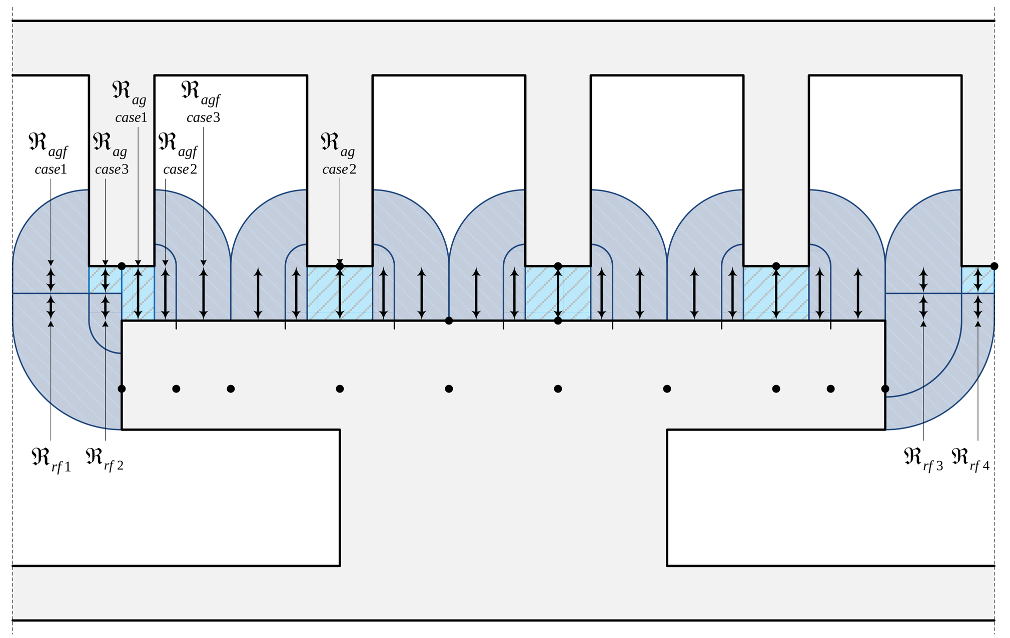
- ❖ Construct non-linear magnetic equivalent circuit for Wound Field Synchronous Motor.
- ❖ Make design algorithm of WFSM considering magnetic saturation.

Methods

Non-linear Magnetic Equivalent Circuit



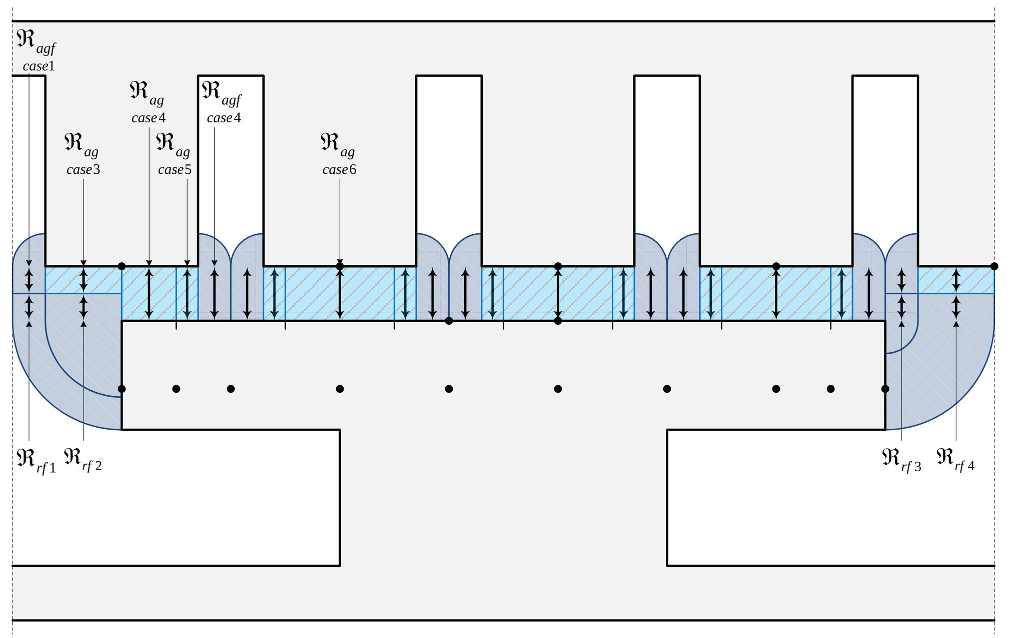
Non-linear MEC for WFSM is constructed and calculated using Newton-Raphson Method.



Construction of air gap reluctance is divided into 2 cases.

Case1 :
Stator teeth width ≤ Half of the slot pitch

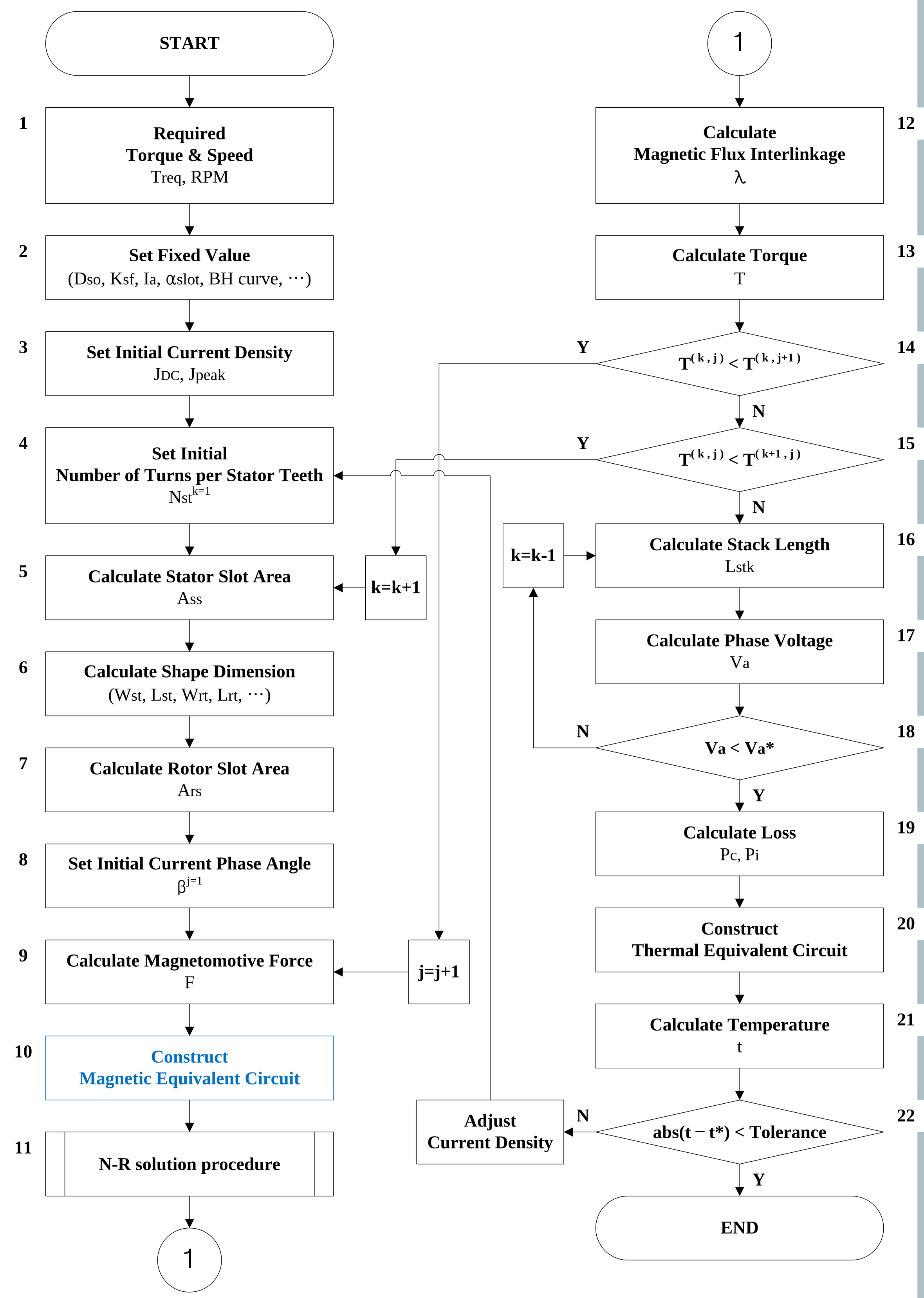
$$\Re_{ag1} = \Re_{agf.case1} \left(= \Re_{ag14} \right)$$
$$\Re_{ag2} = \Re_{ag.case3} \left(= \Re_{ag15} \right)$$
$$\Re_{ag3} = \Re_{ag.case1} \,||\, \Re_{agf.case2}$$
$$\Re_{ag4} = \Re_{agf.case3} \left(= \Re_{ag5}, \Re_{ag7}, \Re_{ag8}, \Re_{ag10}, \Re_{ag11}, \Re_{ag13} \right)$$
$$\Re_{ag6} = \Re_{agf.case2} \,||\, \Re_{ag.case2} \,||\, \Re_{agf.case2} \left(= \Re_{ag9}, \Re_{ag12} \right)$$



Case2 :
Stator teeth width > Half of the slot pitch

$$\Re_{ag4} = \Re_{ag.case5} \,||\, \Re_{agf.case4} \left(= \Re_{ag5}, \Re_{ag7}, \Re_{ag8}, \Re_{ag10}, \Re_{ag11}, \Re_{ag13} \right)$$
$$\Re_{ag6} = \Re_{ag.case6} \left(= \Re_{ag9}, \Re_{ag12} \right)$$

Design WFSM



Design algorithm :
When stator outer diameter is given as a constraint, Iteration is performed according to the turns of stator and current phase angle. Find shape and current phase angle that generate maximum torque in unit core length and calculate the core length satisfying the required torque.

Conclusion

- ❖ Non-linear MEC of WFSM is constructed to consider magnetic saturation.
- ❖ Design algorithm using non-linear MEC is presented.
- ❖ Torque of design model finally selected is compared with that of FE Analysis and verified accuracy of non-linear MEC
- ❖ Experiment was conducted for the final design model.

Result

Design result

Torque [Nm]		β [degE]						
		-40	-30	-20	-10	0	10	20
N_{st}	1	0.283	0.320	0.348	0.365	**0.371**	0.366	
	2	0.544	0.617	0.672	0.707	**0.721**	0.713	
	3	0.771	0.878	0.963	1.020	**1.048**	1.043	
	4	0.951	1.104	1.206	1.290	1.338	**1.344**	1.304
	5	1.078	1.246	1.390	1.504	1.576	**1.592**	1.541
	6	1.150	1.341	1.513	1.646	**1.722**	1.701	
	7	1.171	1.379	1.560	**1.676**	1.666		

Current Phase Angle [degE]	Nonlinear MEC [Nm]	FEM [Nm]	Error [%]
-40	1.171	1.139	2.8
-30	1.379	1.354	1.8
-20	1.560	1.536	1.6
-10	1.676	1.671	0.3
0	1.666	1.746	4.6

Result of design algorithm :
Torque is presented according to the turns of the stator and current phase angle. Final design model is selected considering mechanical aspects. (stator turns : 7)
Torque of final design model calculated by non-linear MEC is compared to that of FE Analysis.

Experiment

Torque, Efficiency Test