Magnet Weight Minimization of Electric Traction Interior Permanent Magnet Motor Over Multiple Operating Points

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Introduction

To satisfy the vehicle emission reduction mandates around the world such as China for 2020 and 2030 and for Europe centered around 2030, the focus is more and more on electric motors to power the vehicle traction either in addition to the internal combustion engine such as hybrid electric vehicles (HEVs) or only electric power train with battery, with the later technology becoming more and more preponderant.

The electric motors used in the hybrid or electric powertrain are generally synchronous permanent magnet motors, synchronous wound field, induction, synchronous reluctance or switched reluctance motors. The synchronous permanent magnet motor, especially with the interior permanent magnet (IPM) rotor, is the preferred design choice for electric vehicle traction powertrain due to its specific advantages such as high efficiency, wide constant torque speed range, high torque density, and sensorless rotor position detection capability due to rotor saliency. However, the drawbacks would be the motor costs mainly due to the use of expensive high energy rare earth magnets such as NdFeB or SmCo. In the last few years, the volatile supply chain and the perspective of limited availability of rare earth materials have driven up the cost of rare earth magnets significantly and have pushed motor design engineers into efficiently using of these materials in the synchronous permanent magnet motor design.

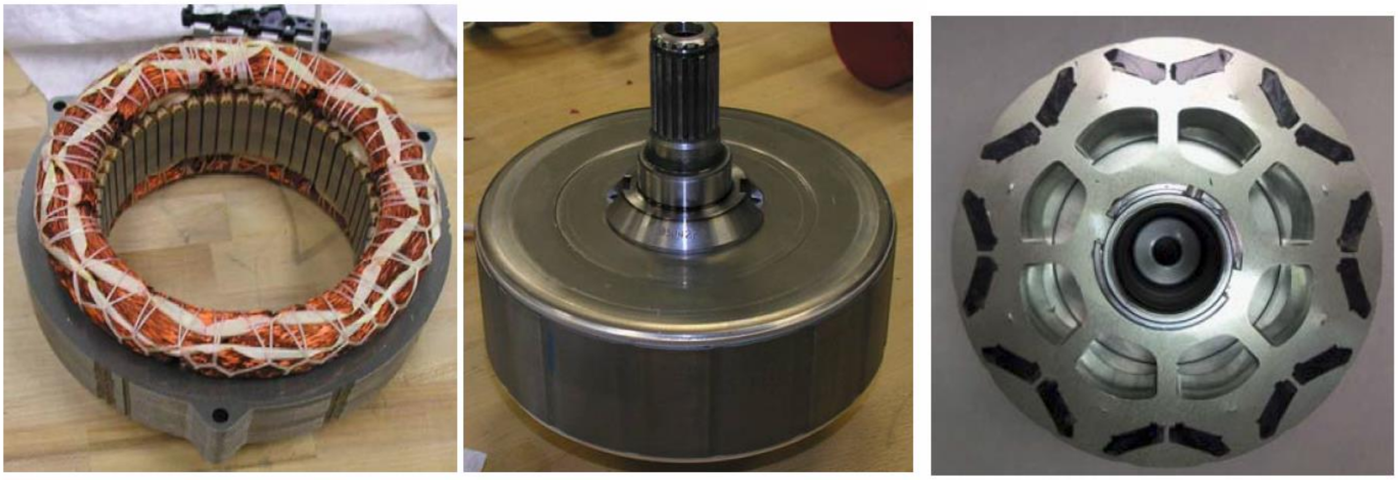
This paper describes the process of using Altair tools such as Flux for synchronous permanent magnet motor EM FEA analysis and HyperStudy to minimize the weight of the NdFeB magnets of a typical IPM motor for electric traction application such as the IPM motor of the Toyota Prius 2010.

Prius 2010 IPM

The IPM motor for electric traction powertrain in the Prius 2010 is studied and analyzed in depth by the Oak Ridge National Laboratory (ORNL). Its reports published the motor details that allow us to create the Flux model. The two most significant reports used are listed below:

Burress, Timothy A, Campbell, Steven L, Coomer, Chester, Ayers, Curtis William, Wereszczak, Andrew A, Cunningham, Joseph Philip, Marlino, Laura D, Seiber, Larry Eugene, and Lin, Hua-Tay. *Evaluation of the 2010 Toyota Prius Hybrid Synergy Drive System*. United States: N. p., 2011. Web. doi:10.2172/1007833.

Motor Packaging with Consideration of Electromagnetic and Material Characteristics. Principal Investigator: John M. Miller. U. S. Department of Energy, Advanced Power Electronics and Electric Motors – 2011 Annual Progress Report – DOE/EE-0676



Prius 2010 IPM Stator and Rotor

Table 1: 2010 Prius, LS600h, Camry, and 2004 Prius motor design characteristics

Parameter	2010 Prius	LS 600h	Camry	2004 Prius	Comments
Lamination Dimensions					
Stator OD, cm	26.4	20.0	26.4	26.9	
Stator ID, cm	16.19	13.086	16.19	16.19	
Stator stack length, cm	5.08	13.54	6.07	8.4	
Rotor OD, cm	16.04	12.91	16.05	16.05	
Rotor lamination ID, cm	5.1	5.3	10.5	11.1	
Rotor stack length, cm	5.0165	13.59	6.2	8.36	
Air gap, mm	0.73	0.89	0.73025	0.73025	
Lamination thickness, mm	0.305	0.28	0.31	0.33	
Mass of Assemblies					
Rotor mass, kg	6.7	11.93	9.03	10.2	Includes rotor shaft.
Stator mass, kg	15.99	18.75	18.0	25.9	
Stator core mass, kg	10.36	15.15	12.38	19.05	Laminations only.
Stator Wiring					
Number of stator slots	48	48	48	48	
Stator turns per coil	11	7	14	9	
Parallel circuits per phase	0	2 legs	2 legs	0	
Coils in series per phase	8	4 per leg	4 per leg	8	
Number of wires in parallel	12	9 per leg	9 per leg	13	18 total per phase
Wire size, AWG	20	~0.032" ≡ 20	20	19	
Phase resistance at 21°C, ohms	0.077	0.0225	0.023	0.069	Average of phase-to-phase divided by two.
Total mass of stator copper, kg	4.93	3.59	5.6	6.8	
Slot depth, mm	30.9	19.25	30.9	33.5	
Slot opening, mm	1.88	1.88	1.88	1.93	At air-gap
Casing					
Motor casing mass, kg	14.1	14	14.67	8.9	Resolver, pump, etc
Motor casing diameter, cm	30.2	27.5	30.2	29.9	
Motor casing axial length, cm	16.1	27.9	17.0	20.5	
Magnets (neodymium iron boron [NdFeB])					
Magnet dimensions, mm	49.3×17.88×7.16	66.4×18.7×3.05	60.6×19.1×6.6	83.1×18.9×6.5	One magnet.
Magnet volume, cm^3	6.31	3.78	7.63	10.2	One magnet.
Magnet mass, grams	48	28.1	58	77	One magnet.
Total mass of magnets, kg	0.768	1.349	0.928	1.232	Entire magnet mass in rotor.

Table 2: 2010 Prius IPM Motor Dynamometer Test at 5000 rpm and 60 N.m

U_{dc} (V_{dc})	I_{dc} (A_{dc})	P_e (kW)	P_m (kW)	U_{an} (V_{rms})	I_{an} (A_{rms})	m (Nm)	n (rpm)	η (#)
652.4	50.8	32.9	31.4	310	43	60	5,000	0.954

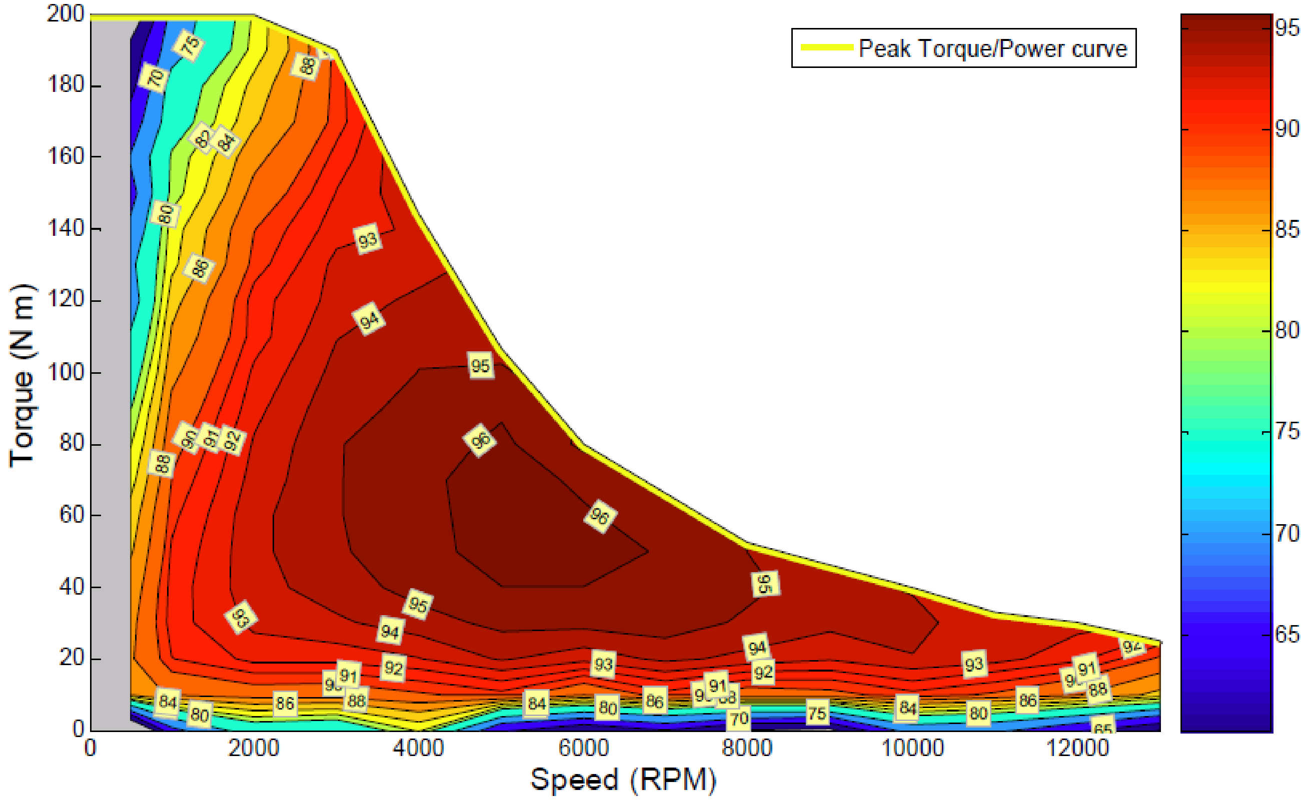


Figure 2: Prius 2010 IPM Motor Efficiency Contour for 650 Vdc

2010 Prius IPM Motor Flux Model and Benchmark

Only 1/8 of the motor needs to be modeled in Flux using a periodicity boundary condition, thus resulting in an economical 2D FEA mesh as shown in Fig. 3.

The windings are represented by coil components in the external circuits. They are star-connected and supplied in power with 3 phase current sources. The rotating motion is handled by the sliding interface in the air gap between the stator and rotor regions.

We compared the Flux model results with the dynamometer test at 5000 rpm. The computed shaft torque is 60.54 N.m vs. 60 N.m measured at 43 A rms. The computed efficiency is 95.06% vs. measured efficiency of 95.4%.

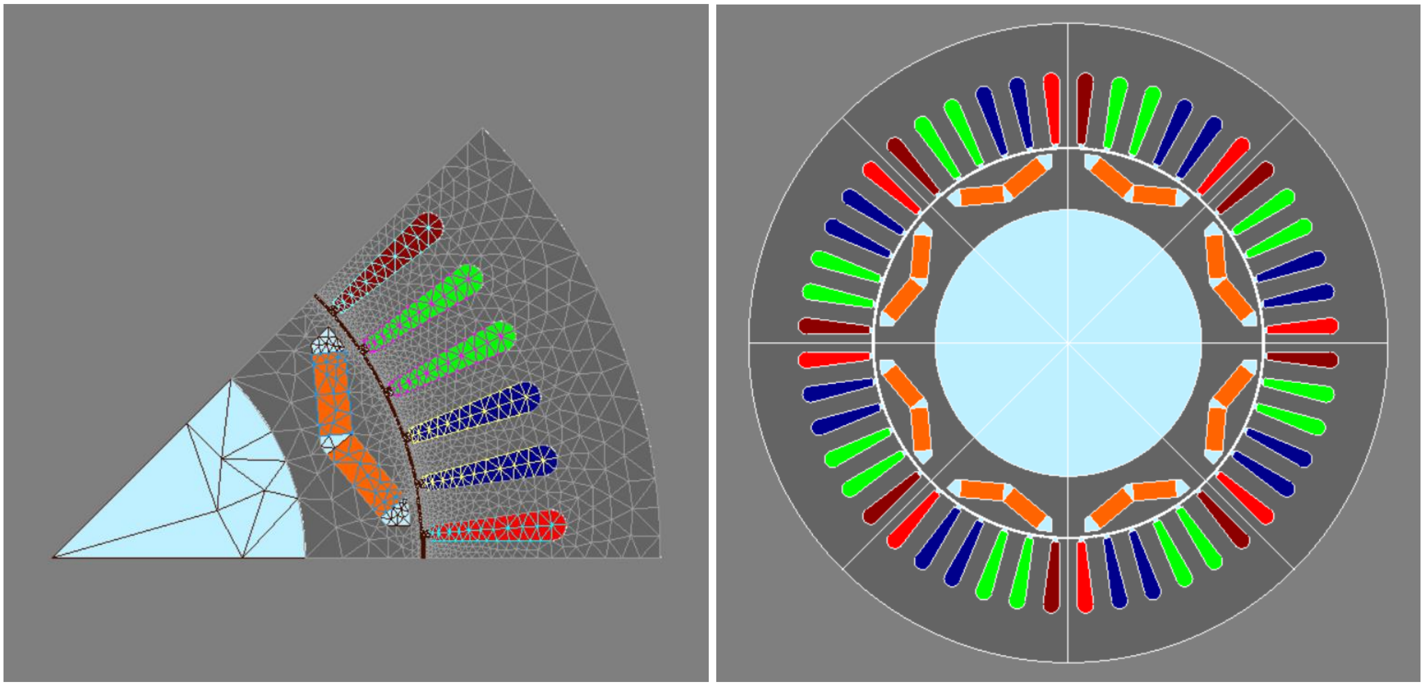


Figure 3: 2010 Prius IPM Flux Geometry and Mesh

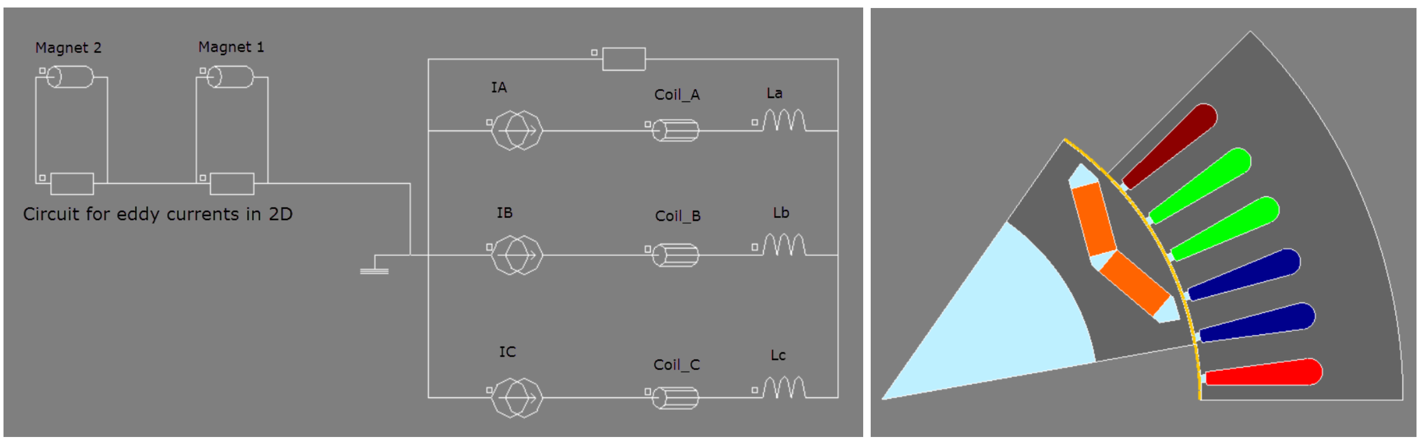


Figure 4: 2010 Prius IPM External Circuit and Rotating Motion

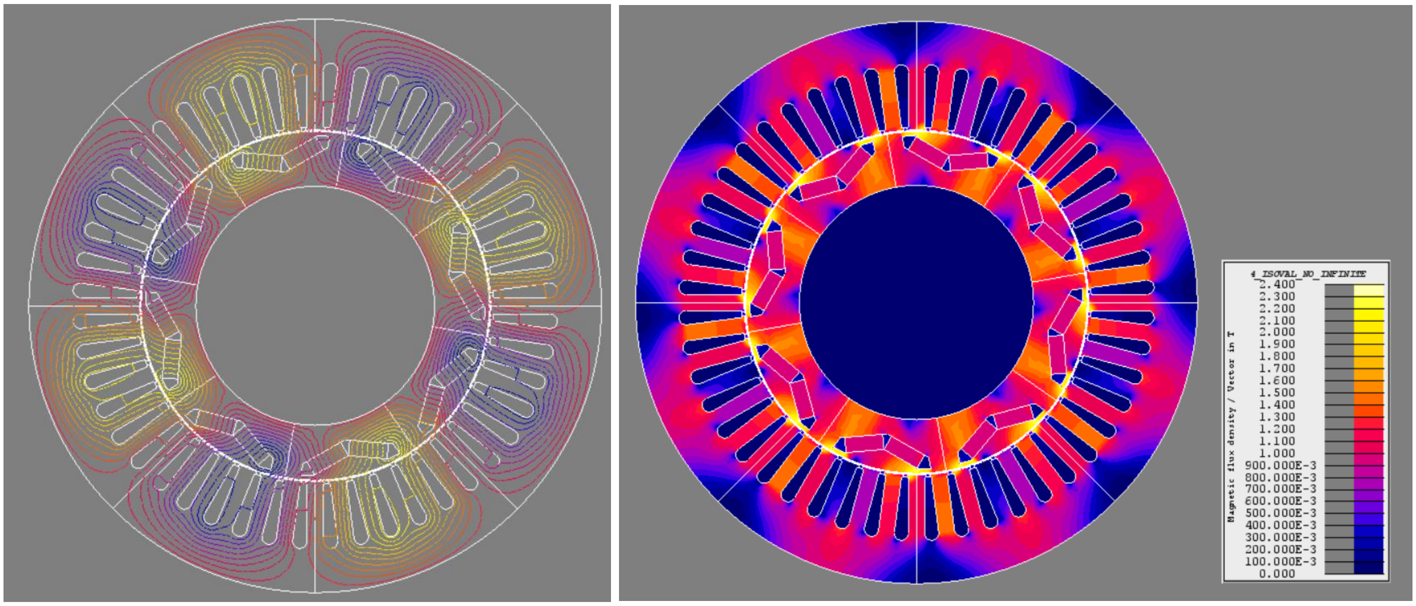


Figure 5: Isoflux Lines and Flux Density Map at 5000 rpm – 43 A rms – 60 N.m

We also computed the motor performances at max torque from low speed to the maximum speed of 13500 rpm.

The peak torque is 203 N.m vs. the Prius published data of 205 N.m. The corner speed is about 3200 rpm for a max phase voltage of 275 V rms and max phase current of 125 A rms. The computed peak torque-speed curve and efficiency-speed curves as displayed in Fig. 6 show good agreement with the ORNL test data (see Fig. 2).

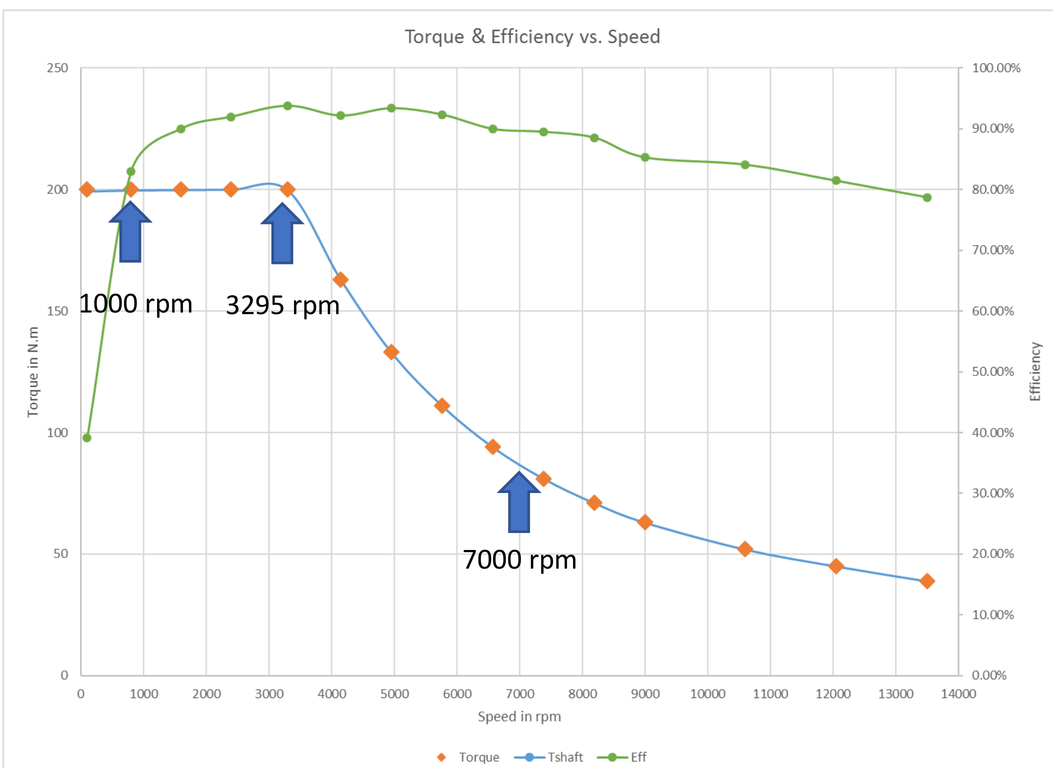


Figure 6: Flux Computed Torque-Speed and Efficiency Curves for 2010 Prius IPM Motor

Problem Formulation – Magnet Weight Minimization of Prius 2010 IPM Motor Over Peak Torque-Speed Curve

The operating mode of the IPM motor changes with the torque and the speed. At low speed, the peak torque is limited by the drive current, at the corner speed or the maximum power point, the peak torque and corner speed are limited by both the drive current and voltage, and at higher speed, the IPM motor is operated with field weakening to maintain the constant power as it is limited by the voltage. Because of the specific requirements, generally, optimizing an IPM motor design at one specific operating point wouldn't meet the performance requirements at other operating regions.

Historically, the motor design engineer would design and optimize the IPM motor at the corner speed point and then check back at low speed high torque and at high speed to see if his design would satisfy all the requirements. This design and optimization process would require multiple trials until a satisfactory configuration can be achieved.

We developed a process using multiple Flux computations for the IPM motor at important operating points and HyperStudy to minimize the motor magnet weight while satisfying different motor constraints at these operating points.

3 operating points are considered as shown in the peak torque-speed curve of Fig. 6.

1) 1000 rpm, 205 N.m – Max current point

2) 3295 rpm, 205 N.m – Max current and max voltage point (corner speed point)

3) 7000 rpm, 75 N.m – Max voltage in field weakening operating point

Table 3: 2010 Prius IPM Motor Performances at 1000 rpm, 3295 rpm and 7000 rpm

SPEED	MAX_CURR	GAMMA	TSHAFT	EFF	PELEC	PMEC	IRMS	V1ARMS	MEC_LOSSES	CU_LOSSES	FE_LOSSES	MAG_LOSSES	PF
RPM	A	eDeg.	N.m	%	Watts	Watts	A rms	V rms	Watts	Watts	Watts	Watts	PU
1000	177	42	202.02	77.47%	27307.16	21155.07	125.16	93.40	38.33	6052.76	59.84	1.16	0.78
3295	177	45	202.06	91.38%	76296.87	69721.15	125.16	274.08	191.69	6052.76	320.26	11.02	0.74
7500	130	75	78.10	91.92%	66733.67	61341.52	91.92	266.89	581.86	3265.08	1524.51	20.70	0.91

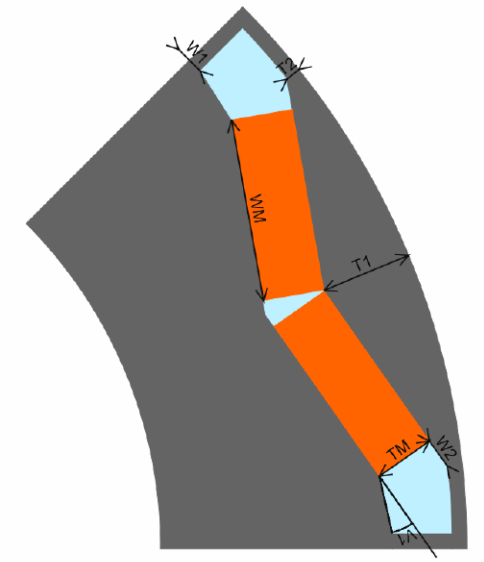
Table 3 provides the 2010 Prius motor performances at the 3 selected operating points with the magnet size of width = 17.88 mm, thickness = 7.16 mm and length = 49.3 mm. There are 2 magnets per poles and it is a 8 poles motor, thus the total magnet weight is 0.77 kg.

Optimization Formulation – Magnet Weight Minimization with Constraints at Multiples Operating Points

1) Design parameters

   a. Geometric parameters common to motors operating at 1000, 3295 and 7000 rpm, such as magnet width, WM, magnet thickness, TM, and 4 other rotor geometric parameters (T1, T2, W1, W2) for saliency, resulting in a total of 6 geometric parameters as shown in Fig. 7

   b. For each speed, the drive control parameters such as motor current and the torque control angle, Gamma, resulting in 6 physical parameters (2 x 3)



Name	Comment	Value
TM (mm)	Magnet thickness (on its axis) (mm)	7.16
WM (mm)	Magnet width (mm)	17.88
T1 (mm)	Height of rotor pole cap (mm)	9.56
T2 (mm)	Bridge thickness (mm)	1.99
W1 (mm)	Q-axis width (mm)	13.9
W2 (mm)	Windows width (mm)	0.7
V1 (deg)	Windows angle (deg)	0.0

Figure 7: Prius 2010 IPM Rotor Geometric Parameters

2) Objective function: Minimizing the common magnet weight of the motors operating at 1000, 3295 and 7000 rpm
3) Constraints: Each operating speed has its own constraints such as specified torque and drive voltage limit (rms value of phase voltage fundamental)
    a. 1000 rpm: 200 N.m and 275 Volts rms
    b. 3295 rpm: 200 N.m and 275 Volts rms
    c. 7000: 75 N.m and 275 Volts rms

HyperStudy

For the optimization problem, we used HyperStudy's unique feature of having multiple models of the same type or different physical types (multi-physics) to pilot 3 Flux models as shown in Fig. 8. Each Flux model is the parametrized IPM motor simulation at a specified speed with geometric parameters and physical parameters as displayed in Fig. 9.

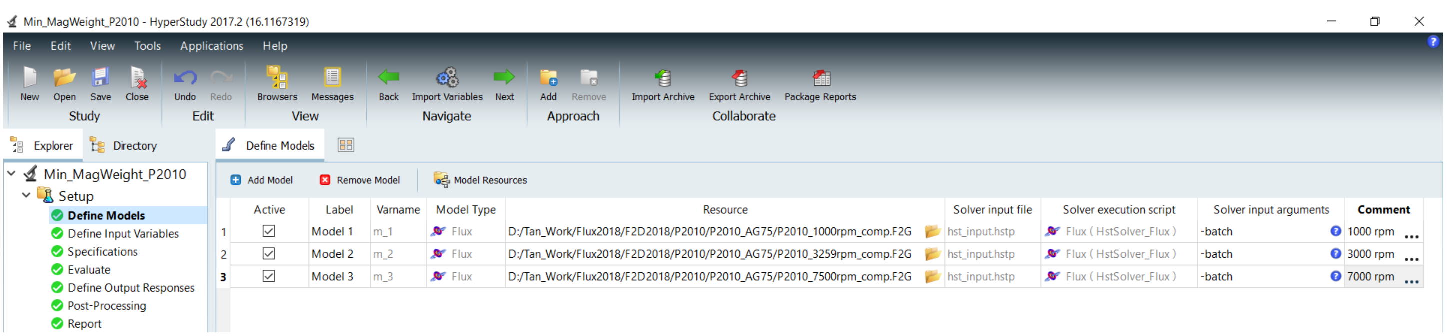


Figure 8: HyperStudy with 3 Different Operating Point Models

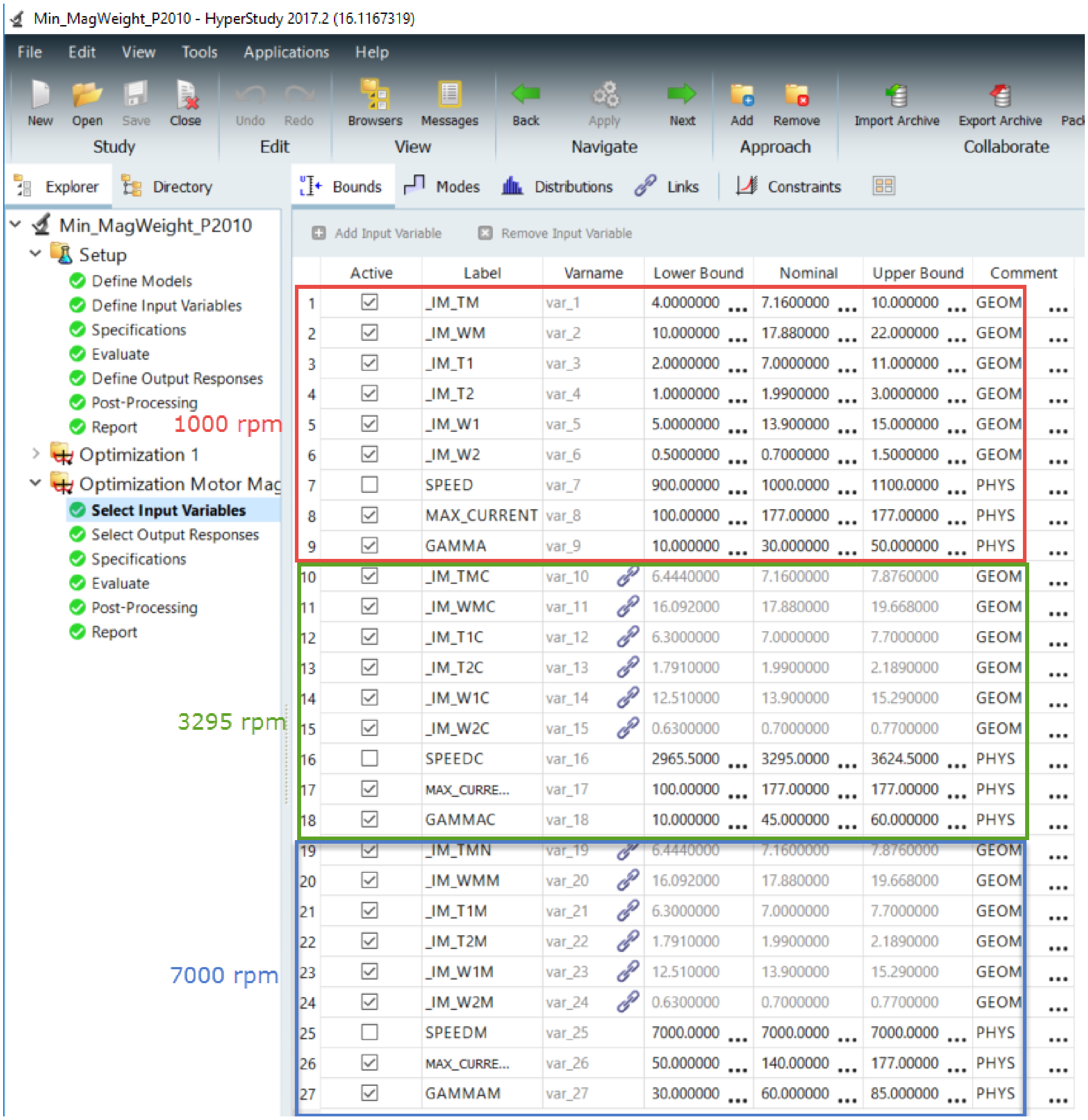


Figure 9: Design Parameters for 3 Flux Models

The geometric parameters that are common to the 3 operating speed simulations are linked together resulting in a common geometric parameter set as shown in Fig. 10.

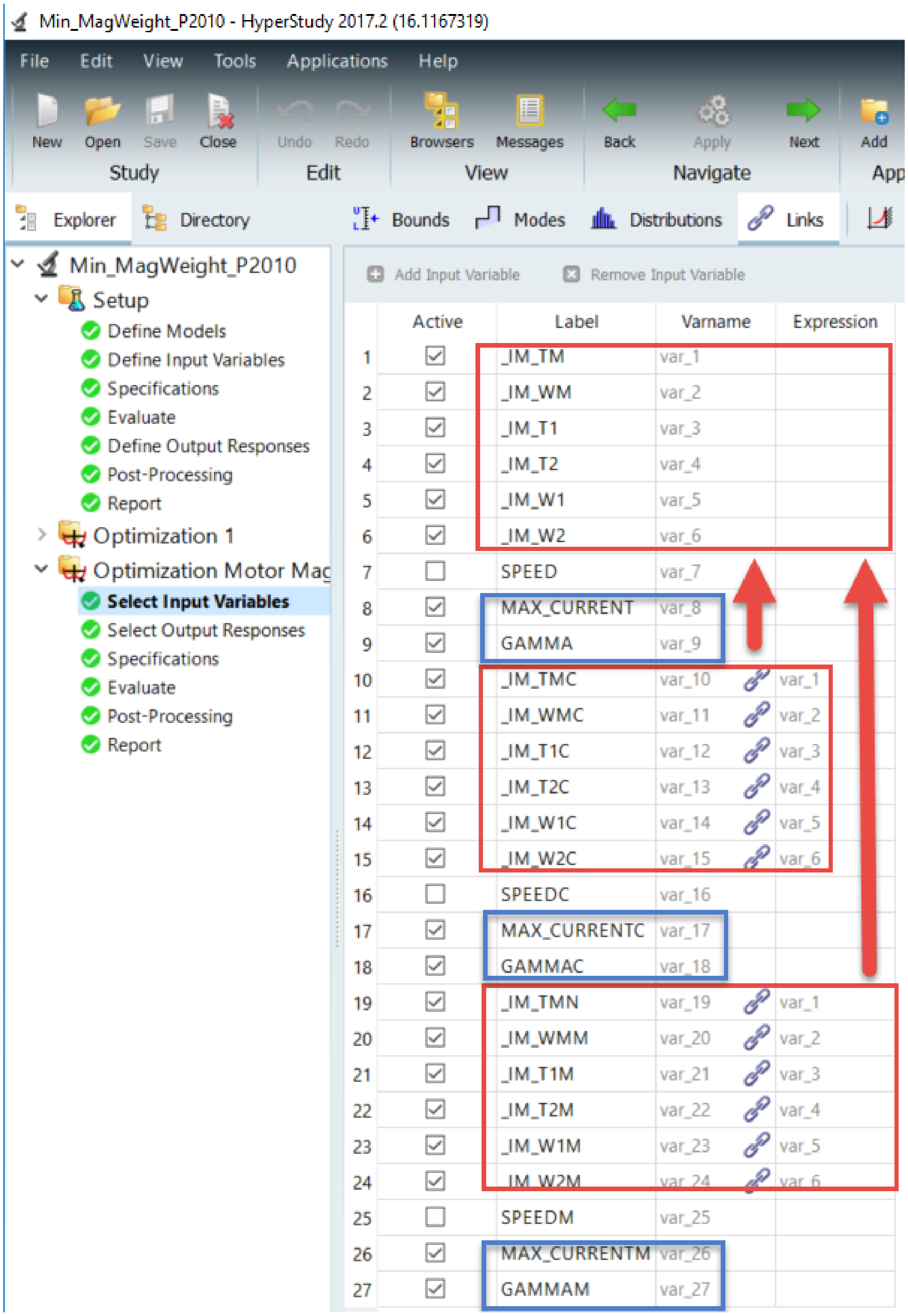


Figure 10: Links for Common Geometric Parameters

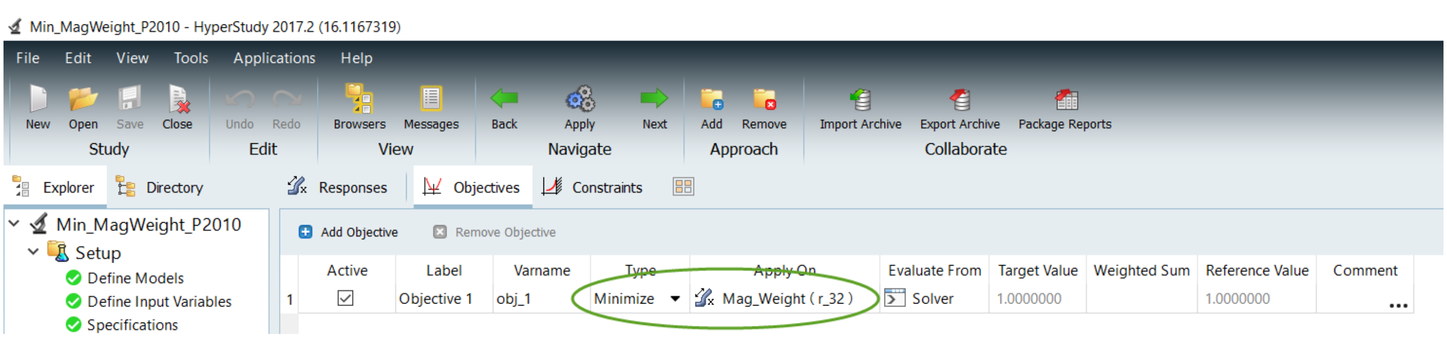


Figure 11a: Minimum Magnet Weight Objective Function

The objective function is common to the 3 Flux models and it consists of minimizing the IPM rotor magnet weight (Fig. 11a). The constraints are specific to each operating point of the 3 Flux model (Fig. 11b). This results in a total of 6 constraints.

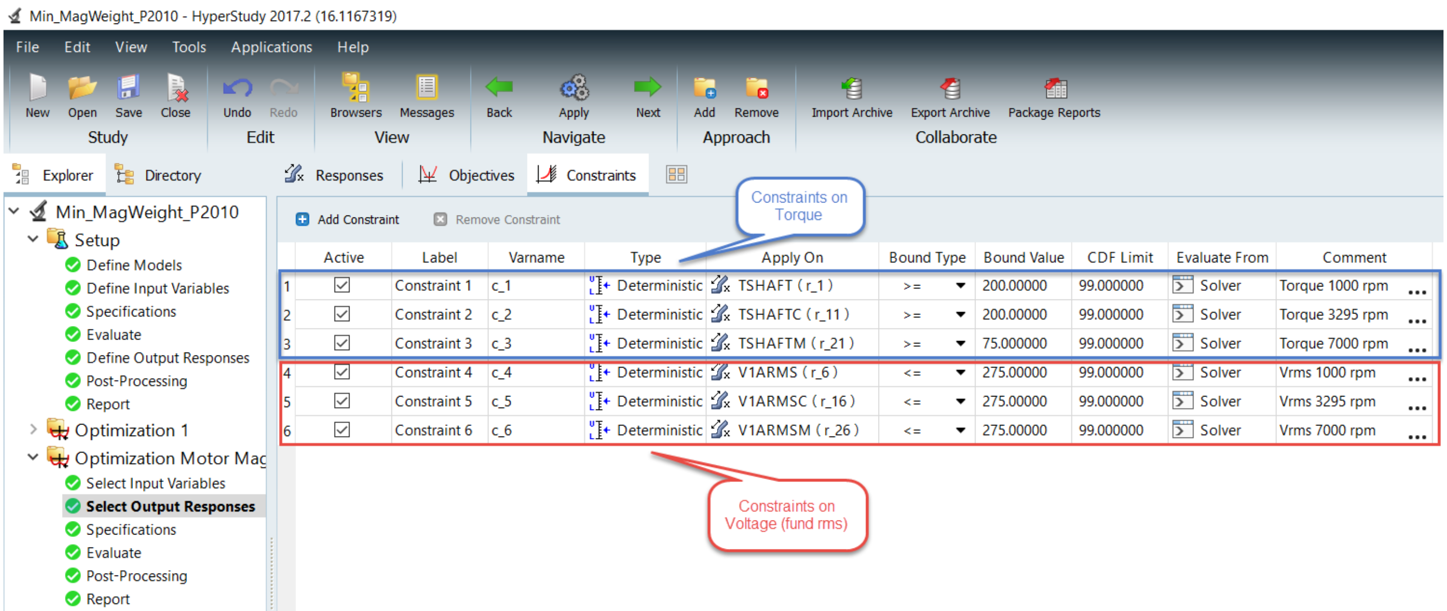


Figure 11b: Torque and Voltage Constraints for Each Operating Point

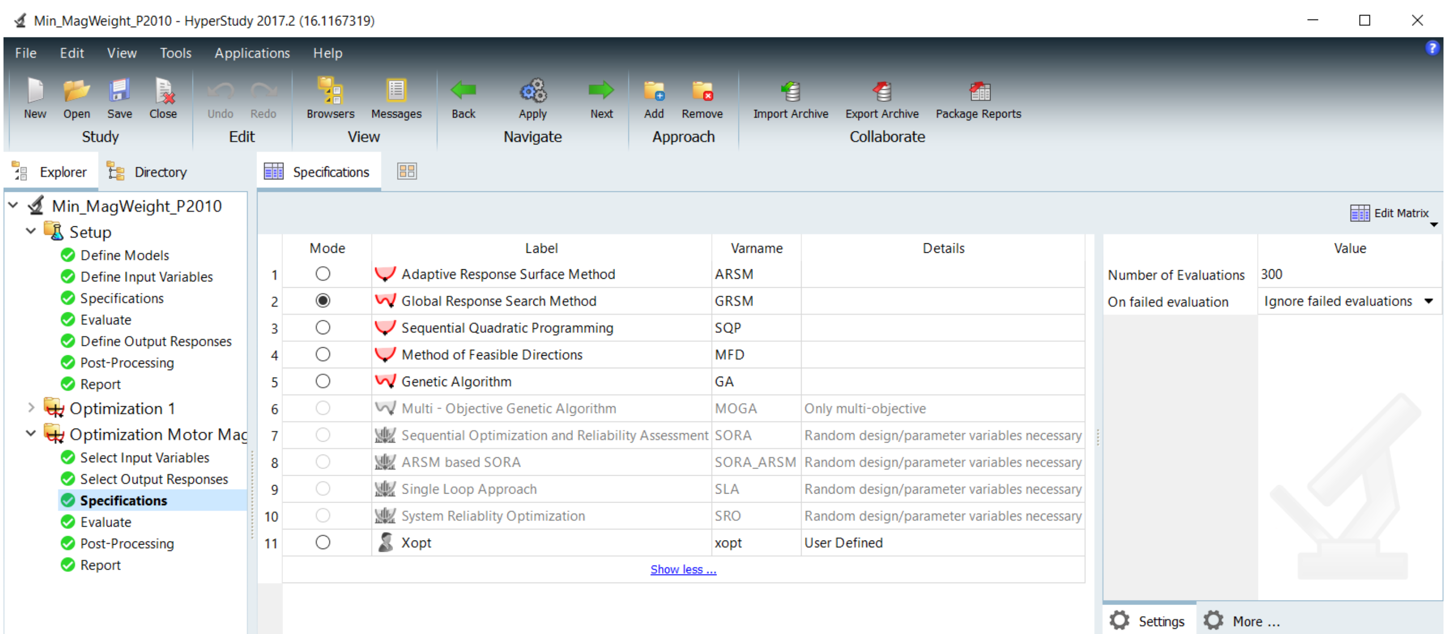


Figure 12: GRSM Optimizer

The Altair proprietary optimizer GRSM is used for the magnet weight minimization with constraints. The GRSM optimization algorithm can efficiently yield an optimum design with a reasonable number of evaluations even in cases where there is a large number of design parameters, compared to a common Genetic Algorithm which would require more processing time. The number of evaluations is set to 300. With 3 Flux models, it results in a total of 900 Flux simulations (300x3 operating points).

The total time takes less than 10 hours on an I7 processor laptop. We also take advantage of another unique feature of HyperStudy that allows Multi-Exe where multiple models can be run in parallel. In this optimization, the Multi-Exe is set to 3 permitting up to 3 Flux simulations to run in parallel on 3 different cores, speeding up the optimization process.

Figures 13, 14a and 14b show respectively the iteration plots of the Prius 2010 magnet weight (objective), the greater than constraints on the torque and less than constraints on the phase voltage. Up to iteration 24, there are 117 designs evaluated that are not satisfactory for all the constraints, especially for the phase voltage at 7000 rpm.

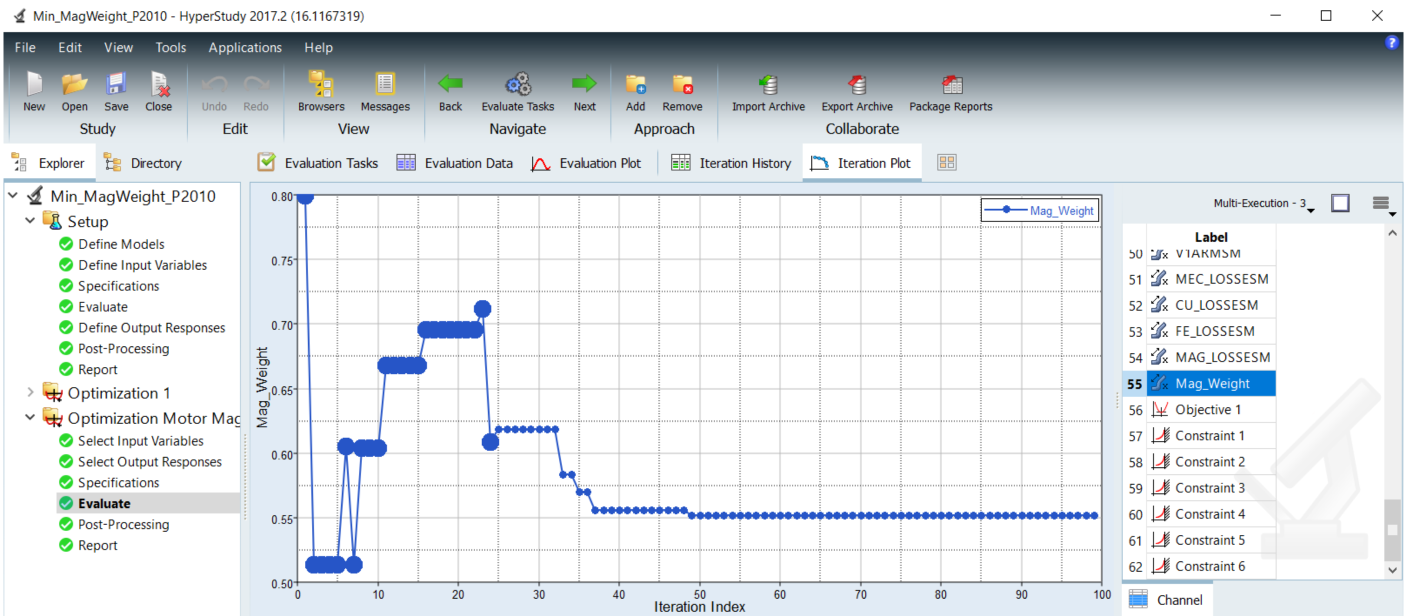


Figure 13: Magnet Weight Iteration Plot and Convergence

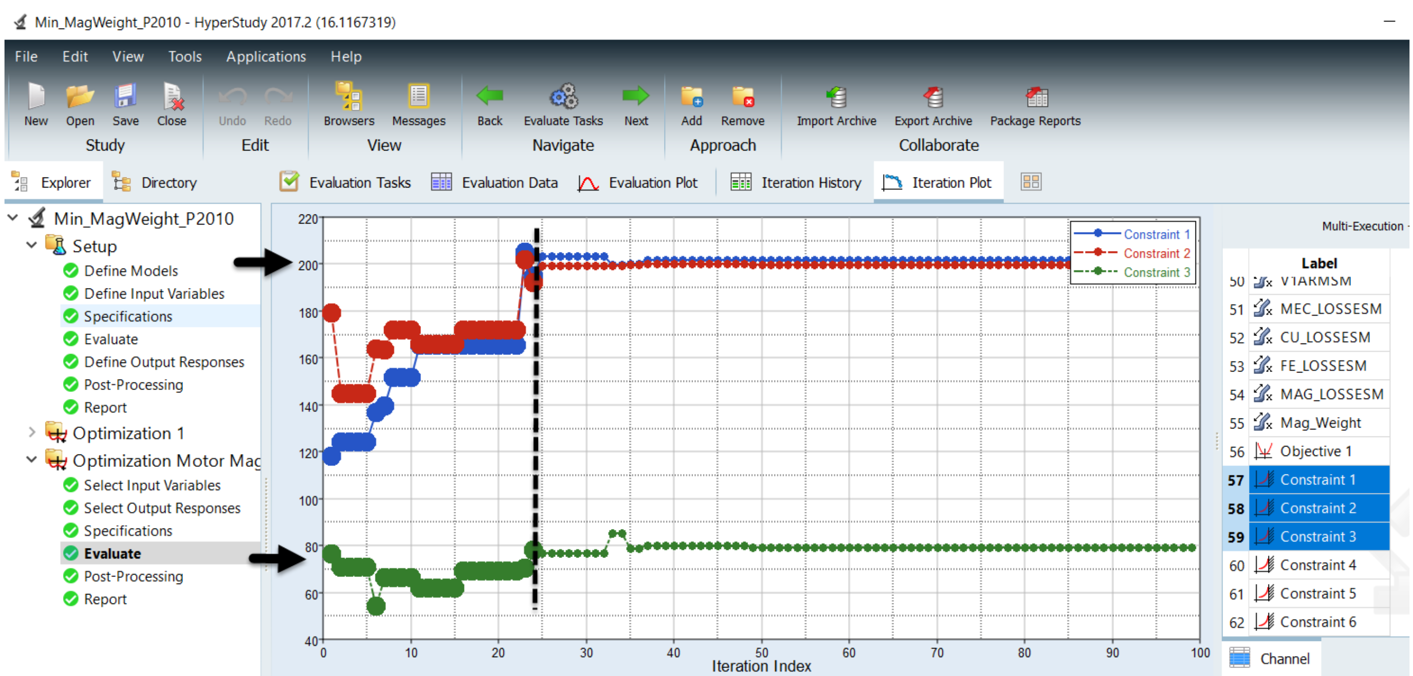


Figure 14a: Torque Constraints Iteration Plot

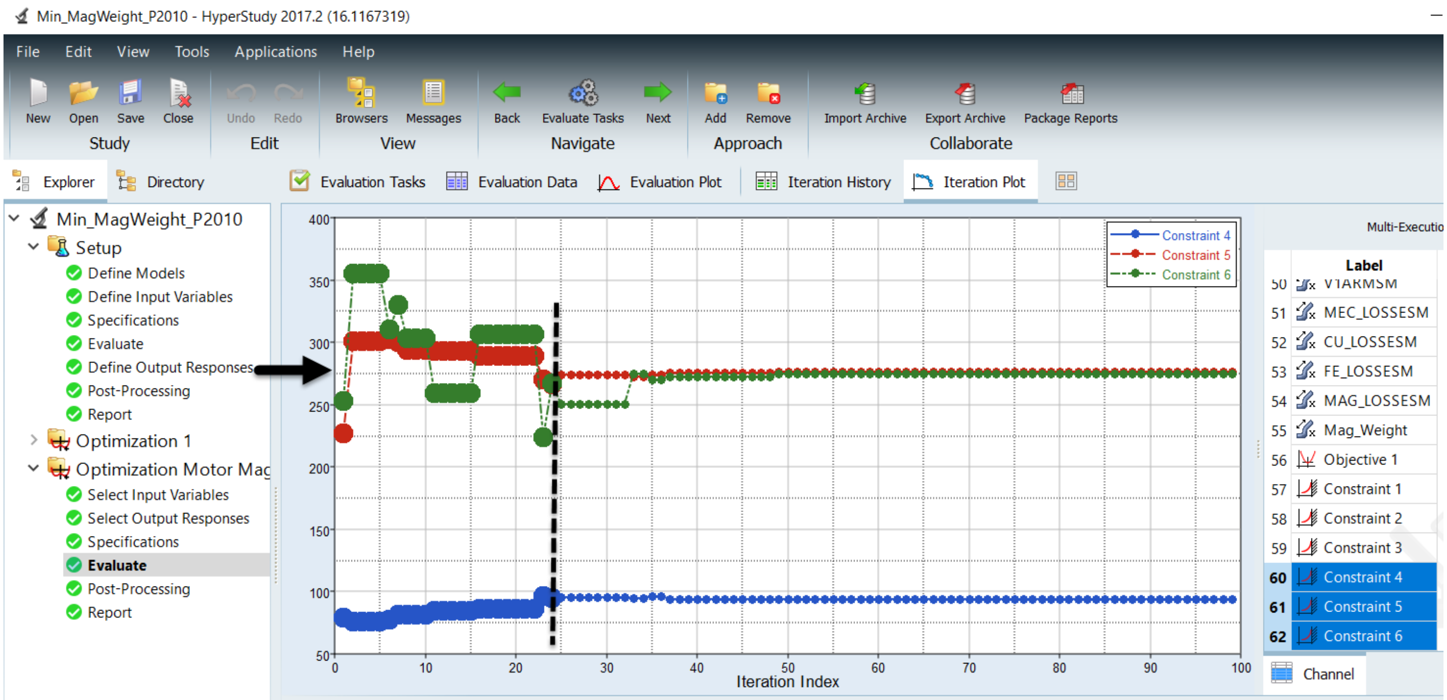


Figure 14b: Voltage Constraints Iteration Plot

Figures 15a and 15b are respectively the iteration plot of the magnet thickness and width. The magnet thickness is reduced by 31% in order to achieve a smaller magnet weight, whereas the magnet width is slightly increased compared to the initial size to help meet the torque and voltage constraints.

Table 4 and Fig. 16 compare the geometry of the initial rotor vs. the optimum rotor. We achieved a weight of 0.55 kg vs. the initial weight of 0.77 kg resulting in a 28% weight reduction.

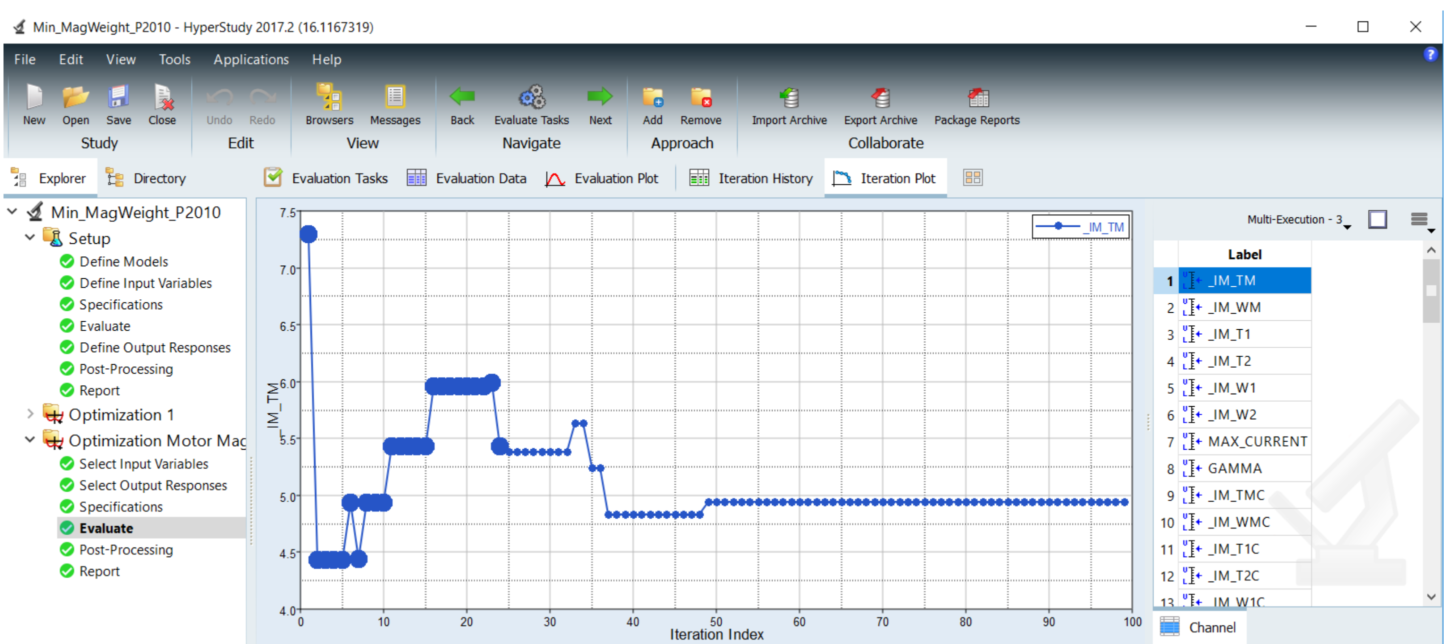


Figure 15a: Magnet Thickness Iteration Plot

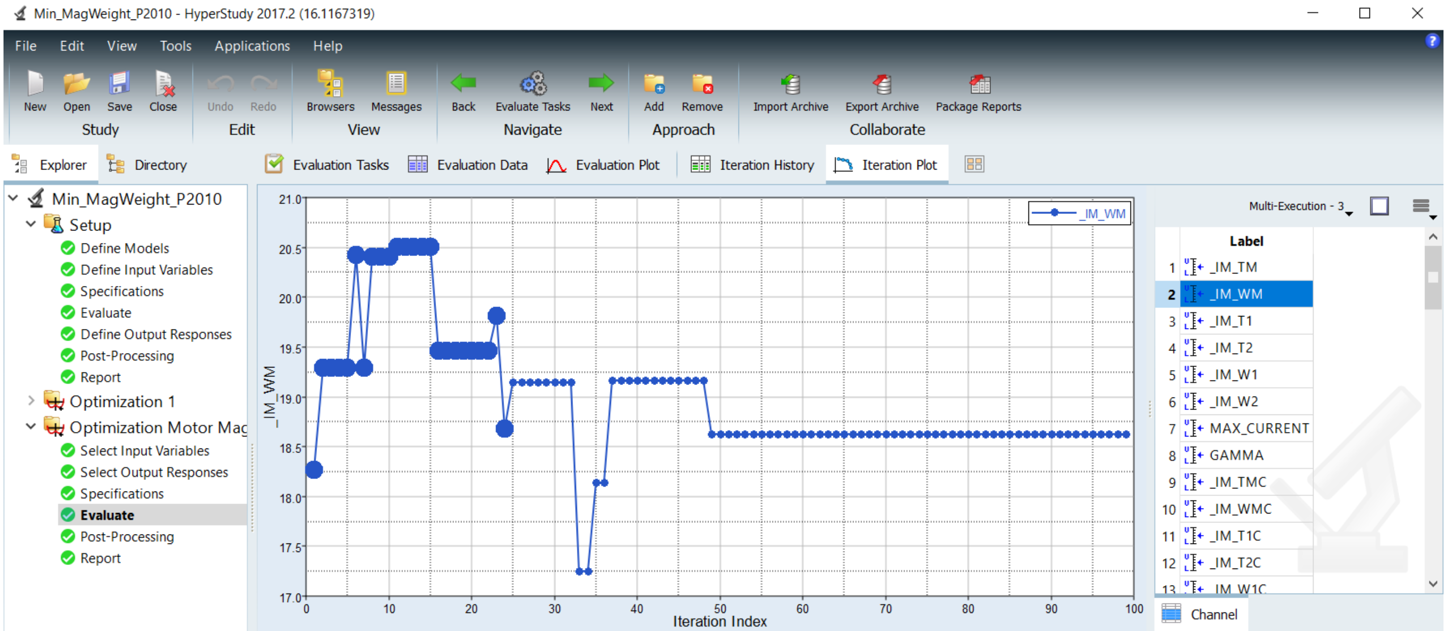


Figure 15a: Magnet Width Iteration Plot

Table 4: Prius 2010 IPM Rotor Initial Geometric Parameters vs. Optimum Parameters

	Weight	_IM_TM	_IM_WM	_IM_T1	_IM_T2	_IM_W1	_IM_W2
	kg	mm	mm	mm	mm	mm	mm
Initial	0.77	7.16	17.88	7.00	1.99	13.90	0.70
Optimum	0.55	4.94	18.62	10.13	1.00	14.97	0.70

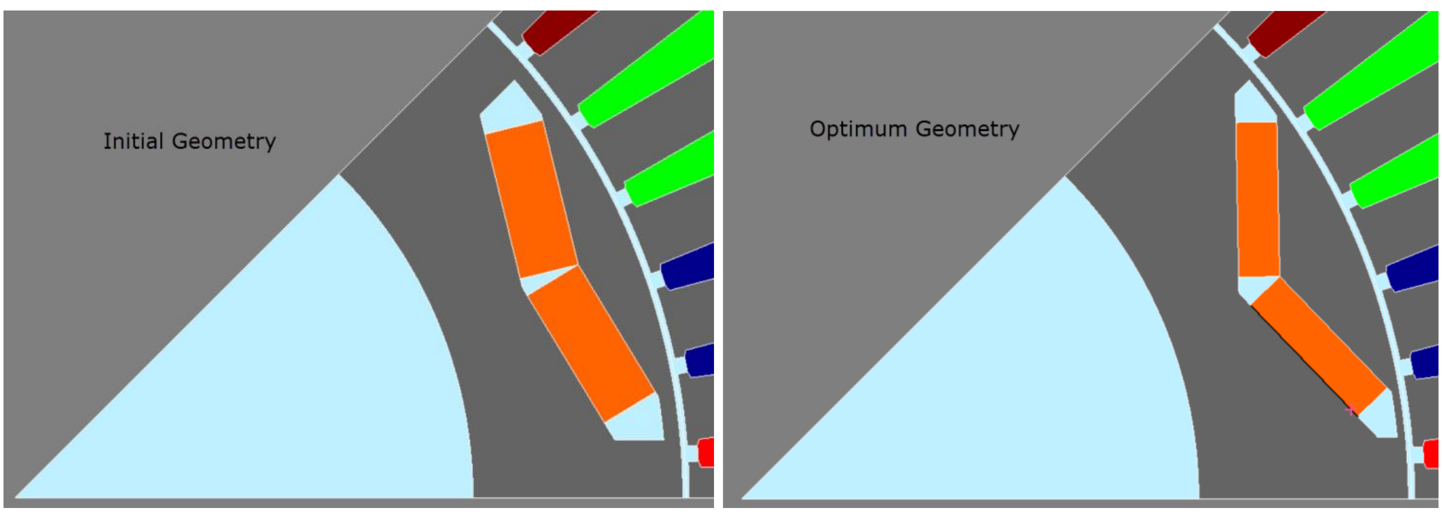


Figure 16: Prius 2010 IPM Rotor Initial Geometry vs. Optimum Geometry

Table 5 shows the performances comparison of the smaller magnet weight design vs. 2010 Prius IPM Motor at 1000, 3295 and 7000 rpm. Both designs yield similar performances with the smaller magnet design being a little less efficient at high speed.

Table 5: 2010 Prius IPM Motor Performances with Initial Rotor vs. Optimum Rotor

	SPEED	MAX_CUR	GAMMA	TSHAFT	EFF	PELEC	PMEC	IRMS	V1ARMS	MEC_LOS	CU_LOSSE	FE_LOSSE	MAG_LOS	PF
Initial	RPM	A	eDeg.	N.m	%	Watts	Watts	A rms	V rms	Watts	Watts	Watts	Watts	PU
Geometry	1000	177	42	202.02	77.47%	27307.16	21155.07	125.16	93.40	38.33	6052.76	59.84	1.16	0.78
	3295	177	45	202.06	91.38%	76296.87	69721.15	125.16	274.08	191.69	6052.76	320.26	11.02	0.74
	7000	103	70	75.46	93.72%	59020.15	55314.98	72.65	276.35	530.11	2039.27	1129.54	6.25	0.98
Optimum	1000	176.96	48.74	201.62	77.44%	27265.15	21113.67	125.13	94.01	38.33	6050.23	61.71	1.21	0.77
Geometry	3295	176.94	51.49	199.90	91.25%	75585.12	68974.34	125.12	276.14	191.69	6048.95	358.60	11.54	0.73
	7000	142.82	77.30	79.18	90.47%	64153.38	58039.71	100.99	274.81	530.11	3940.77	1600.32	42.48	0.77

Conclusion

With Flux and HyperStudy, it is possible to solve optimization problems of electric motors with multiple operating points and requirements. Besides electromagnetics, we can also solve other multi-physics optimization problems for electric motors on a design domain and along with the Multi-Exe feature. Furthermore, the optimization can be performed in a reasonable amount of time.

Acknowledgement

My special thanks to the HyperStudy team for the technical support to unlock so many wonderful features in the tool.

Also, special acknowledgement to the FluxMotor team for providing the Prius 2010 parametrized model and Dr. Silvain Perez and Dr. Patrick Lombard for many discussions on how to properly benchmark the Prius 2010 IPM motor with Flux and FluxMotor.