Flux Conference 2012

High – Efficiency Motor Design for Electric Vehicles

CEDRAT
design solutions for
electrical engineering

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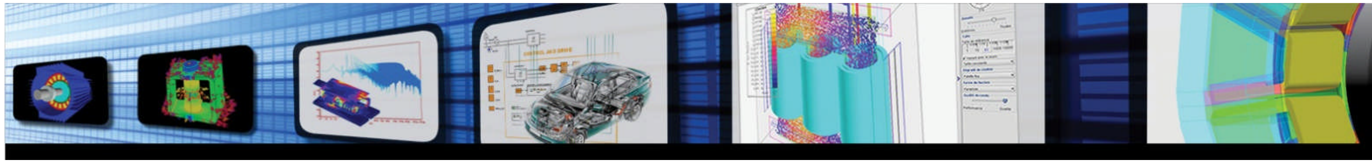
Presented by: P. Lazari

Outline

- Requirements and design challenges for EV traction machines
- Computationally efficient design technique for EV traction machines against driving cycle
- Optimisation objective and constraints
- Optimisation methodology and tools
- Design case studies
- Conclusions



Requirements and design challenges for EV traction machines

- **Requirements:**
  - High **energy efficiency** and **cost-effectiveness**.
  - High **torque**, **3~4 times the nominal** value, required for acceleration and hill climbing.
  - Peak **power twice the rated value** at high speeds.
- **Design Challenges:**
  - Wide operating torque-speed range, imposes **significant constraints** on achievable machine efficiency.
  - Machine design should be targeted **for overall energy saving over driving cycle**.
  - **Enormous computation time** is required for FE evaluation over a driving cycle. This makes **multi-parameter** optimisations with FE models practically impossible.

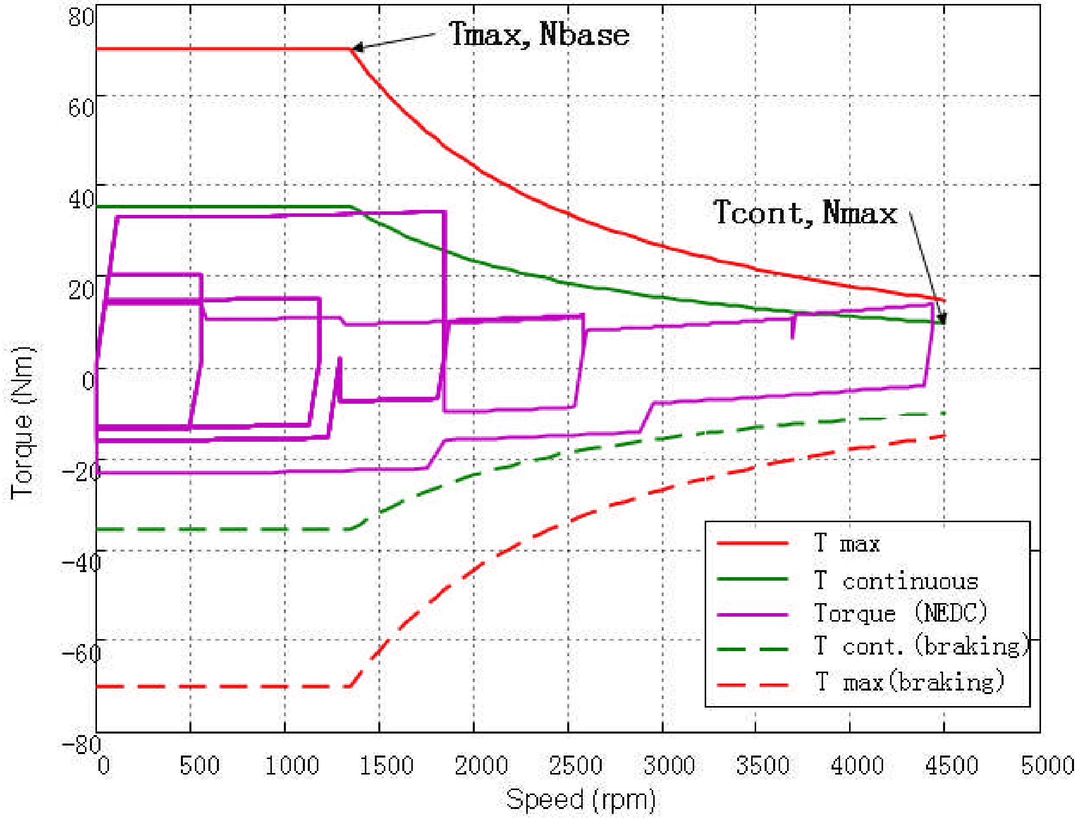
Solutions

- Derivation of **representative driving cycle operating points** - dramatically reduce the number of FE computations.

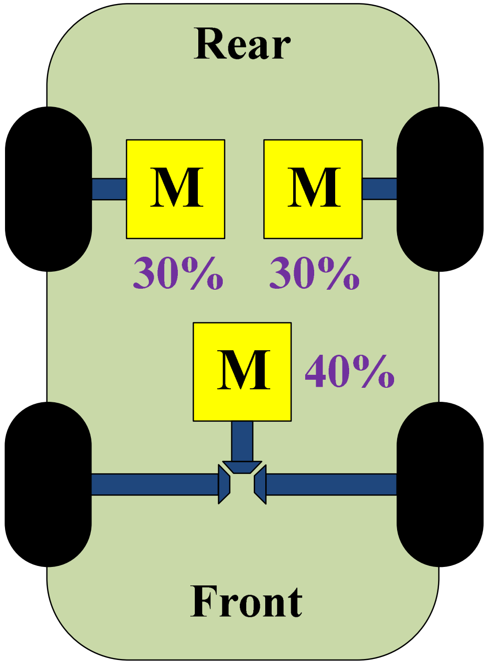
- Use of efficient FE coupled **optimisation** tool **--Flux & GOT-IT** provides an ideal and effective design optimisation environment for EV traction machines.

Requirements of EV traction

- Max speed – 120 km/h
- Base speed
- Peak power
- Max continuous power at max speed – From **NEDC**
- Contin. Torque – **10%** slope at 20km/h
- Peak Torque – **20%** slope at given acceleration



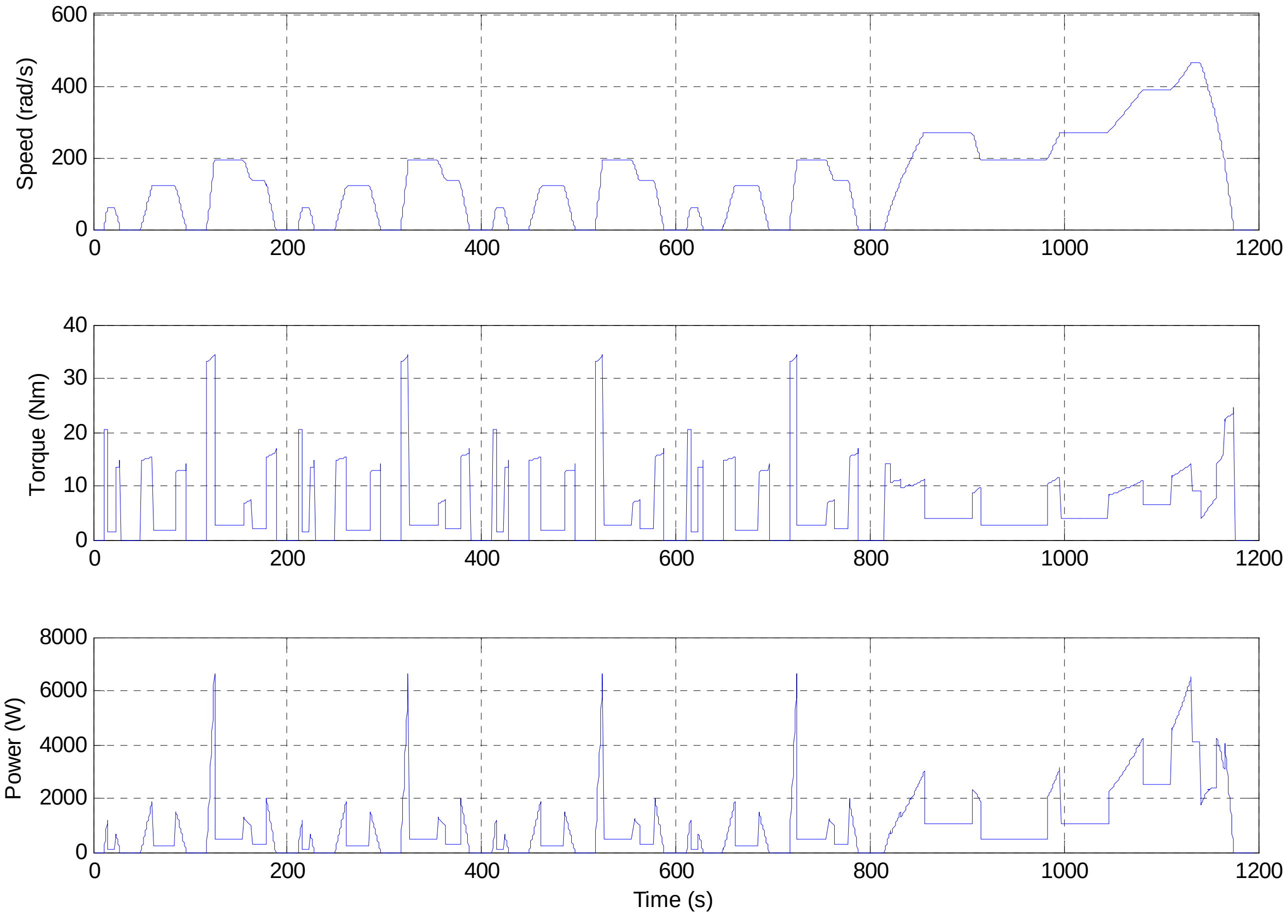
Investigated vehicle data



Parameter (Unit)	Value
Tire size	165/50 R15
Radius of wheels (m)	0.273
Vehicle mass (kg)	800
Gravitational acceleration (m/s^2)	9.807
Rolling resistance	0.007
Product of drag coefficient and front area (m^2)	0.35
Air density (kg/m^3)	1.25
Efficiency of differential	0.980
Gear Ratio	4.0 & 7.0

- Vehicle power-train employs a **distributed drive** with **three** motors coupled to the front and rear axle.
- **40%** and **60%** of traction power is shared between front and rear motors respectively.

Vehicle characteristics over NEDC



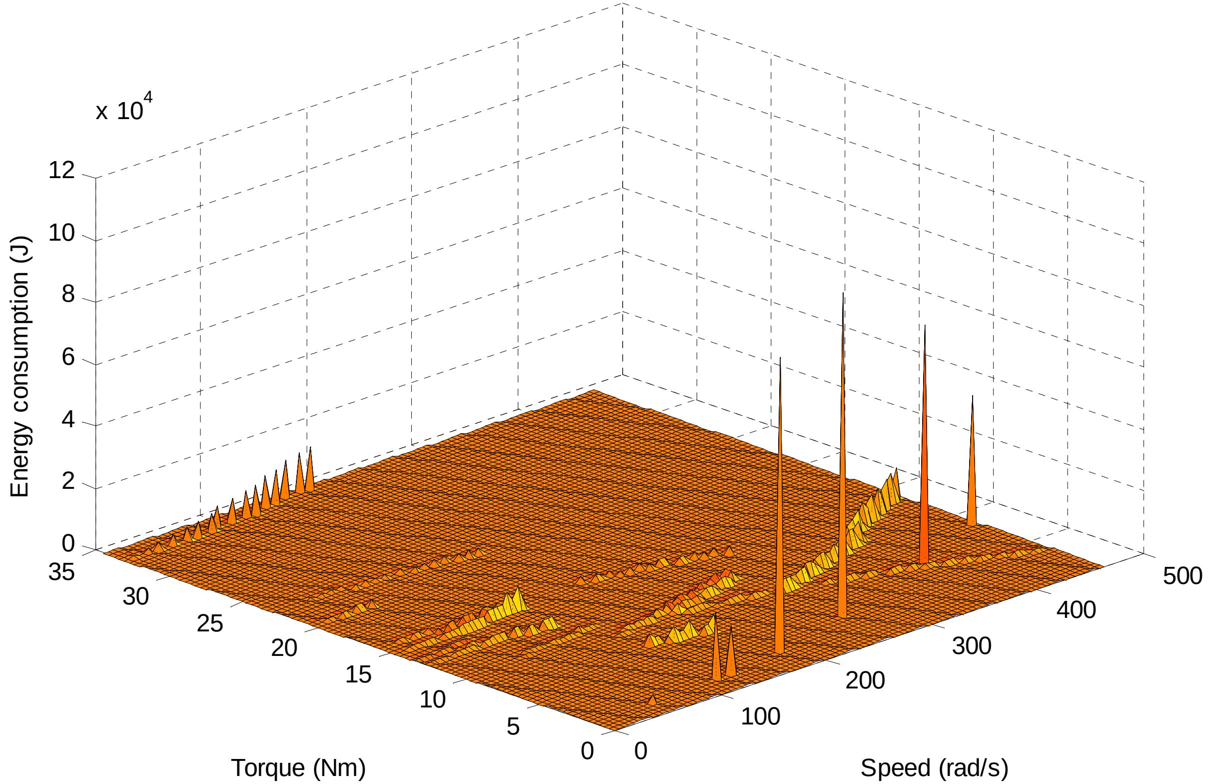
- Speed, torque and power plots of front motor **derived from vehicle specification**.

Motor design specification

- Traction machine should be **optimized against NEDC**, while satisfying **thermal** and **volumetric constraints**.
- **Problem** – **Require enormous amount of calculation time** viz. 600 operating points over NEDC, ~ **200 hours just for one design**

Parameter (Unit)	Value
Base speed (rpm)	1350
Maximum cruise speed (rpm)	4500
Tpeak at base speed (Nm) for 120 sec	70.0
Tcont. at base speed (Nm)	35.0
Tpeak at maximum cruise speed (Nm)	18.0
Peak power (kW)	**8.8**
Continuous power (kW)	5.0
Nominal DC link voltage (V)	**120**
Max line-to-line voltage (V)	< 250 (for safety)
Cooling	**Air-cooled**

Energy distribution over NEDC



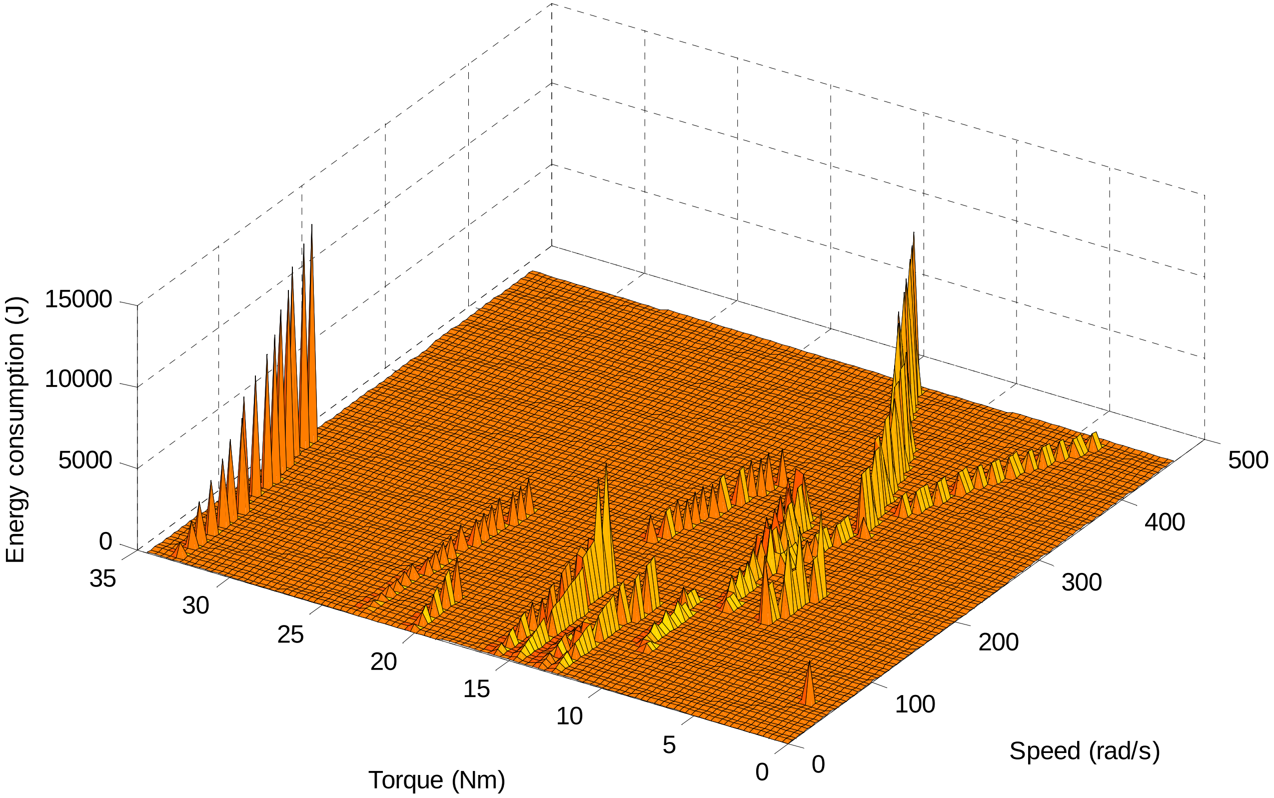
- **Energy consumption** on the motor output shaft over NEDC of reference vehicle.
- There exist **six dominant points** where energy consumption is significantly high.

Energy distribution over NEDC

$$E_i = \sum_{j=1,2,...}^{N_i} E_{ij}$$

$$\omega_{mci} = \frac{1}{E_i} \sum_{j=1,2,...}^{N_i} E_{ij}\omega_{ij}$$

$$T_{mci} = \frac{1}{E_i} \sum_{j=1,2,...}^{N_i} E_{ij}T_{mij}$$

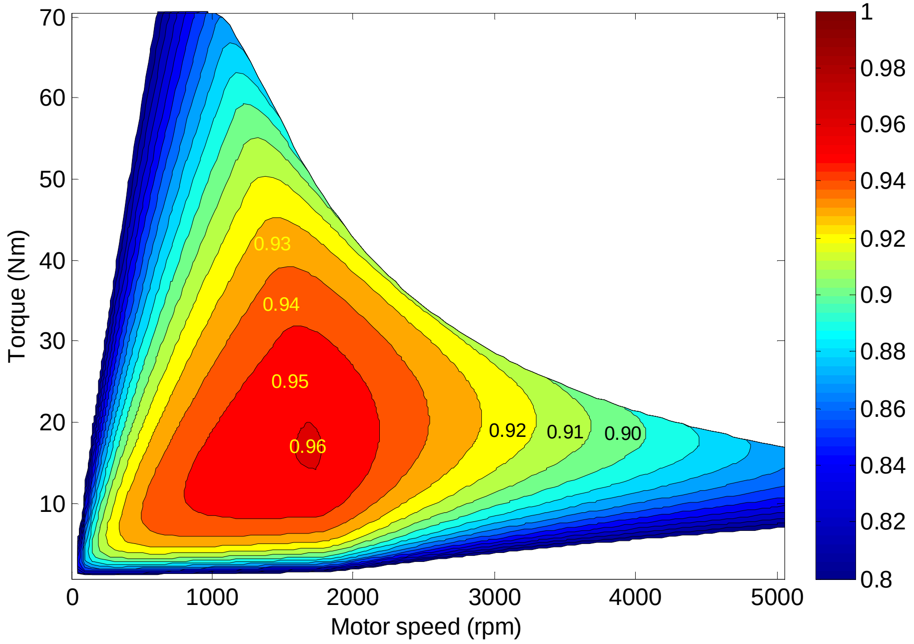


- The remaining points scatter around and can be represented by another six points according to the **energy** **“centre of gravity”**.

Validation of 12 NEDC points

$$EL = \sum_{i=1,2,\ldots}^{N} \omega_m(t_i) T_m(t_i) \Delta t_i (1-\eta_i)/\eta_i$$

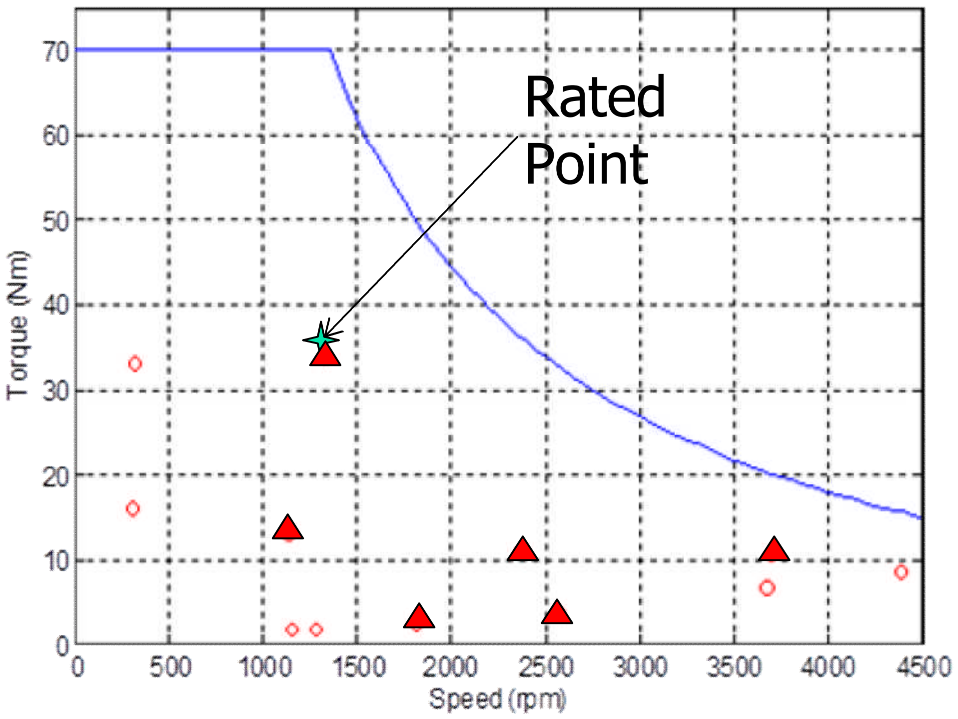
$$EL = \sum_{j=1,2,\ldots}^{12} E_{nj} (1-\eta_j)/\eta_j$$



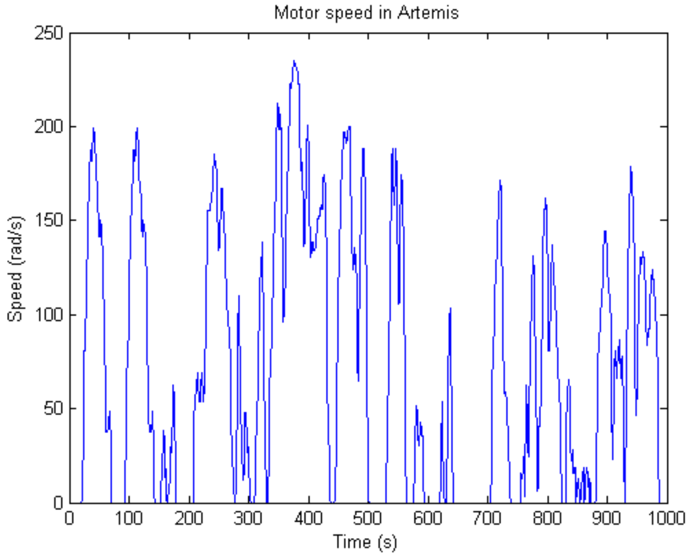
Energy loss over **all points** in **NEDC** cycle (kJ)	55.104
Energy loss over **12 points** (kJ)	53.387
Difference (%)	**3.1%**

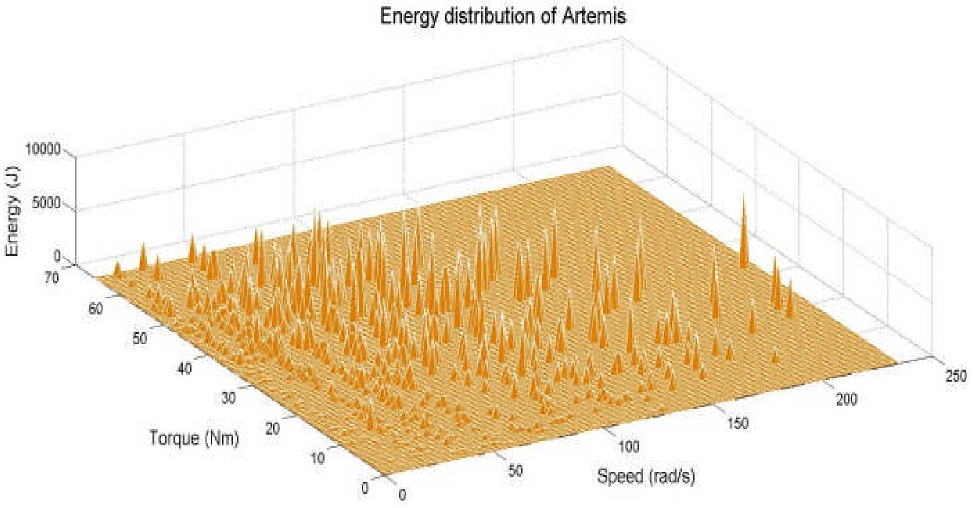
Design technique for EV traction machines

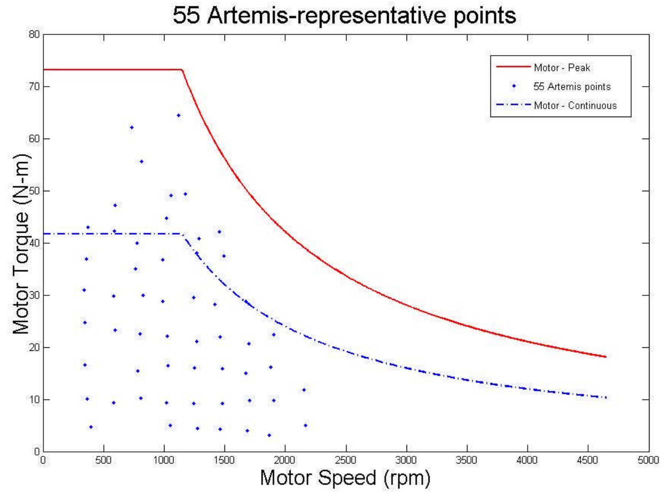
- Calculation time **limitation effectively removed** using 12 representative points.
- NEDC **high energy consumption** is dominated by **low torque/middle-high speed** points.
- Mismatch between **NEDC high operating duty** and **rated** operating points – Significance of optimising against driving cycle.



Design technique on ARTEMIS Urban







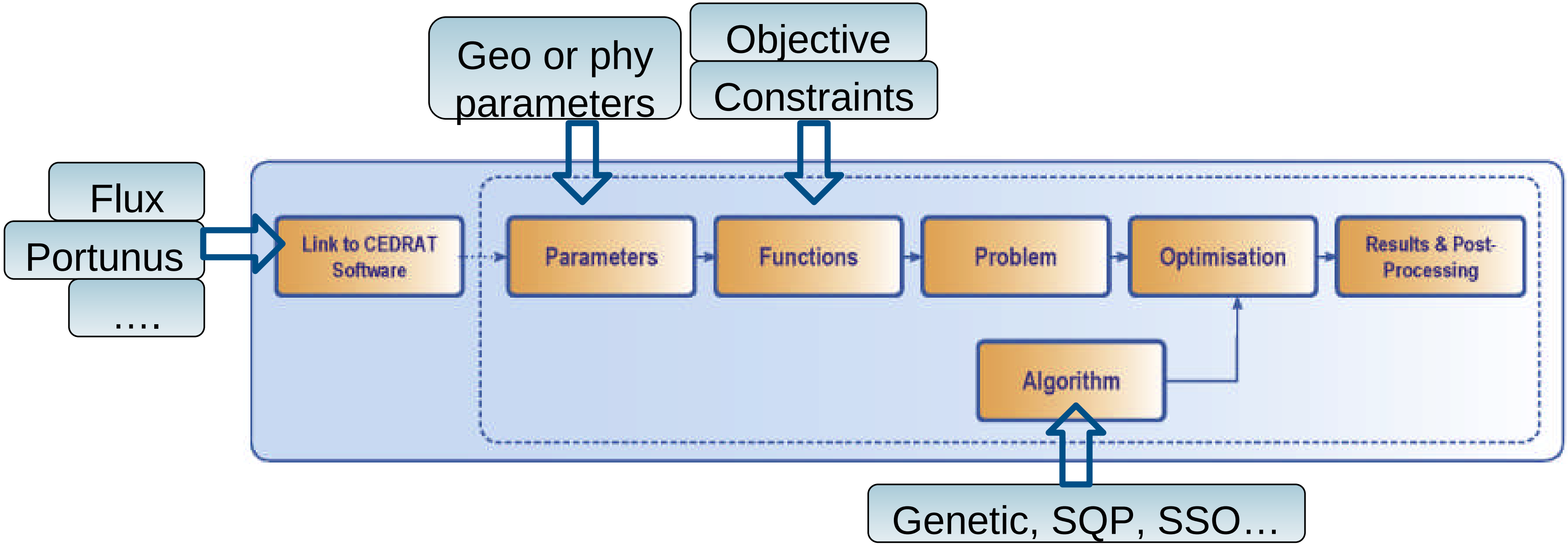
- Frequent variation of Artemis Urban speed.
- **55 representative points** with loss calculation error of **5%**.
- Artemis Urban is dominated by **variable torque/ low to middle speed points**.

Optimisation objective and constraints

- **Objective:**
  - **Minimisation of energy loss over 12 NEDC points.**
- **Constraints:**
  - Dimensional: stack length and outside diameter.
  - Electrical: current, voltage limits imposed by converter.
  - Thermal: temperatures of windings and magnets.
  - Mechanical: stress level of rotor.
  - Demagnetization withstand of magnets.
  - Torque ripple.

Optimisation tool: GOT-It

- GOT-It is a **powerful** and **efficient** optimisation tool developed by CEDRAT.



Geo or phy parameters

Objective

Constraints

Flux

Portunus

….

Link to CEDRAT Software

Parameters

Functions

Problem

Optimisation

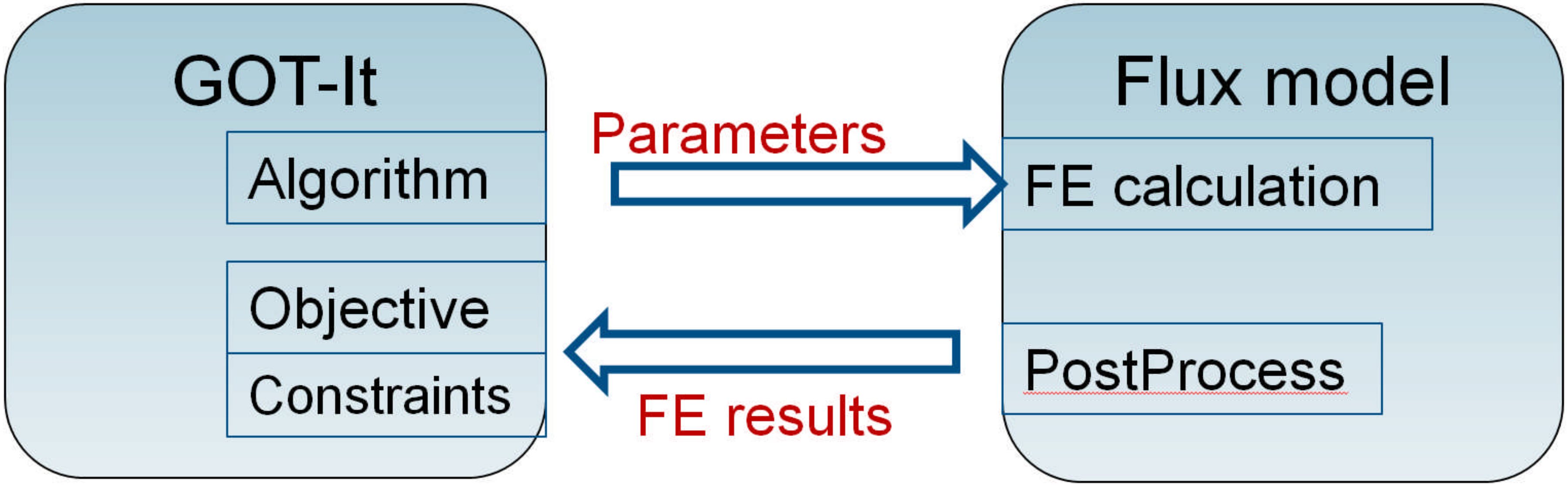
Results & Post-Processing

Algorithm

Genetic, SQP, SSO…

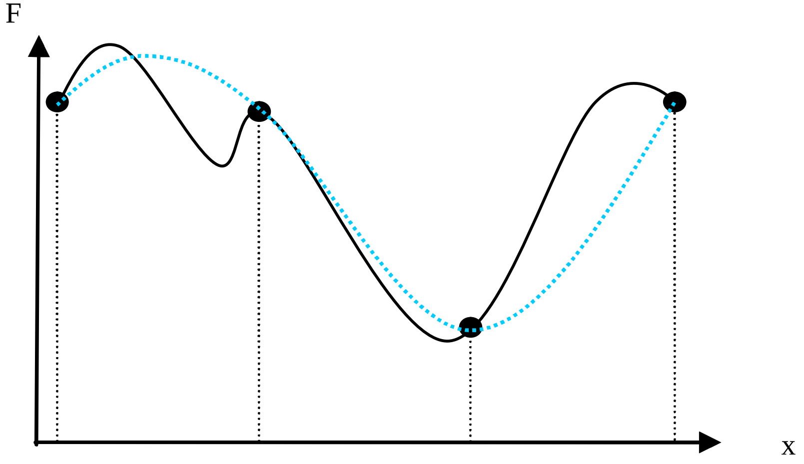
GOT-It coupling with Flux 2D/3D

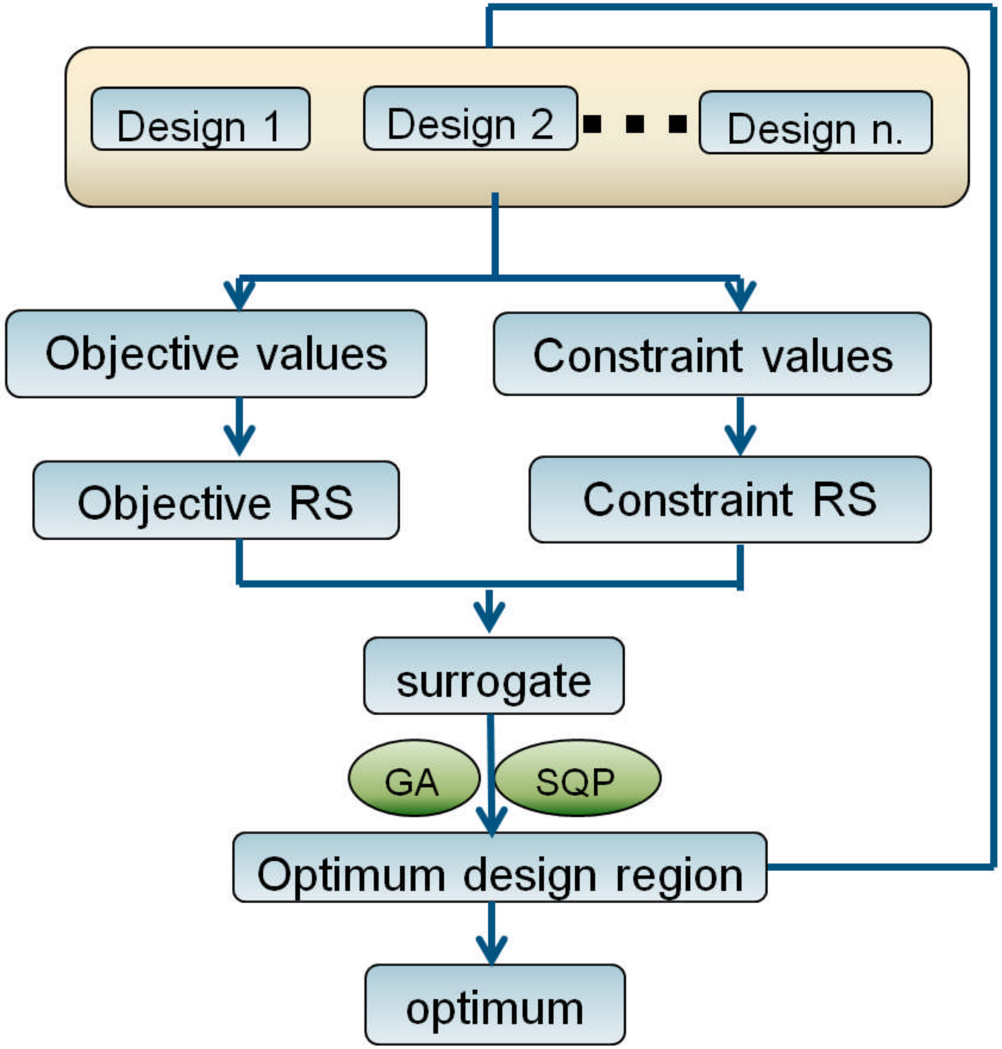
- **Objectives**, **constrains** and selection of **algorithms** are defined in Got-it which performs optimisation by passing parameters **to** and retrieve results **from** Flux FE model.



Sequential Surrogate Optimiser

- Global optimisation
- Response Surfaces (RS)
- Iteratively converging to optimum





Design 1

Design 2 ■ ■ ■ Design n.

Objective values

Constraint values

Objective RS

Constraint RS

surrogate

GA

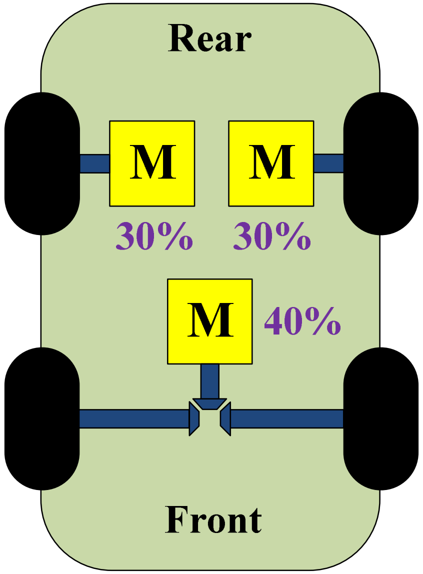
SQP

Optimum design region

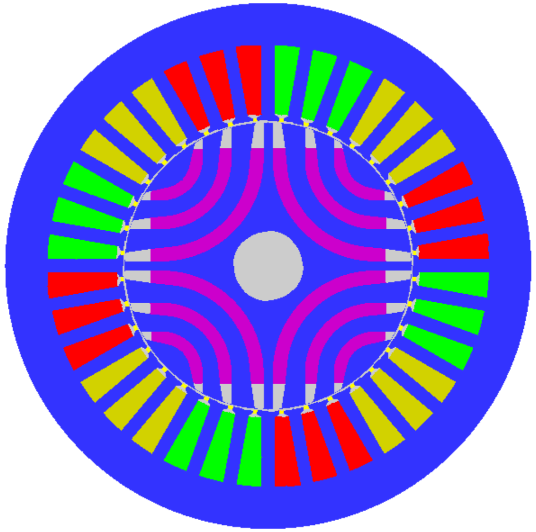
optimum

Optimisation case studies for EV traction motors

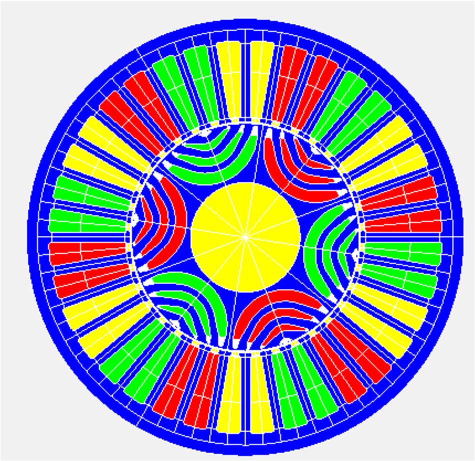
- Micro-sized electric vehicle with front and rear wheel drives.
- Front motor -- **36 slot/4 pole** PMa-SynRM (**1x40%**, gear ratio **4:1**)
- Two rear motors -- **36 slot/6 pole** PMa-SynRM (**2×30%**, gear ratio **7:1**)



Ferrite magnets



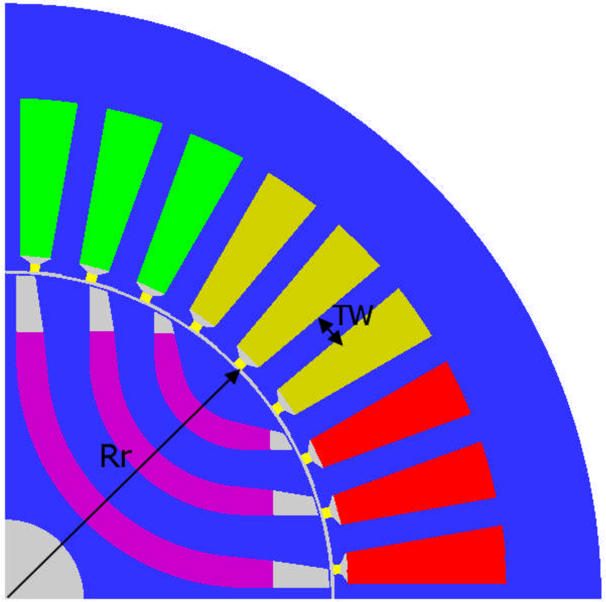
Front motor

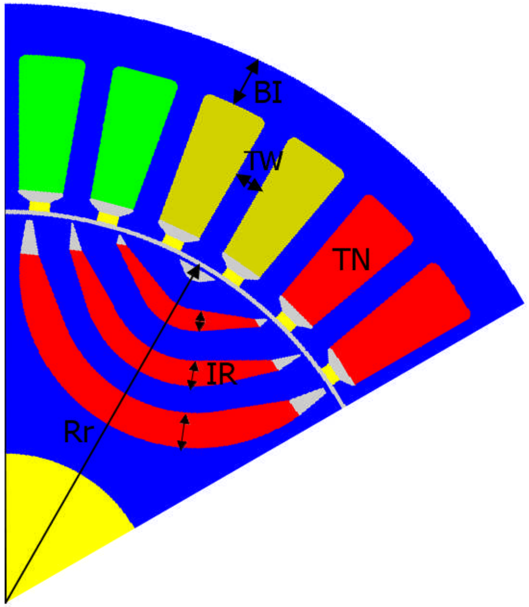


Rear motor

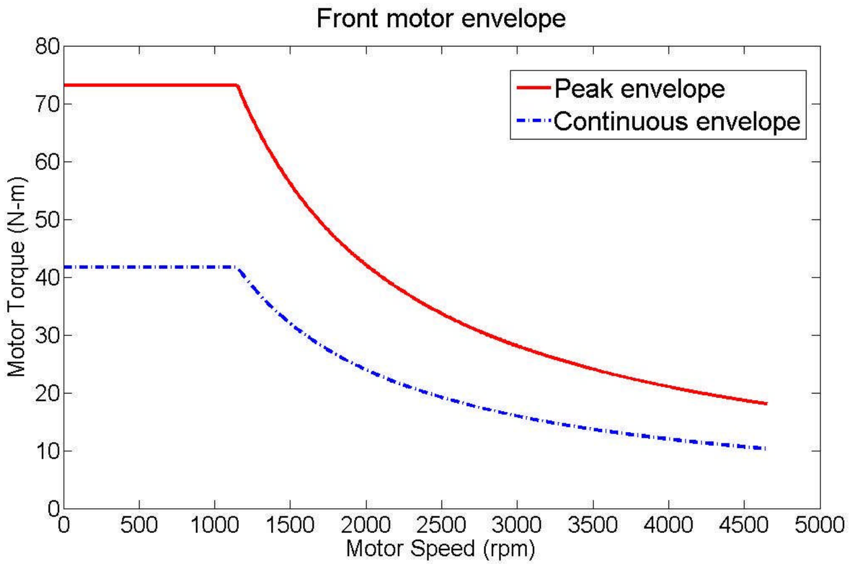
Optimisation design parameters

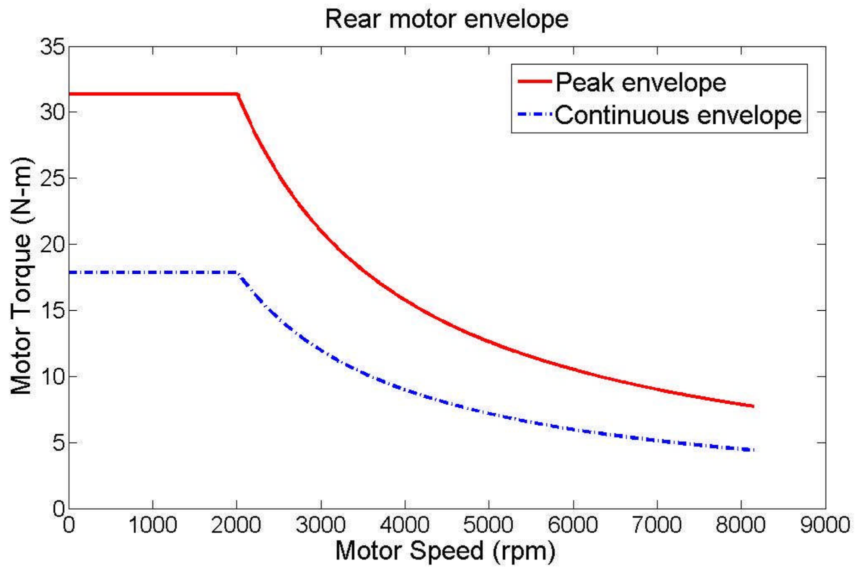
- **2 parameters** for front motor optimisation:
  - Rotor radius (Rr) and tooth width (TW).
- **5 parameters** for rear motor optimisation:
  - Rotor radius (Rr), insulation ratio (IR), tooth width (TW), back iron thickness (BI) and number of turns per coil (TN).





Torque-speed operating range requirements





Parameter	Front	Rear
Base speed	1350 rpm	2100 rpm
Max speed	4500 rpm	8200 rpm
Rated torque	35 Nm	17 Nm
Peak torque at base speed	70 Nm	30 Nm
Peak torque at maximum speed	18 Nm	7.5 Nm

Optimisation design constraints

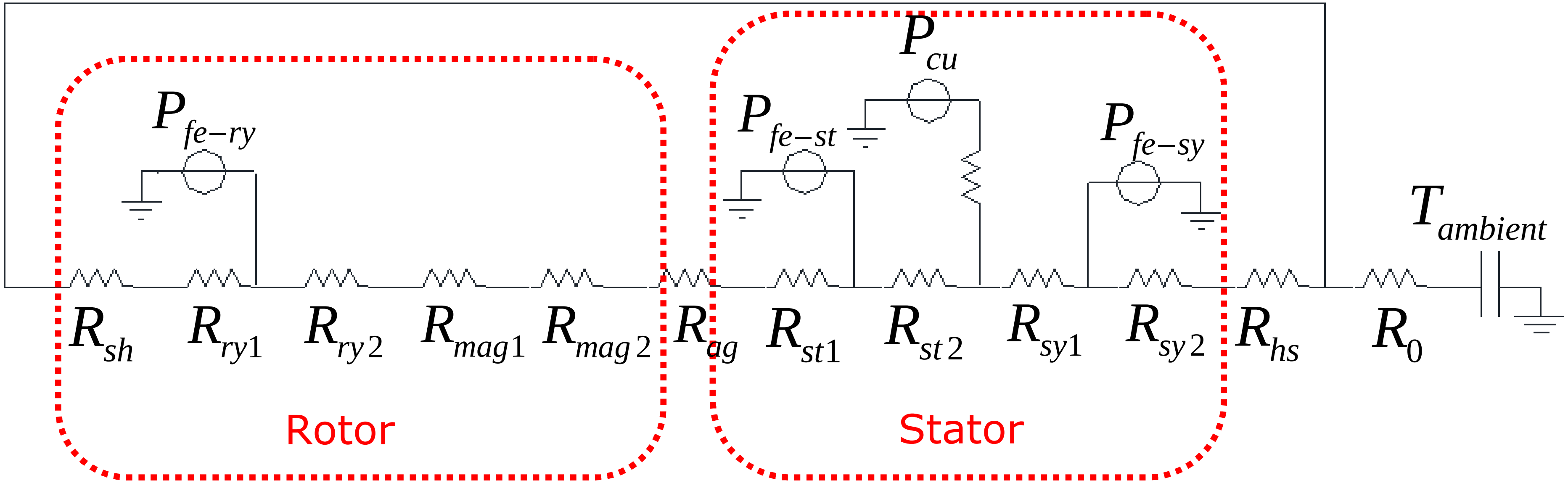
- Dimensional and electrical constraints:

Parameter	Front	Rear
Stack length	118 mm	105 mm
Outer diameter	150 mm	120 mm
Max current	170 A	170 A
DC link voltage	120 V	120 V
Max line-to-line no-load voltage (for safety)	240 V	240 V

- Demagnetisation:
  - Magnets withstand during deep flux weakening.
- Mechanical strength:
  - Stress level on rotor bridges **< 450 MPa at 1.5 * Nmax**.
- Thermal constraints:
  - **Winding** and **magnet** temperature should be **< 120 °C**.

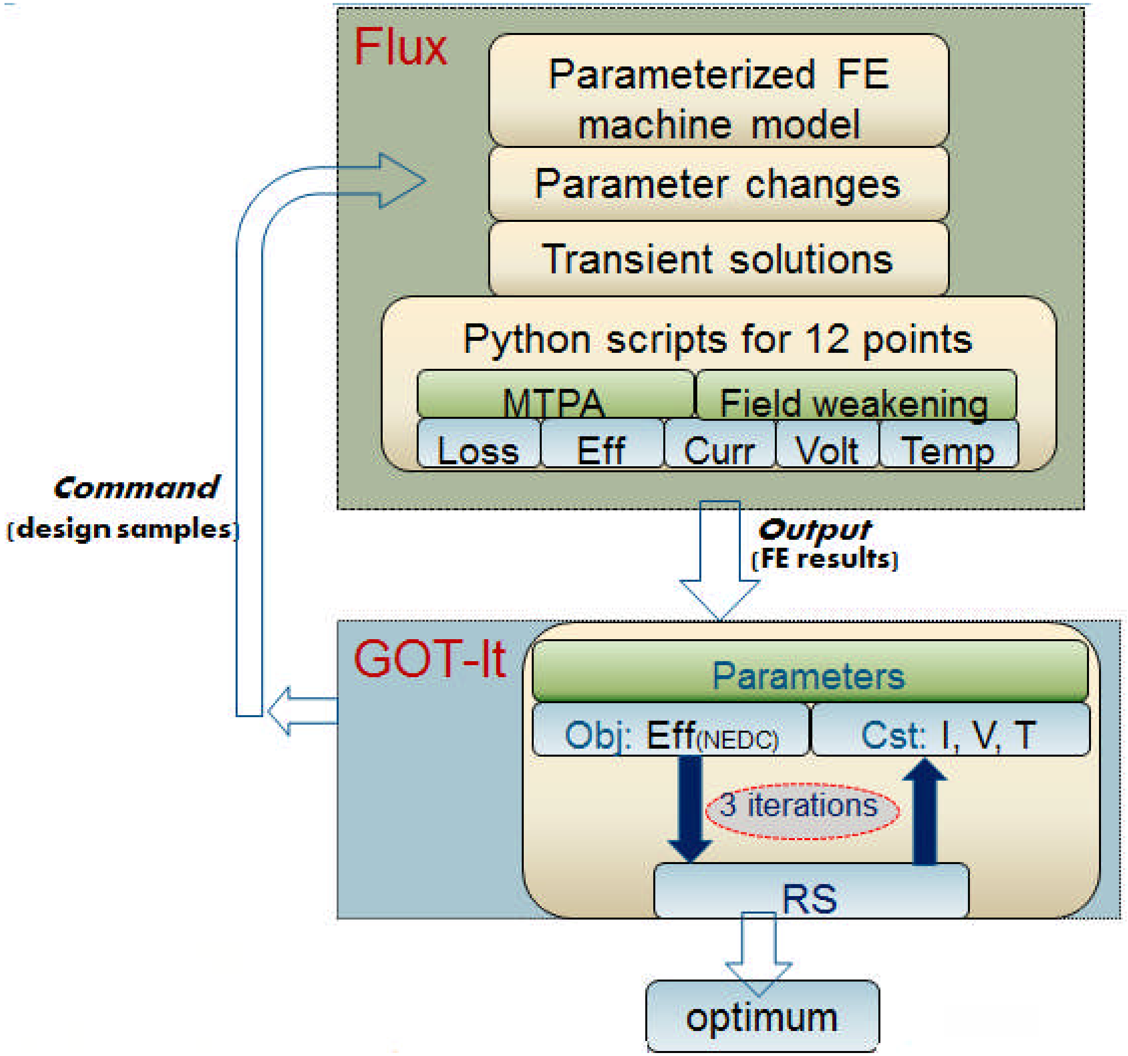
Optimisation design constraints and objective

- **Static thermal model** employed in optimisation process:



- Optimisation objective:
  - **Minimization of energy loss over 12 NEDC points** while satisfying required torque-speed range and other thermal and volumetric constraints.

Optimisation workflow



Flux

Parameterized FE machine model

Parameter changes

Transient solutions

Python scripts for 12 points

MTPA | Field weakening

Loss | Eff | Curr | Volt | Temp

Output (FE results)

GOT-It

Parameters

Obj: Eff(NEDC) | Cst: I, V, T

3 iterations

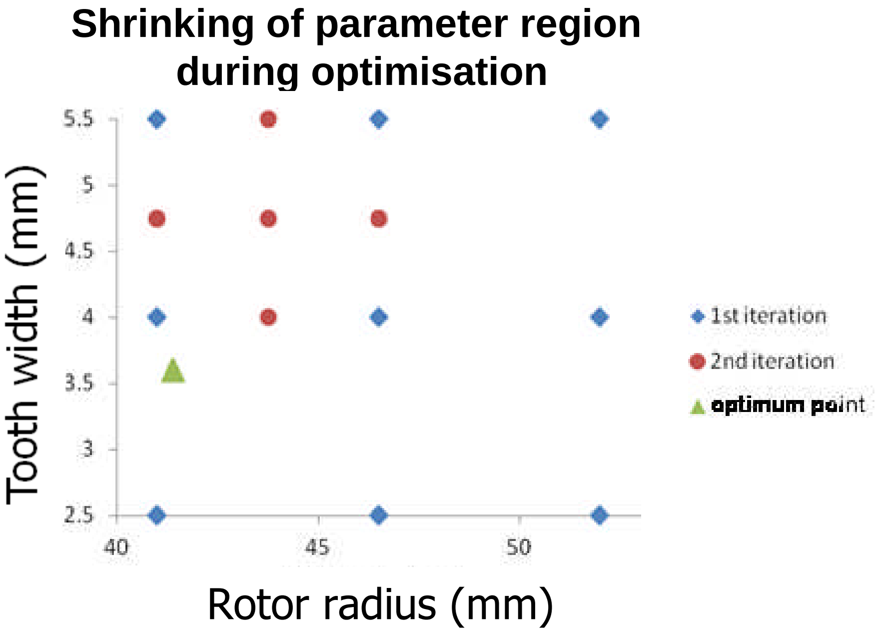
RS

optimum

Command (design samples)

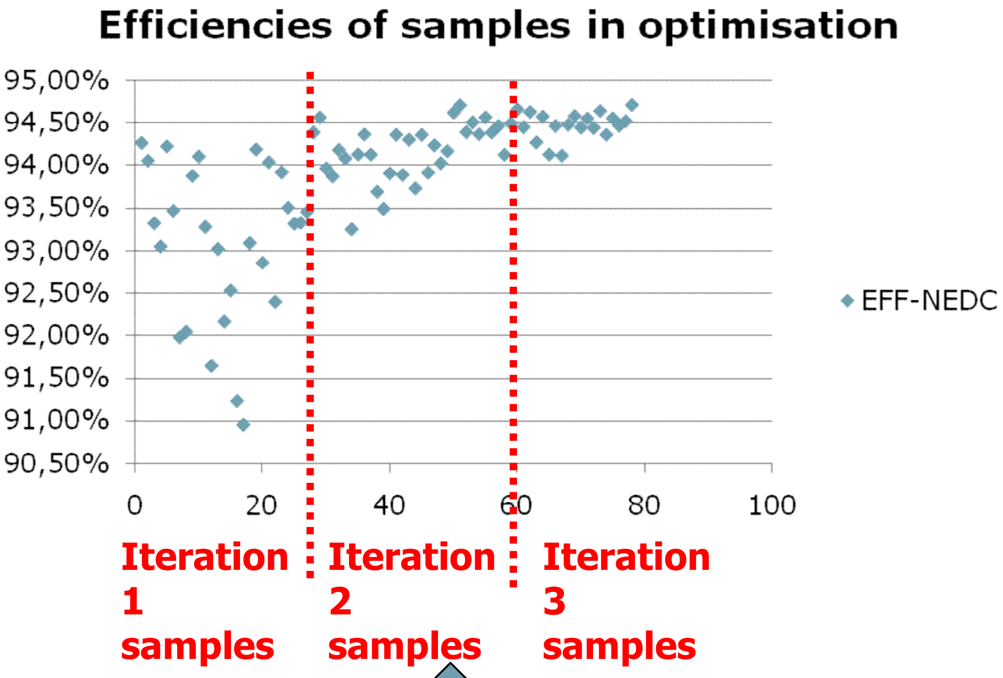
Optimisation evolution

- For the **front** motor:


Shrinking of parameter region during optimisation

- **16 samples**, **8 hours** for the **2**-parameter optimisation

- For the **rear** motor:

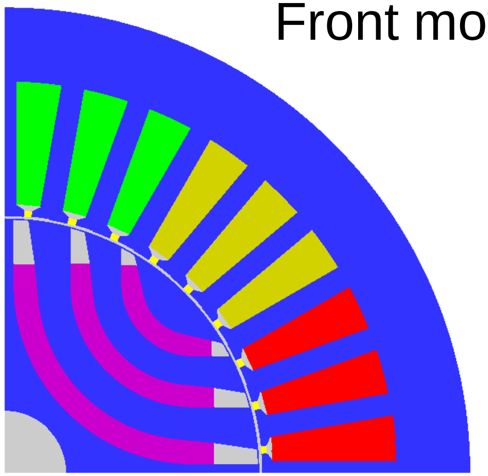

Efficiencies of samples in optimisation

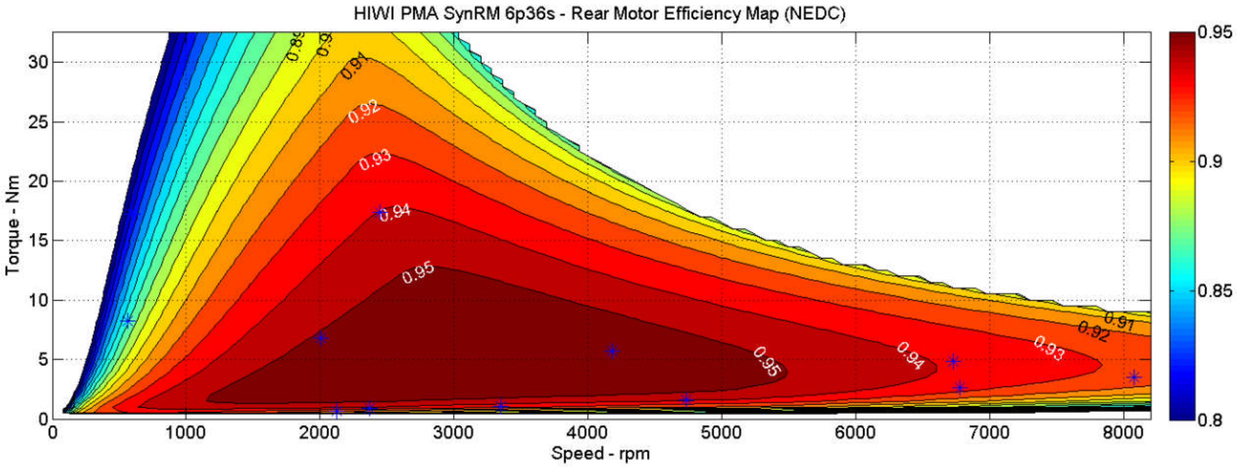
- **78 samples**, **36 hours** for the **5**-parameter optimisation

Optimised design case studies

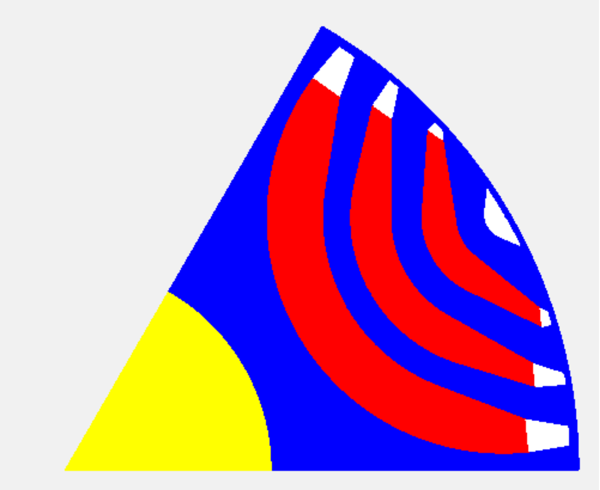
12 NEDC points			
		Front	**Rear**
W_{cu}	kJ	56.97kJ	37.13 kJ
W_{fe}	kJ	15.0 kJ	19.45 kJ
$W_{fe} : W_{cu}$		3.79	1.91
Efficiency	%	**93.67%**	**94.56%**

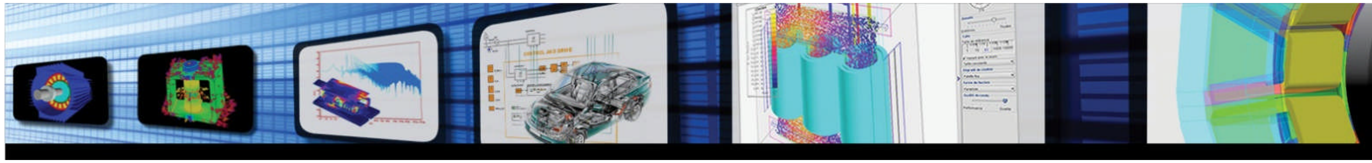
Front motor





Rear motor

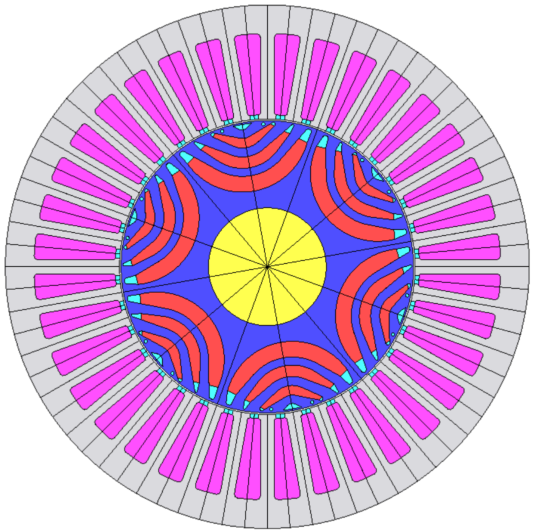


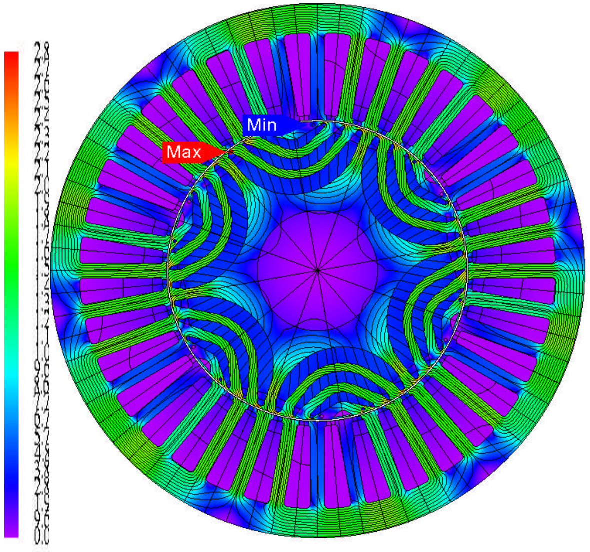


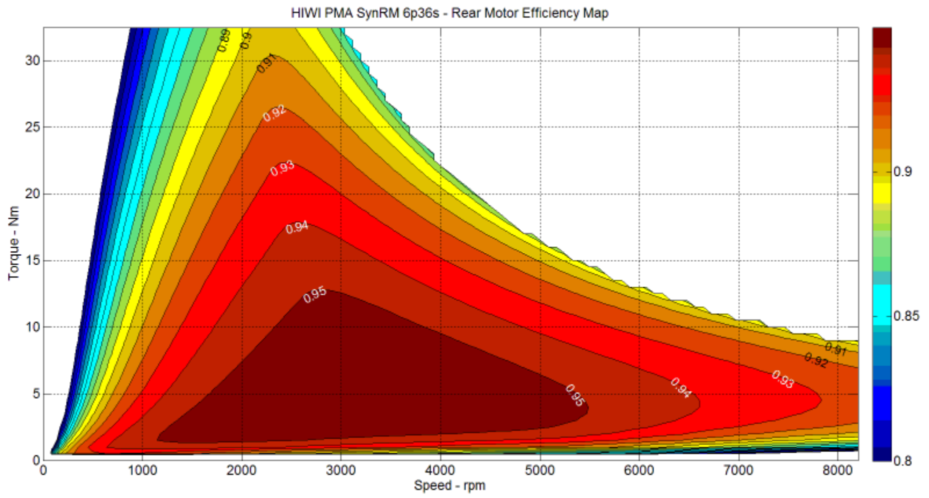
Conclusions

- Energy distribution of NEDC can be represented by 12 points.
- FE based optimization for EV traction machines can be made against 12 representative points, leading to large reduction of computation time.
- Optimum designs with multiple parameters can be efficiently obtained using GOT-It & Flux.
- For PMa-SynRM copper loss is the dominant loss component over NEDC. Optimisation against rated point may also lead to good efficiency over NEDC.

Optimised design case studies – Rear Motor

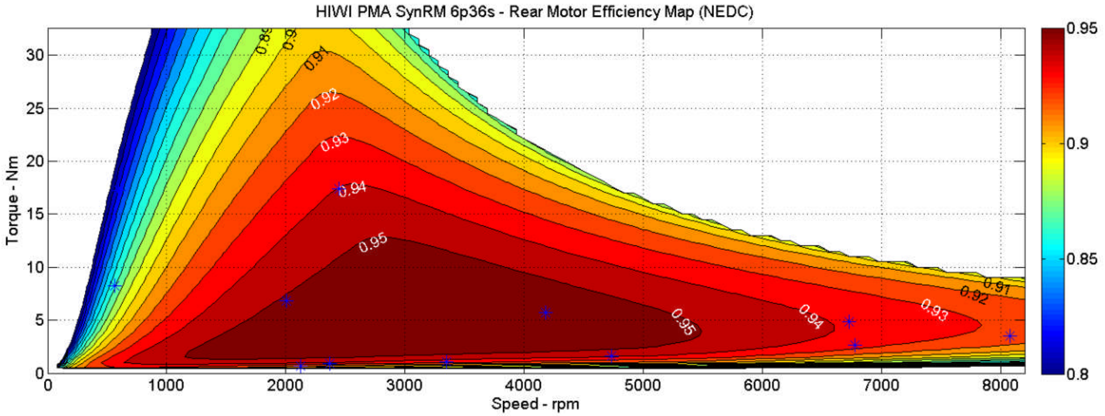






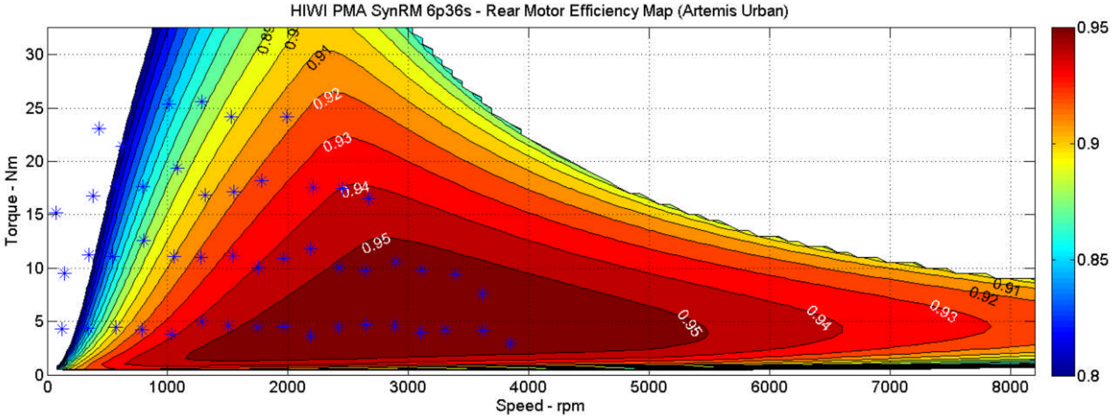
Base Speed	rpm	2100
Peak Torque	N-m	30
Torque density (peak)	kN-m/m^3	26.6
Armature current	A (peak)	80.5
Cu Loss	W	681.1
Iron Loss	W	40.5
Total Loss	W	721.6
Mechanical power	W	6600
Efficiency	%	90.16%
Rated Torque	N-m	17
Torque density (continuous)	kN-m/m^3	15.08
Armature current	A (peak)	47.5
Cu Loss	W	235.9
Iron Loss	W	33.4
Total Loss	W	269.3
Mechanical power	W	3750
Efficiency	%	93.29%
Maximum Speed	rpm	8200
Peak Torque	N-m	7.5
Armature current	A (peak)	69.0
Cu Loss	W	498.0
Iron Loss	W	136.7
Efficiency	%	91.00%
Continuous Torque	N-m	4.4
Armature current	A (peak)	41.0
Cu Loss	W	184.5
Iron Loss	W	79.2
Efficiency	%	93.31%

Optimised design case studies – Rear Motor



NEDC

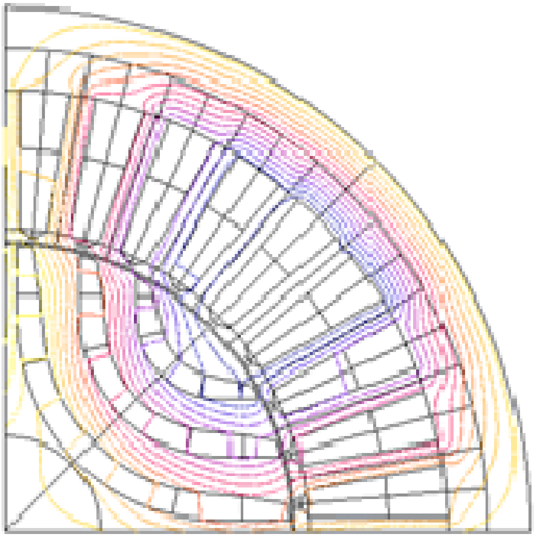
Cycle Wcu	J	3.64E+04
Cycle Wfe	J	2.17E+04
Wcu:Wfe		1.67
Cycle loss	J	5.81E+04
Cycle Wout	J	9.52E+05
NEDC Energy Efficiency	%	94.30%

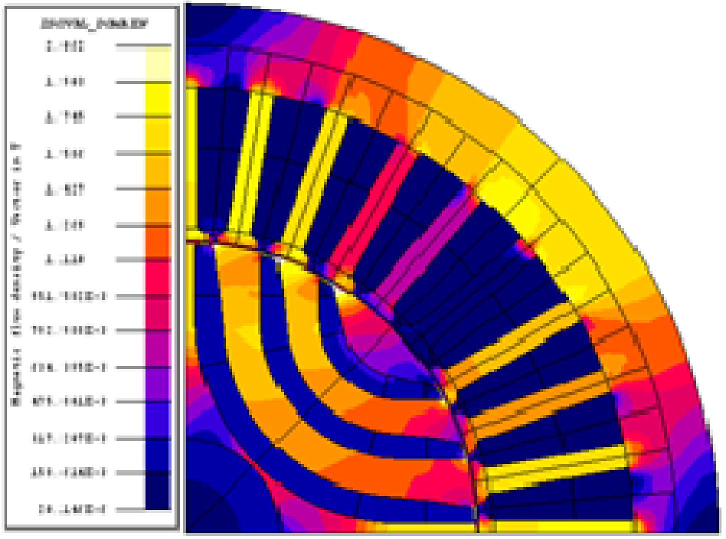


ARTEMIS

Cycle Wcu	J	4.74E+04
Cycle Wfe	J	1.13E+04
Wcu:Wfe		4.19
Cycle loss	J	5.85E+04
Cycle Wout	J	7.59E+05
NEDC Energy Efficiency	%	92.83%

Optimised design case studies – Front Motor





Items	Final optimal design
Peak torque density	35.4 kNm/m^3
Peak current	153 A
Peak current density (rms)	16.38 A/mm^2
Voltage at peak torque/base speed	102 V
Copper Loss at peak torque/base speed	2517 W
Iron Loss at peak torque/ base speed	36.20 W
Efficiency at peak torque/base speed	79.47%
Peak torque/max speed	15 Nm/4500 rpm
Current at peak torque/max speed	68.77 A
Voltage at peak torque/max speed	120 V
Copper Loss at peak torque/max speed	508.33 W
Iron Loss at peak torque/ max speed	165.75 W
Efficiency at peak torque/max speed	91.19%
Copper loss over NEDC	56.97kJ
Iron loss over NEDC	15.0 kJ
Wfe : Wcu	**2.8**
Driving cycle efficiency (NEDC)	**93.67%**