IDAJ
integrated digital advanced solution

IDAJ公司

GT-SUITE拟三维电机热管理分析

IDAJ中国

GT小组

目录

电机开发遇到的问题

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- 不断压缩的前舱空间
  - 发动机、电机
- 电机热管理难度增加
  - 散热量
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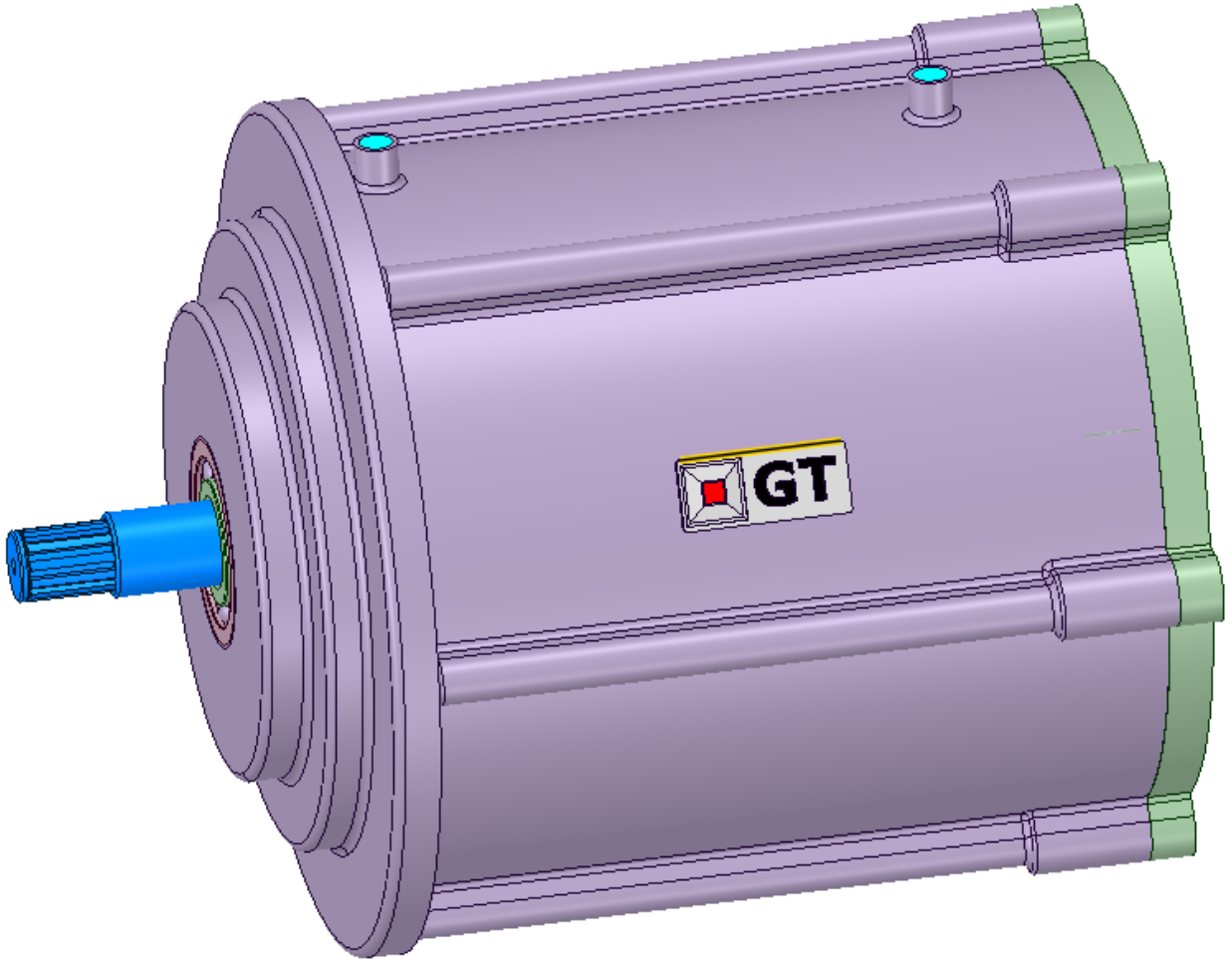
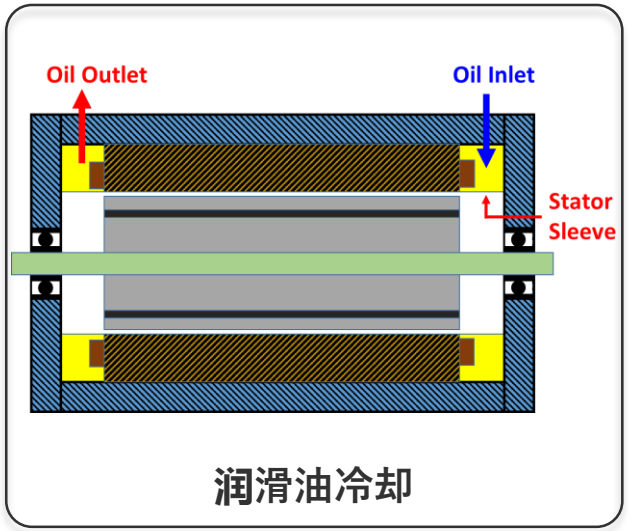
- 不断压缩的产品设计周期
  - 长周期试验、CFD
- 电机热管理如何设计
  - 规格：水泵、换热器、风扇
  - 控制：水泵、阀、风扇

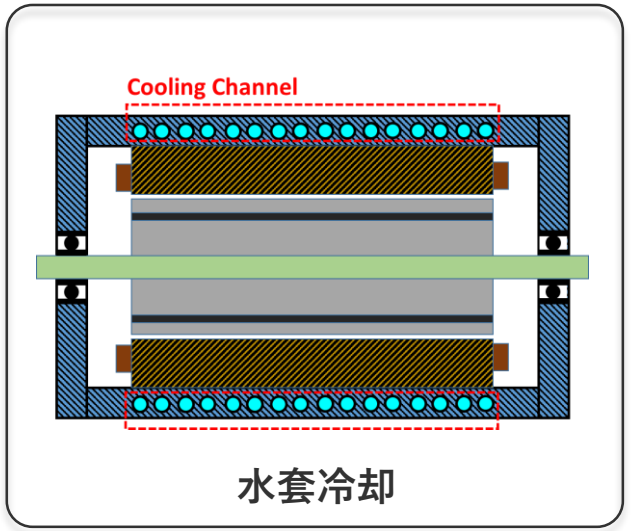


电机热管理类型

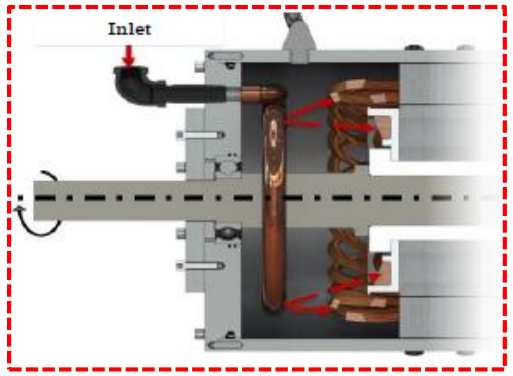
- 电机发热原因
  - 铜损：线圈内阻产生的损耗
  - 铁损：磁滞损耗、涡流损耗
  - 摩擦损失：轴承
- 电机温度过高的危害
  - 磁钢退磁
  - 线圈发热导致铜损增加
- 电机冷却类型
  - 风冷
  - 水冷
  - 油冷



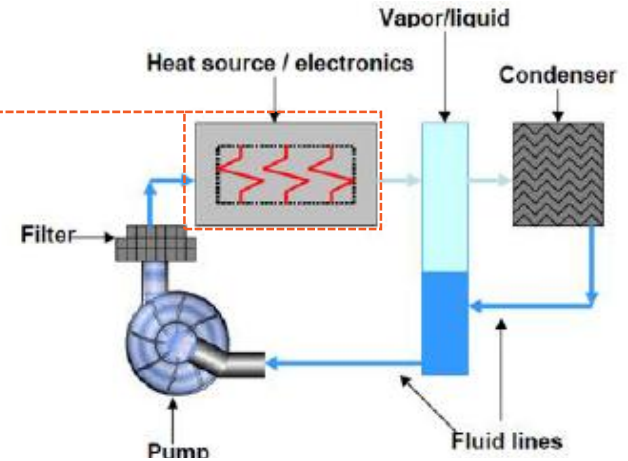
润滑油冷却



水套冷却



喷油冷却

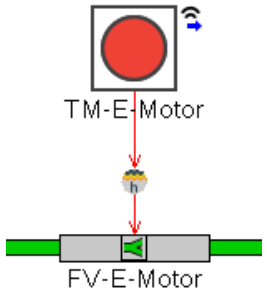


Source: DOI 10.1109/TIE.2018.2835397, IEEE

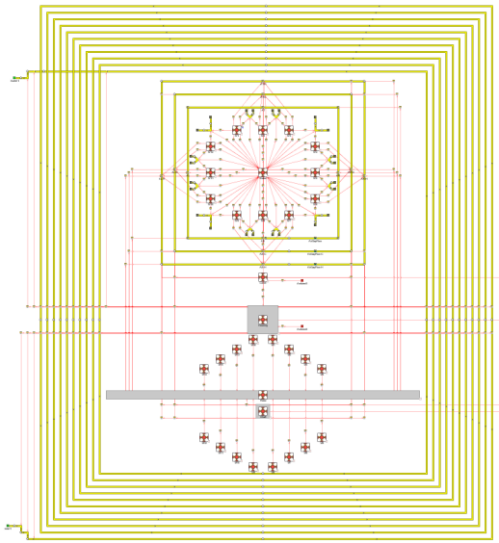
电机热管理仿真的主要方法

预测性

集总参数模型



拟3D模型



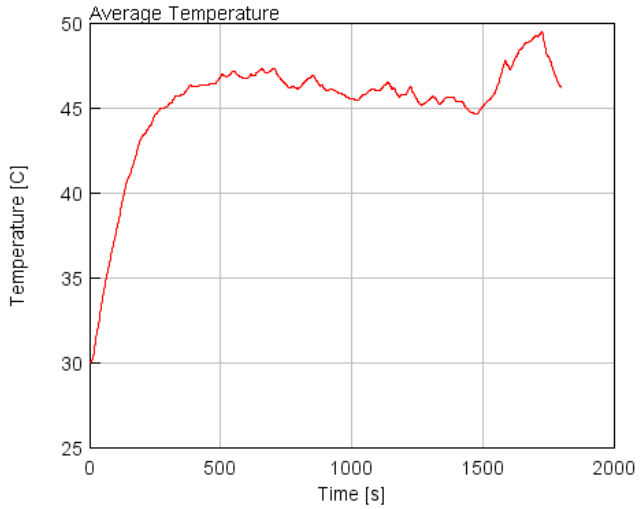
3D有限元模型

计算时间

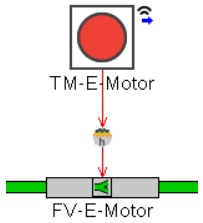
电机热管理仿真的主要方法

预测性

电机平均温度



集总参数模型



技术方案	将电机视为一个整体，不考虑具体结构及参数，通过2~3个简单系数标定电机与冷却系统及环境的换热系数
输入数据	电机发热量、水套流阻、水套换热系数、电机导热系数
温度场预测能力	无，主要输出电机出口水温、电机本体只能输出“平均温度”
水套流阻预测能力	无，需要输入
外部环境影响	只能粗略考虑
网格数量	<5
计算速度	非常快
适用场景	概念设计阶段、系统回路仿真、整车能量管理系统集成

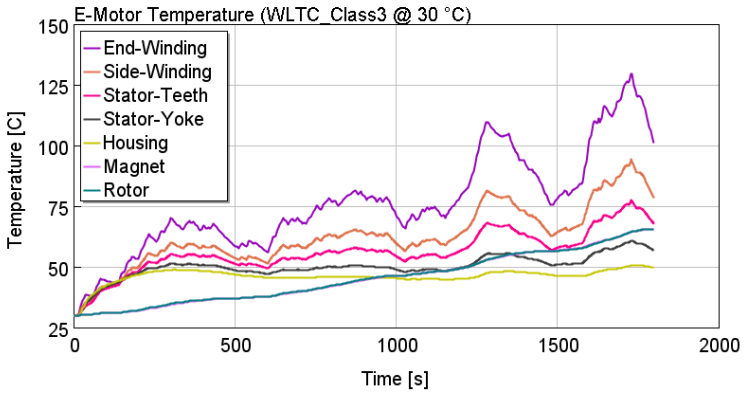
计算时间

电机热管理仿真的主要方法

预测性

技术方案	基于详细几何数模划分网格、输入全部物性参数计算电机温度场
输入数据	电机发热量、几何数模、全部零件材料属性
温度场预测能力	强
水套流阻预测能力	强
外部环境影响	可考虑
网格数量	10^5~10^6
计算速度	慢，需要并行计算
适用场景	详细设计阶段、单一工况模拟，设计方案确认

3D有限元模型

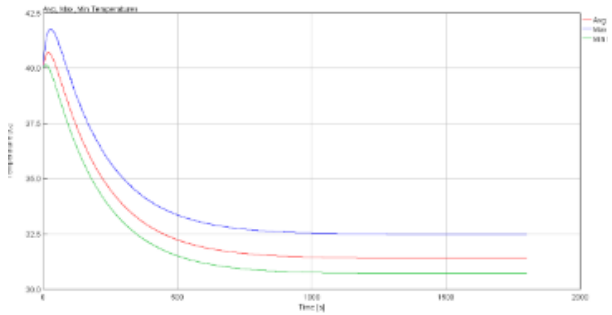


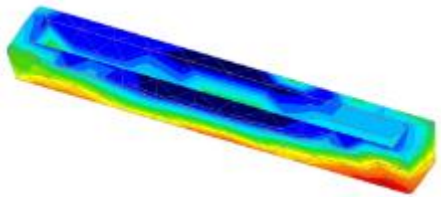
计算时间

电机热管理仿真的主要方法

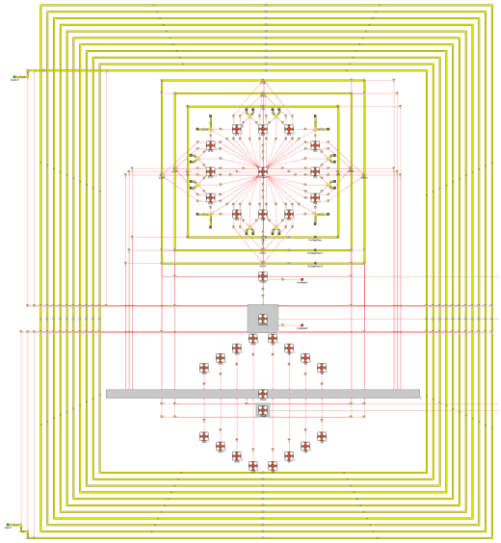
预测性

温度分布及变化

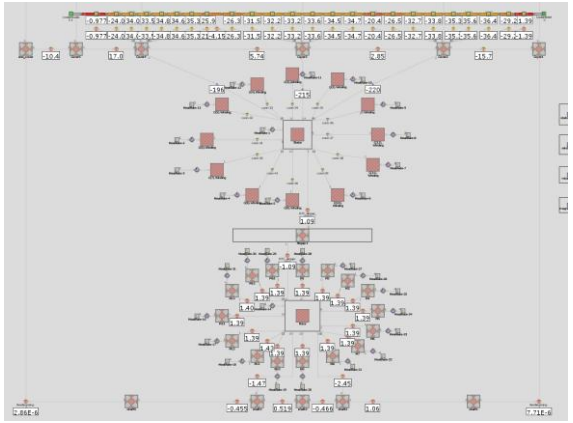




拟3D模型



换热量分布



技术方案	根据几何数模将电机结构离散为1D传热计算单元，结合材料属性计算传热计算单元温度分布
输入数据	发热量、几何数模、全部零件材料属性
温度场预测能力	有，可预测局部温度
水套流阻预测能力	有
外部环境影响	可考虑
网格数量	10^1~10^2
计算速度	快，满足实时仿真需求
适用场景	电机冷却布置方案优化、系统方案验证、控制系统开发、长周期瞬态模拟

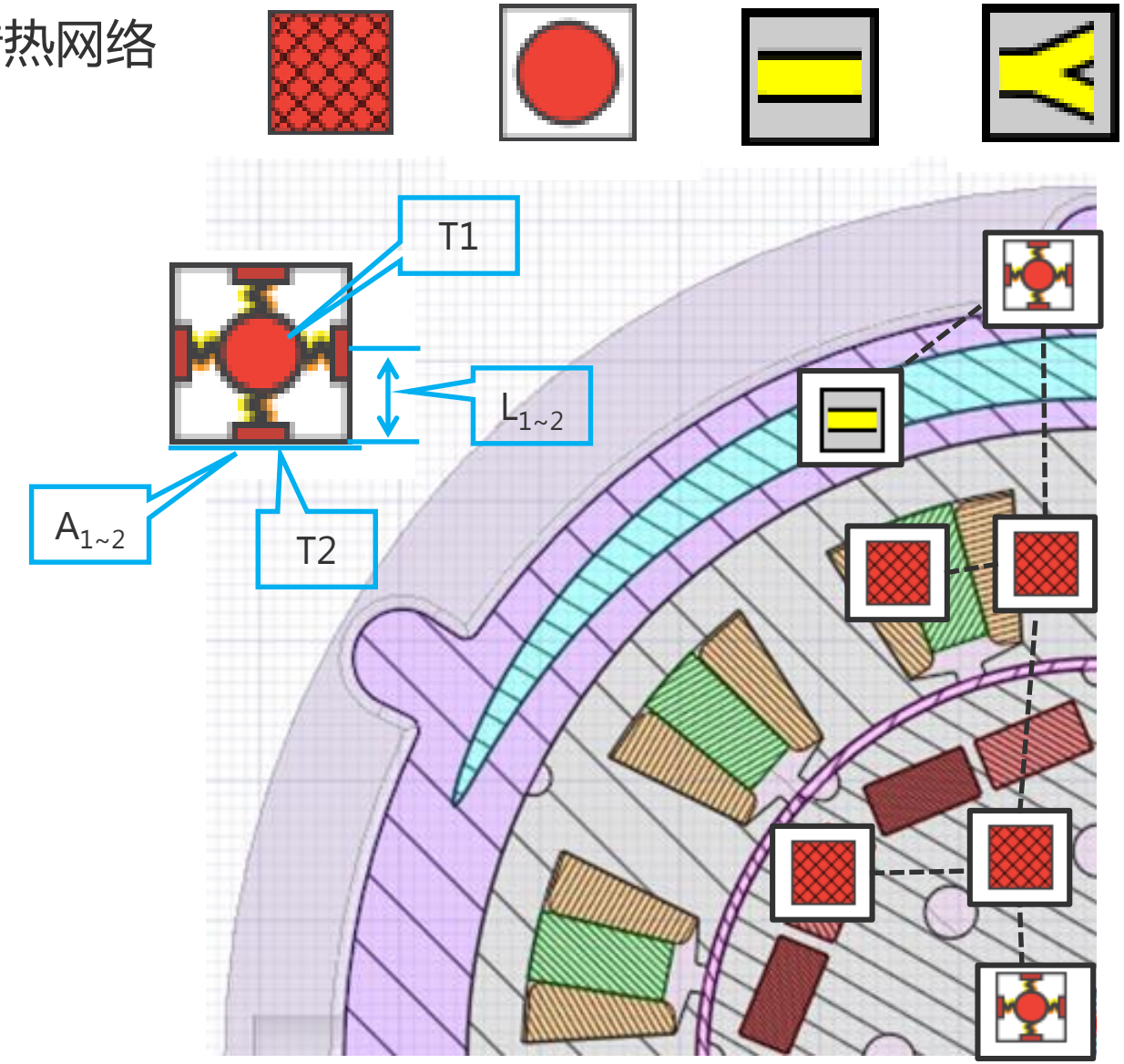
计算时间

拟3D电机仿真方法的基本理论

- 使用基本传热单元和流动单元来描述电机传热网络
  - 基本传热单元：
    - 外壳、定子、线圈、转子、磁钢
    - Thermal mass、ThermalFiniteElement、ThermalNode
  - 流动单元：
    - 管路、腔体
    - Pipe、FlowSplit
  - 电机内传热网络：
    - 冷却液对流换热、固体之间导热、环境辐射
    - CovectionConn、ConductanceConn、RadiationConn 、ResistanceConn

$$Q = \frac{T_1 - T_2}{R}$$

$$R = \frac{L}{kA}$$



拟3D电机仿真解决方案

- 拟3D建模面临的问题
  - 复杂的几何形状如何建模
  - 复杂的传热结构如何体现
  - 复杂的换热边界如何给出

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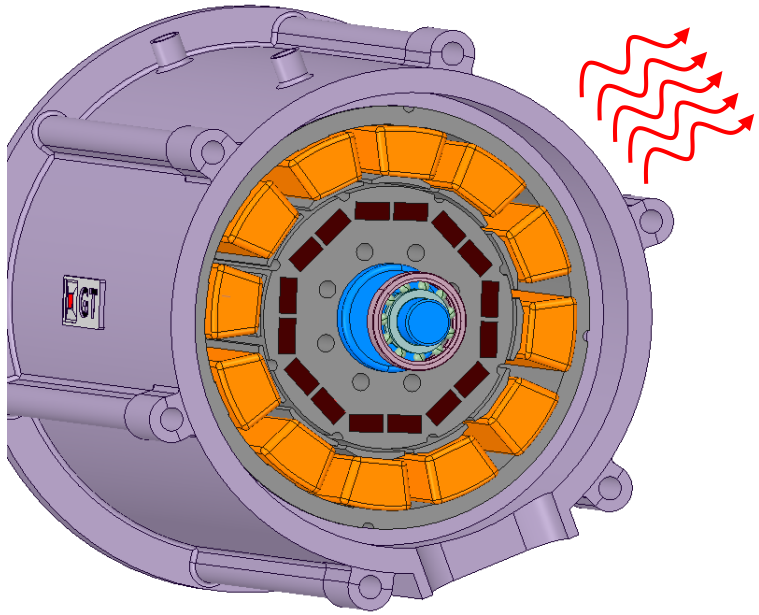

- GT-SUITE解决方案
  - GT-SPACECLAIM数模前处理：数模修整、水套抽取
  - GEM3D数模转换：将复杂几何形状自动转换为1D模型，包括固体、流体、自动识别换热边界、预留换热边界
  - GTISE整机模型：分块建模、通用端口

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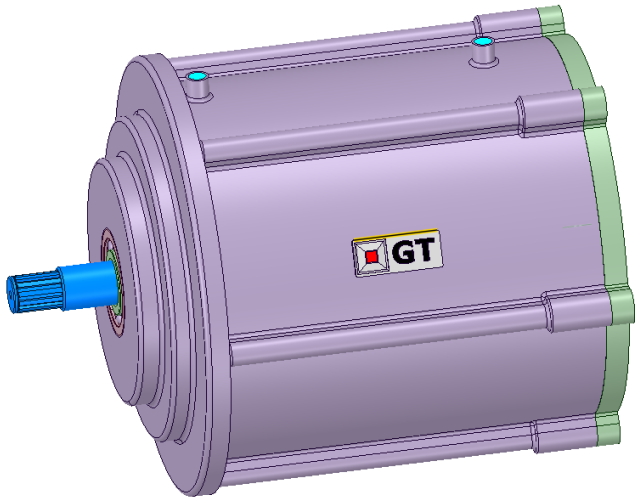
GT-SpaceClaim

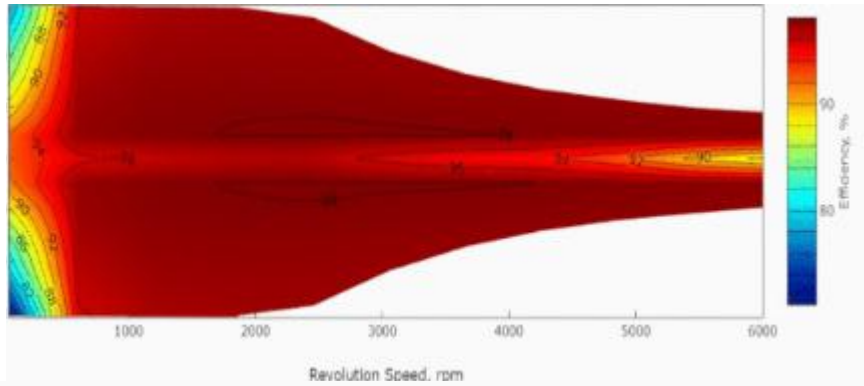
GT-SUITE GEM3D

GT-SUITE GT-ISE

拟3D电机仿真方法

- 数据准备
  - 几何数模
  - 材料属性：密度、比热容、导热系数
    - 定子、转子、线圈、磁钢
  - 热源
    - 发热量
    - 电机效率+工况
    - JMAG Express online+ 工况
- 工作流程
  1. 数模整理：SpaceClaim
  2. 数模转换：GEM3D
  3. 模组模型：GTISE
  4. 整包封装：GTISE





Motor Control:

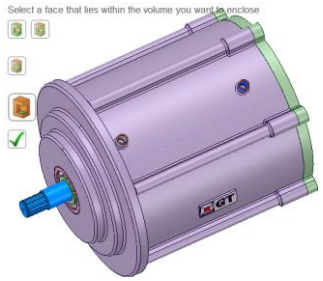
Parameter	Value
Control	Maximum Power
Maximum Voltage, V	360
Maximum Current, A	400
Maximum Speed, rpm	6000

Efficiency and Operation Range:

Efficiency	Operation Range, %
Above 90%	93.7
Above 80%	98.3
Above 70%	100
Above 60%	100

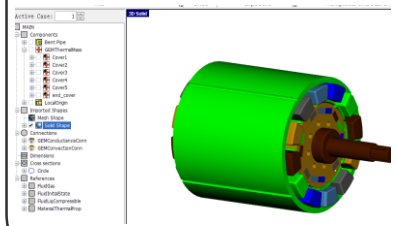
GT SpaceClaim

1、数模整理



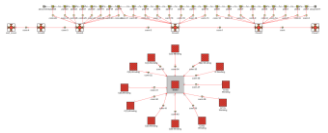
GT-SUITE GEM3D

2、数模转换



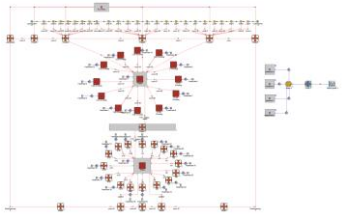
GT-SUITE GT-ISE

3、定子封装
转子封装



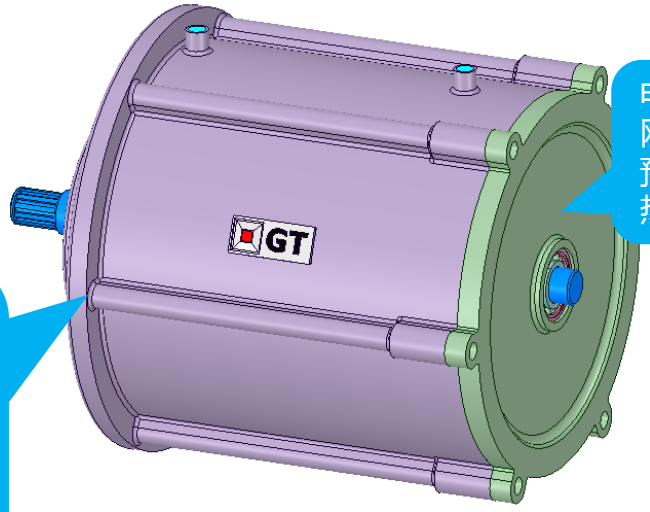
GT-SUITE GT-ISE

4、整机封装



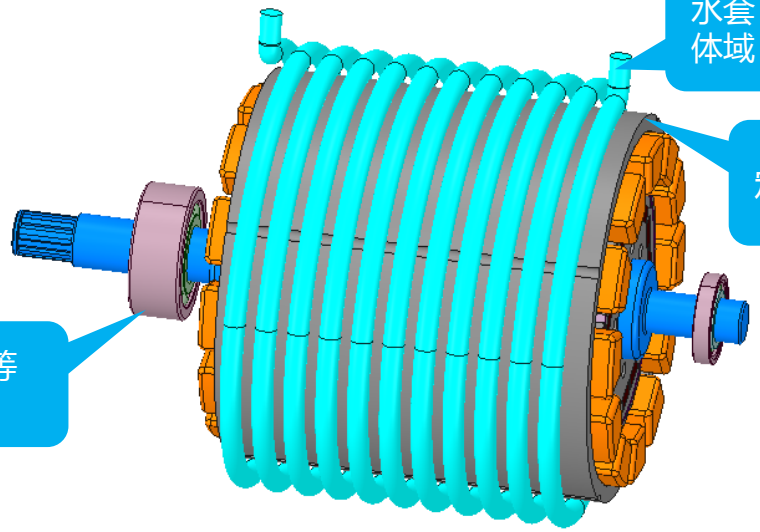
拟3D电机仿真方法

- 电机内主要元件处理方法： 1D +有限元



电机端盖：1个1D网格
预留与环境空气换热边界

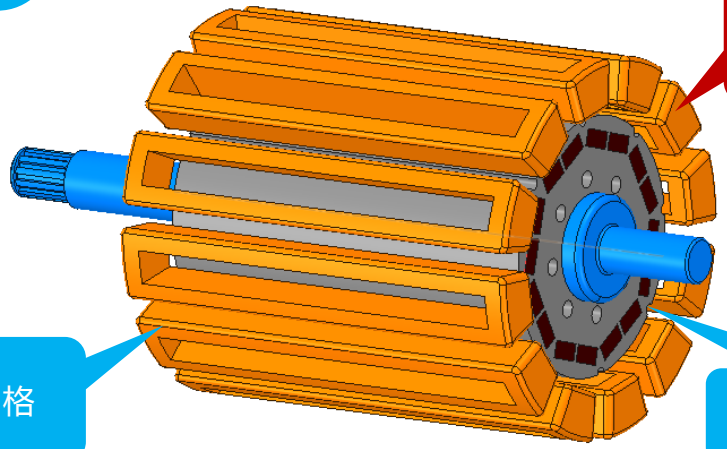
电机外壳：由于冷却液分布会有一定程度的温度梯度，切割成3~5个1D网格
预留与环境空气换热边界



水套：若干个1D流体域

定子：有限元网格

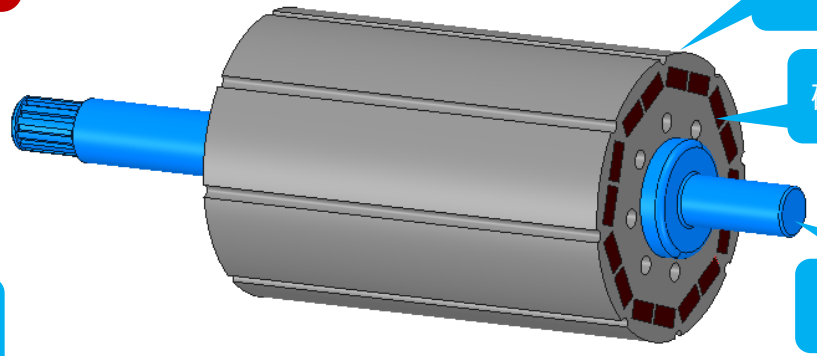
轴承：使用热阻等效或者忽略



各向异性导热

线圈：有限元网格

定子转子气隙：1D流体网格建模

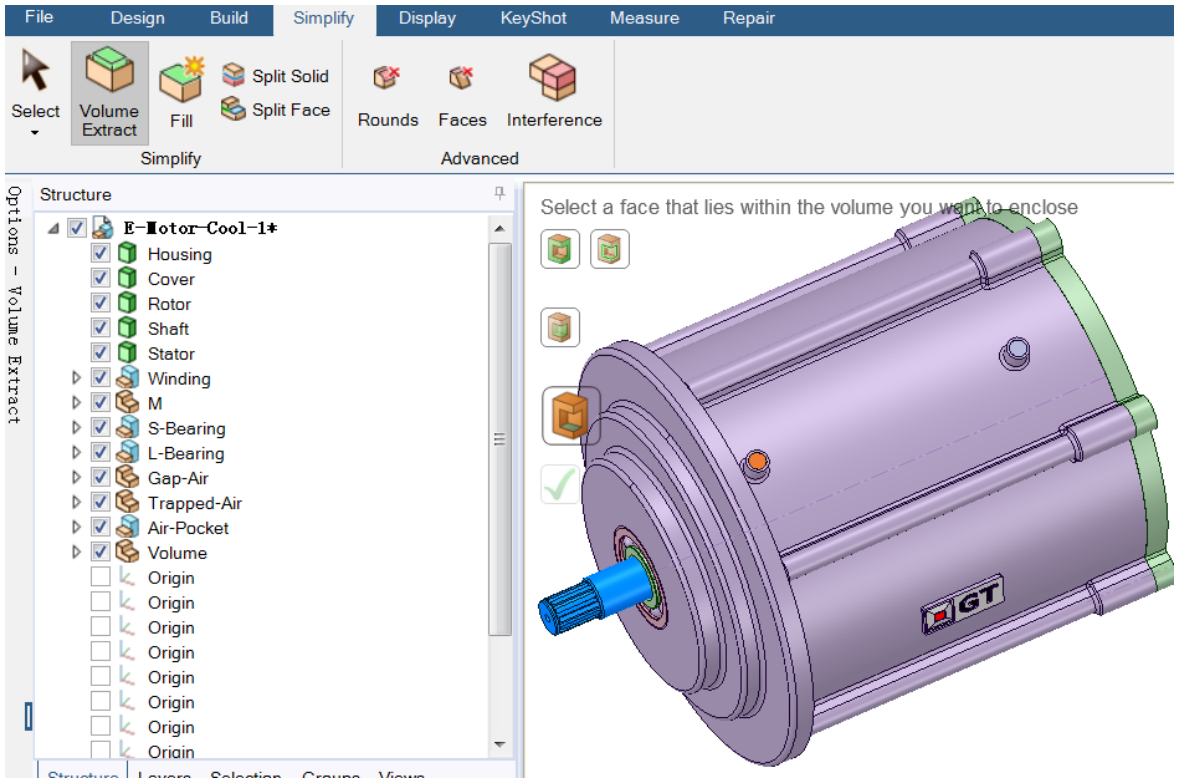


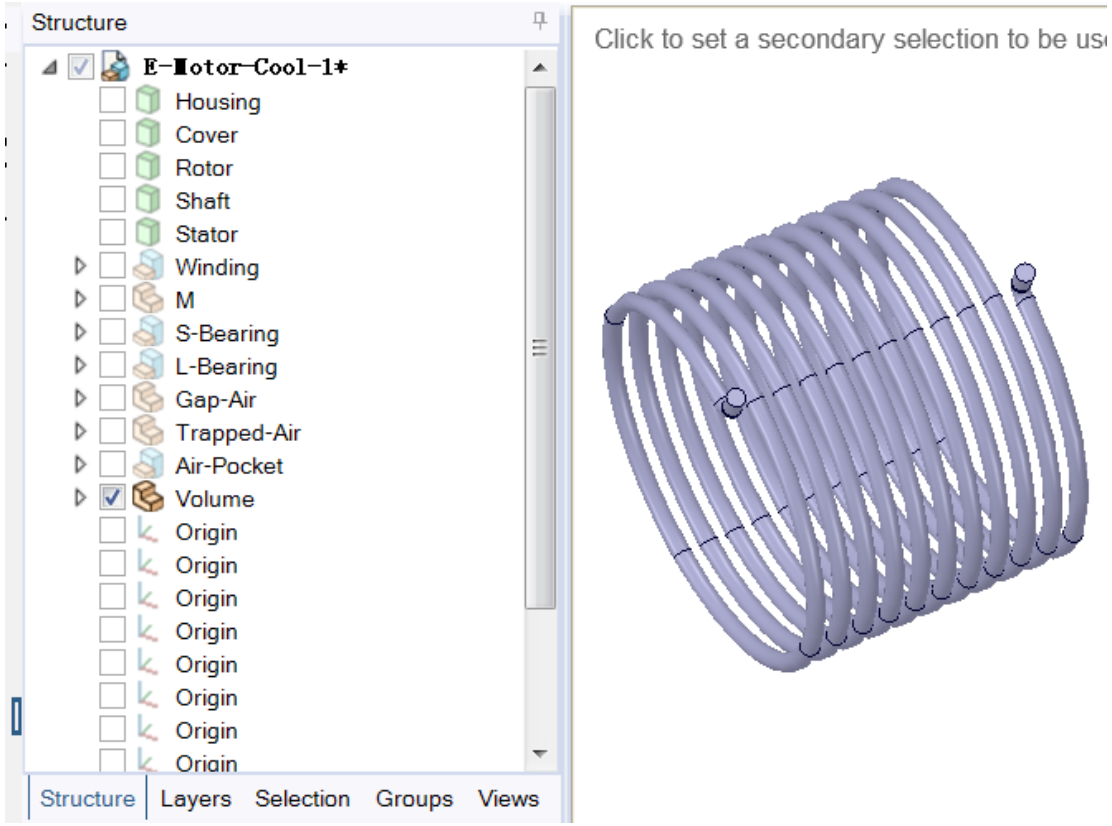
转子：有限元网格

磁钢：有限元网格

轴：3~5个1D网格

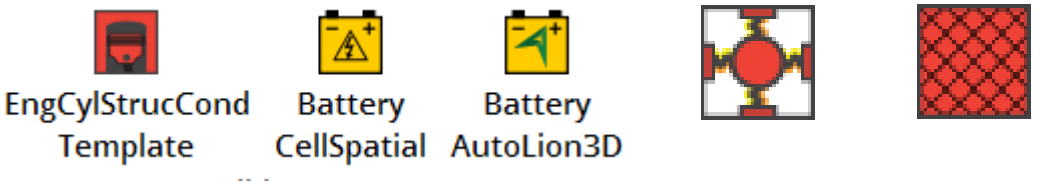
- 目的：水套抽取
  - 支持绝大部分CAD数模格式



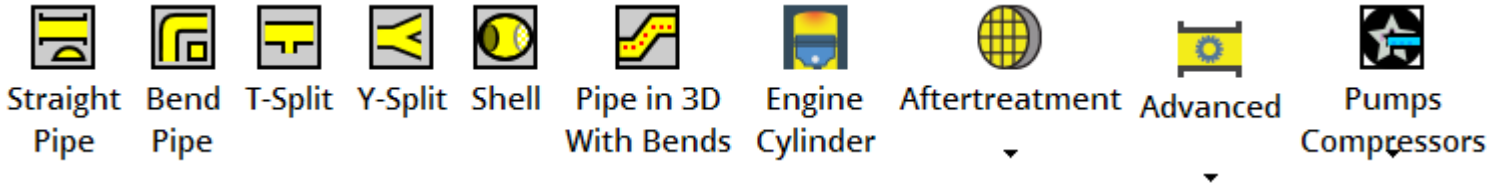


GEM3D功能

- 固体域：

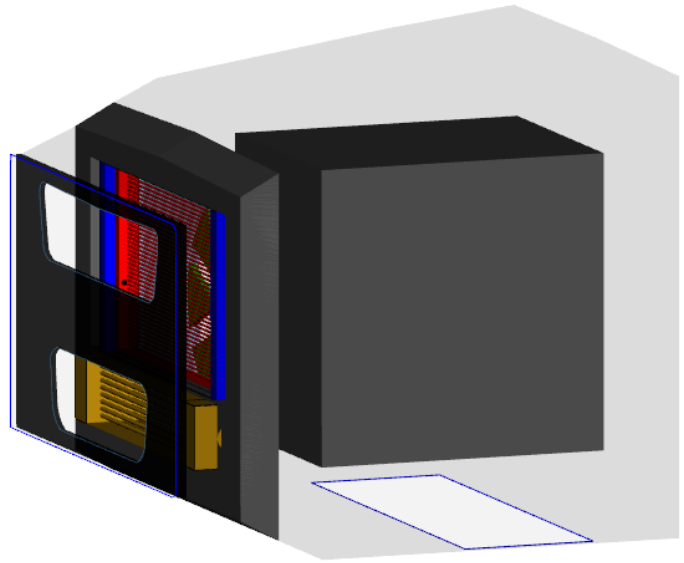


- 流体域：



- 机械域

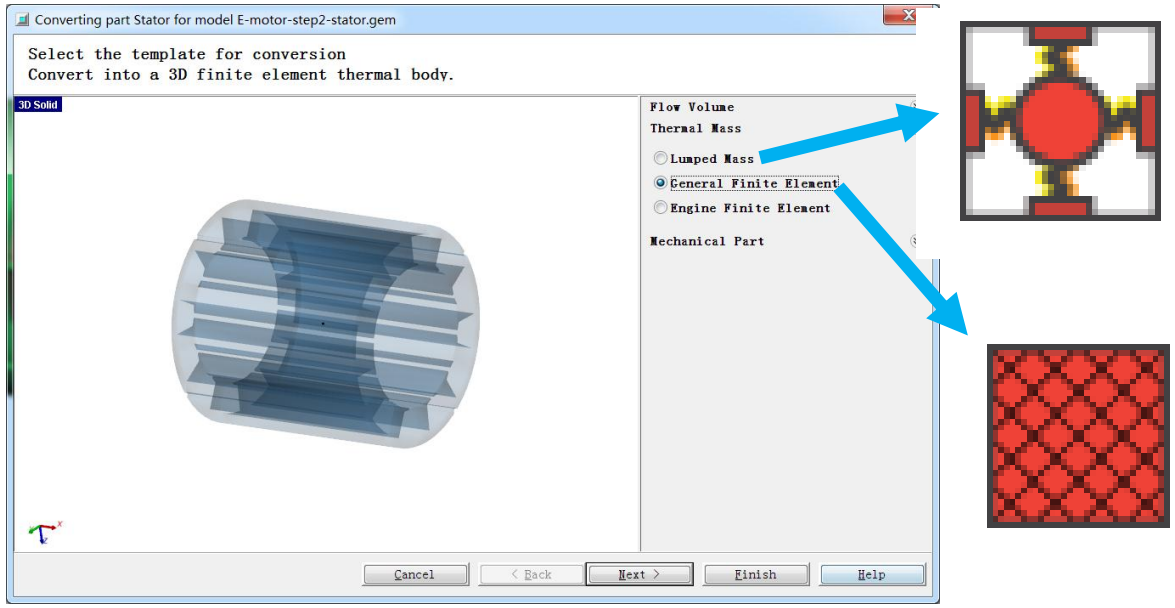
- 乘员舱

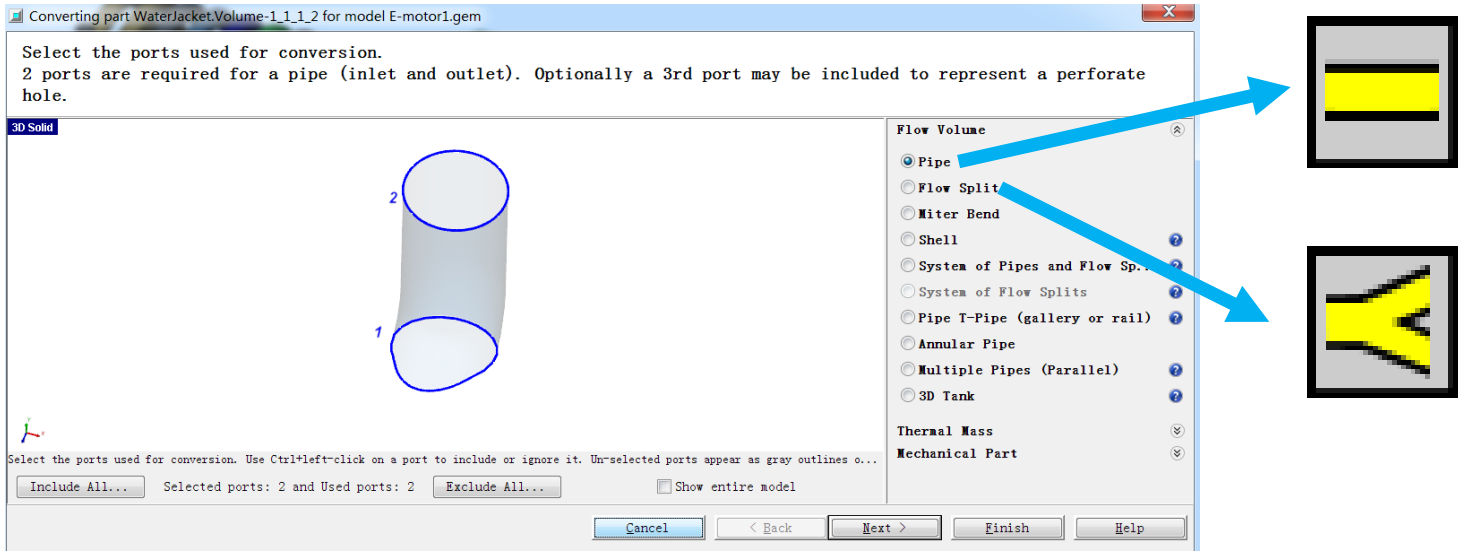


- 动力舱

GEM3D数模转换

- 固体域：
  - Lump Mass：适用于形状规则、不考虑温度分布的零件，如外壳、磁钢、转轴
  - General Finite Element：适用于形状不规则、考虑温度分布、难以手动切割的零件，如定子、转子、线圈
- 流体域：
  - Pipe：管路
  - Flow Split：腔体

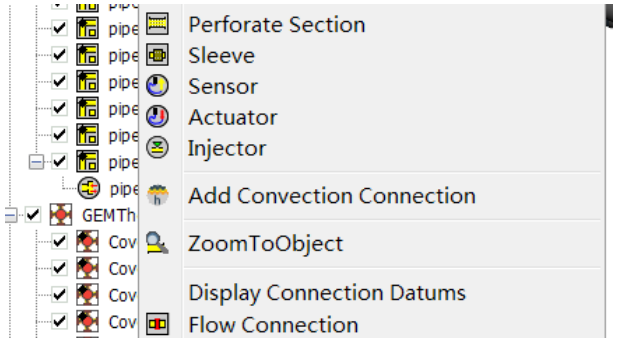




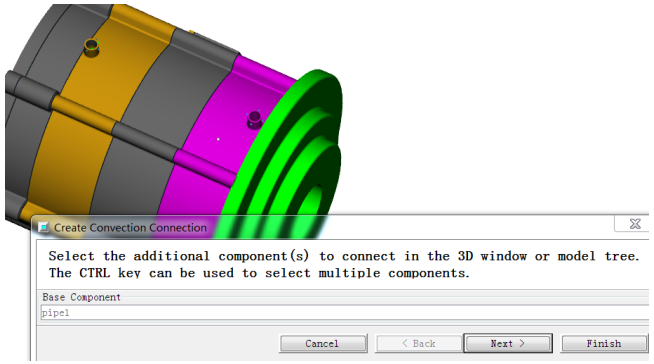
GEM3D数模转换

- 零部件之间换热
  - 自动识别换热面
  - 手动添加换热面
    1. 添加换热端口
    2. 选择换热部件
    3. 确认换热面

1



2



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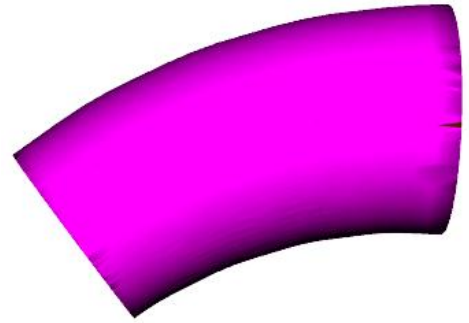
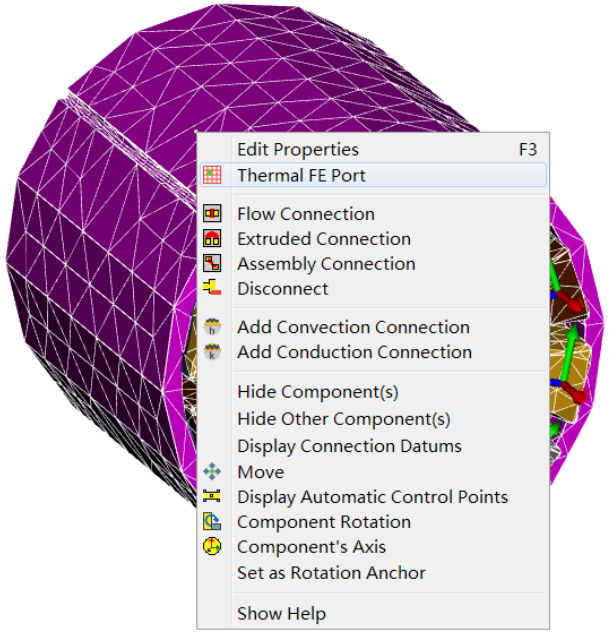


- 预留换热面
  1. 选择零件
  2. 换热面选择

1



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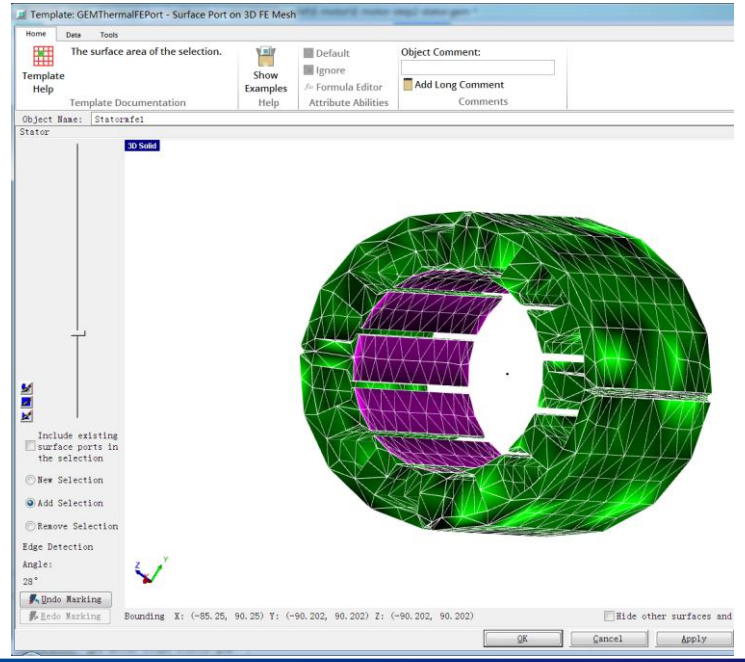
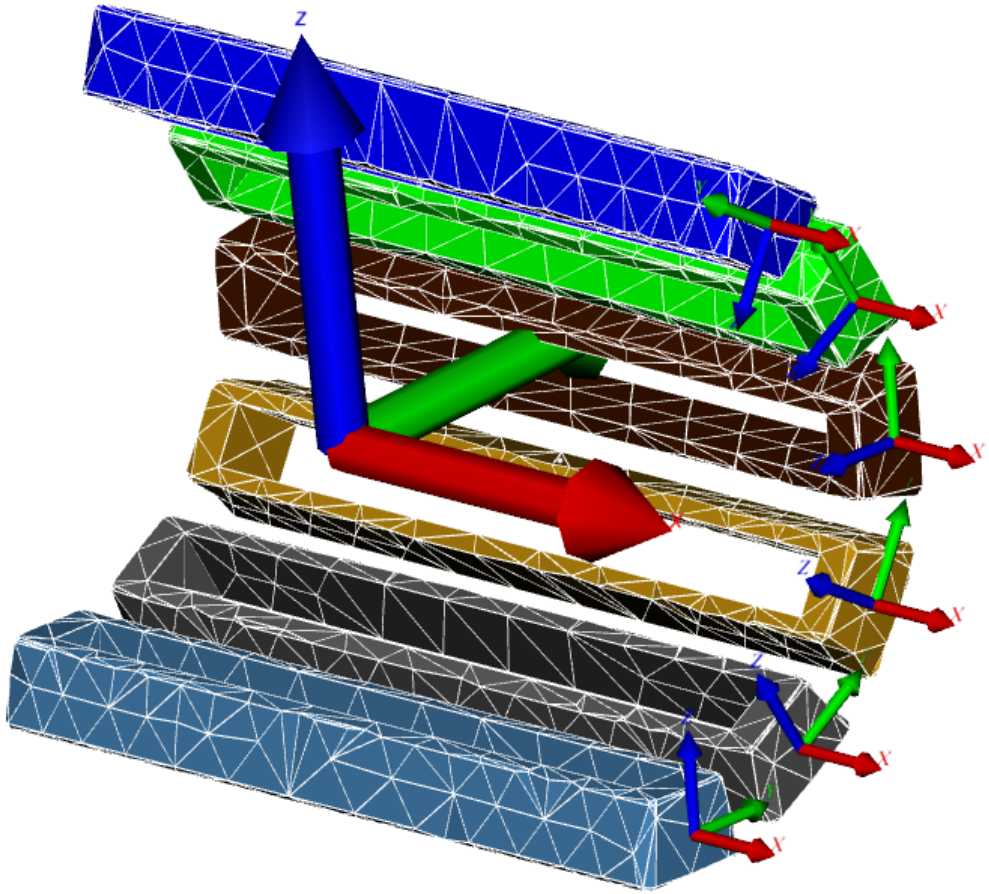
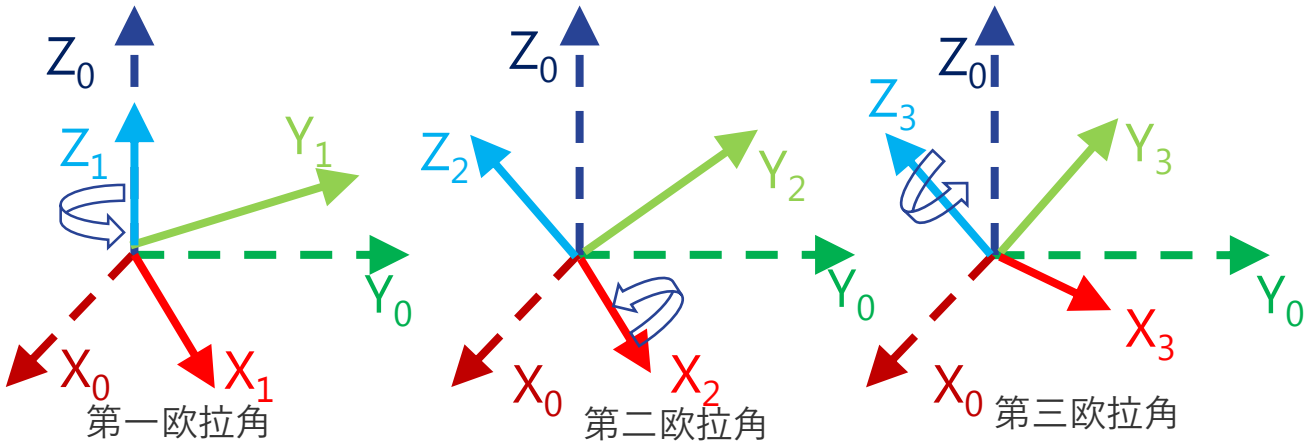
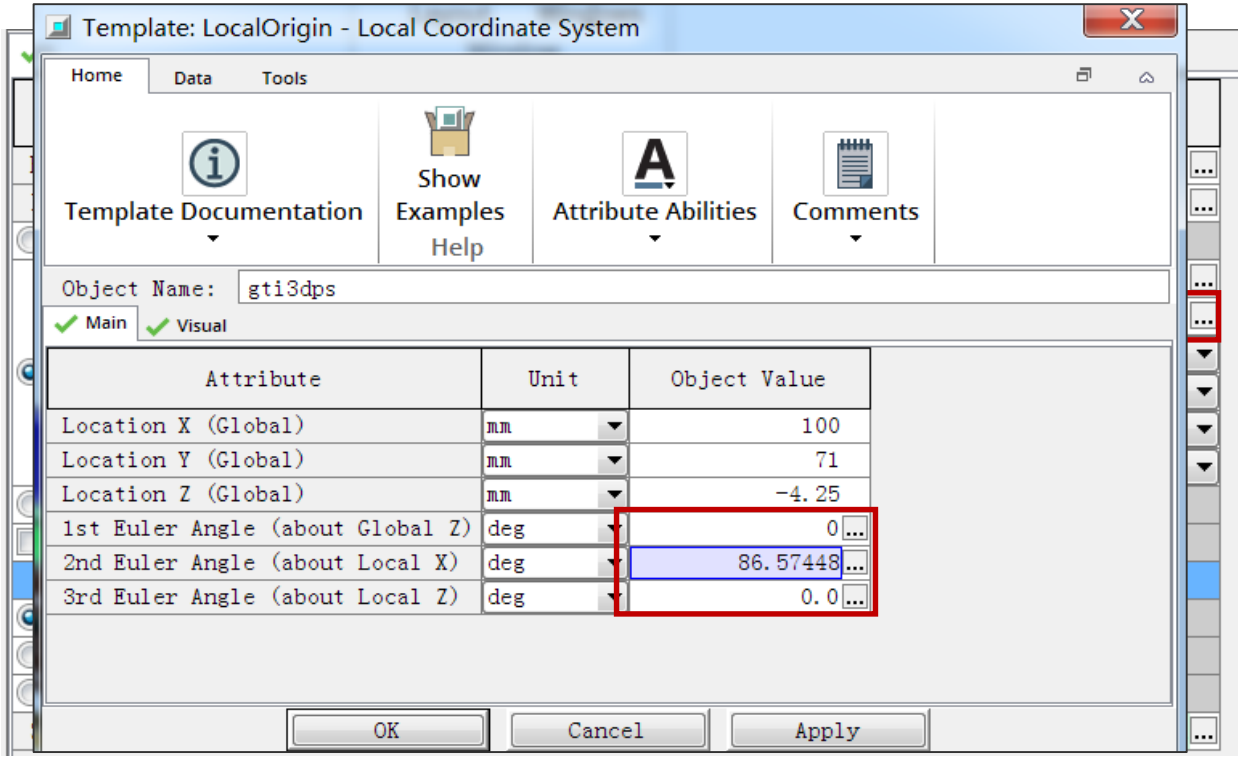


GEM3D数模转换：局部坐标系

- 各向异性导热材料：局部坐标系

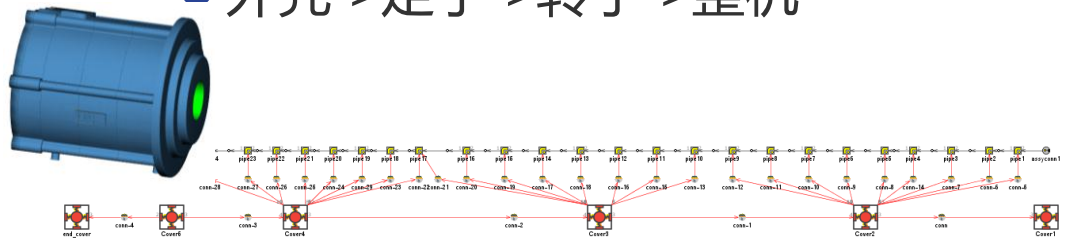


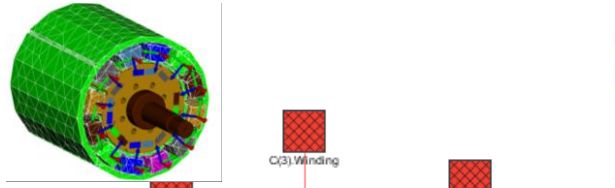


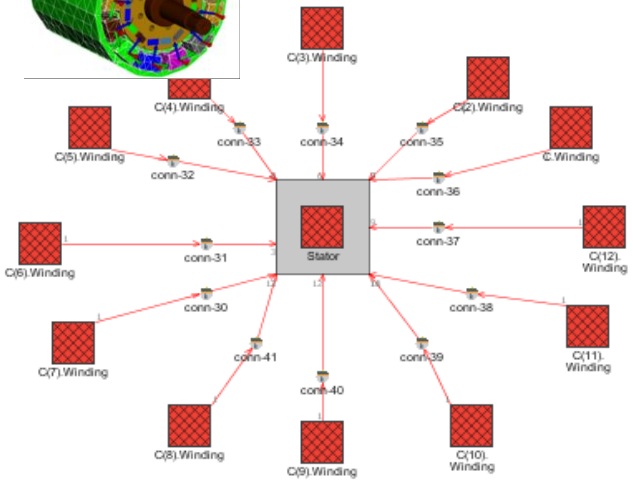


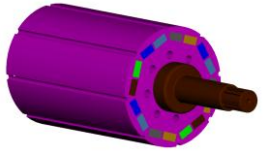
GTISE整机封装

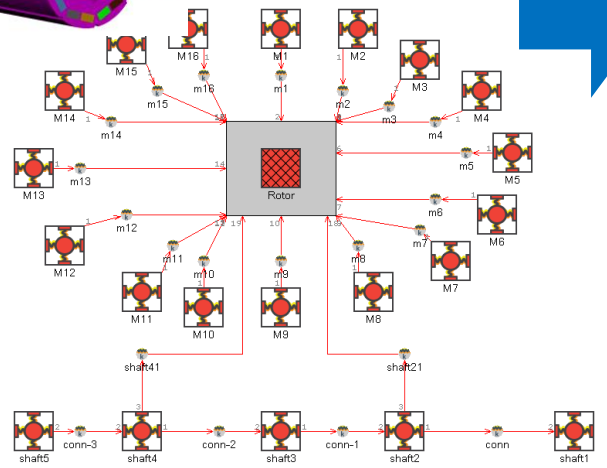
- 问题：由几何数模转换后的计算单元、边界很多，模型面板的整理花费很长世间
- 解决方案：分块建模、预留端口
  - 外壳->定子->转子->整机

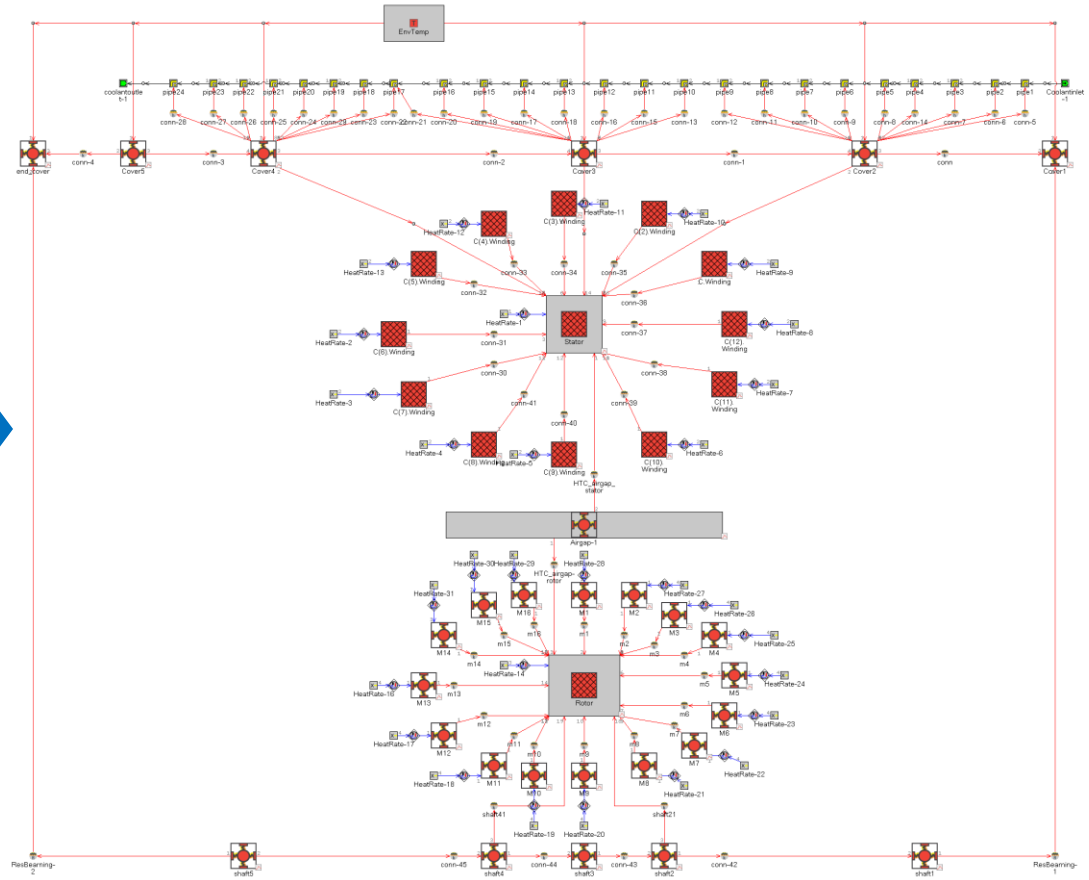










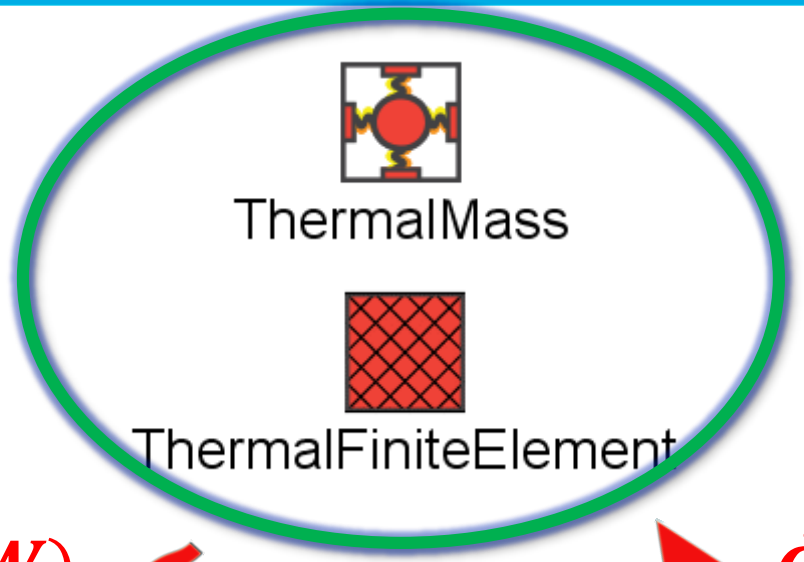


发热源

① 热量

② 电机效率模型

③ JMAG Express Online



$\dot{Q}\ (W)$

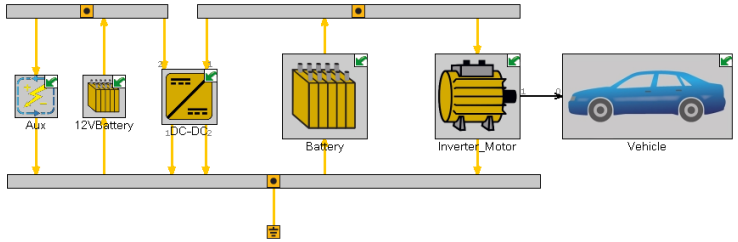
$\dot{Q}\ (W)$

Thermal

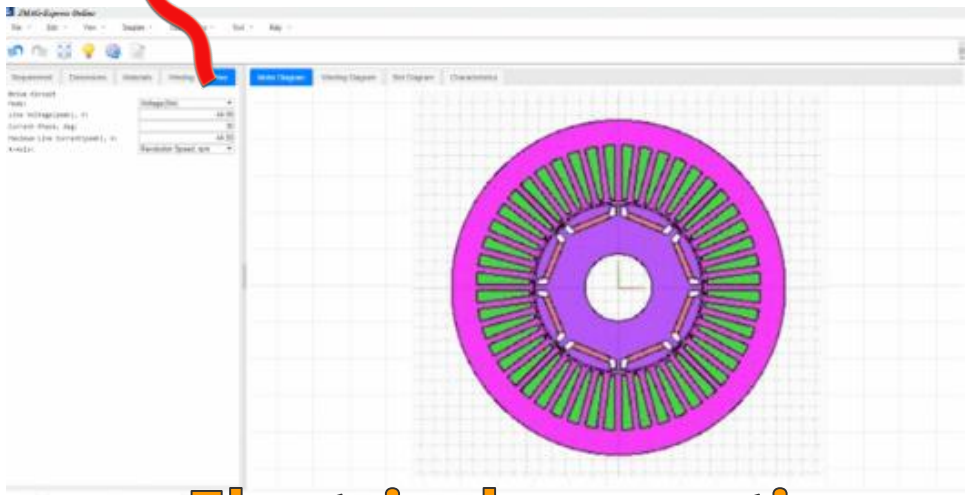
$\dot{Q}\ (W)$

$T\ (°C)$

$eff\ (\%)$



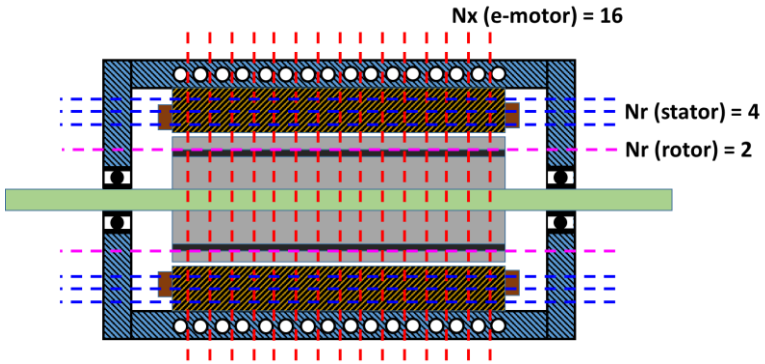
Electrical



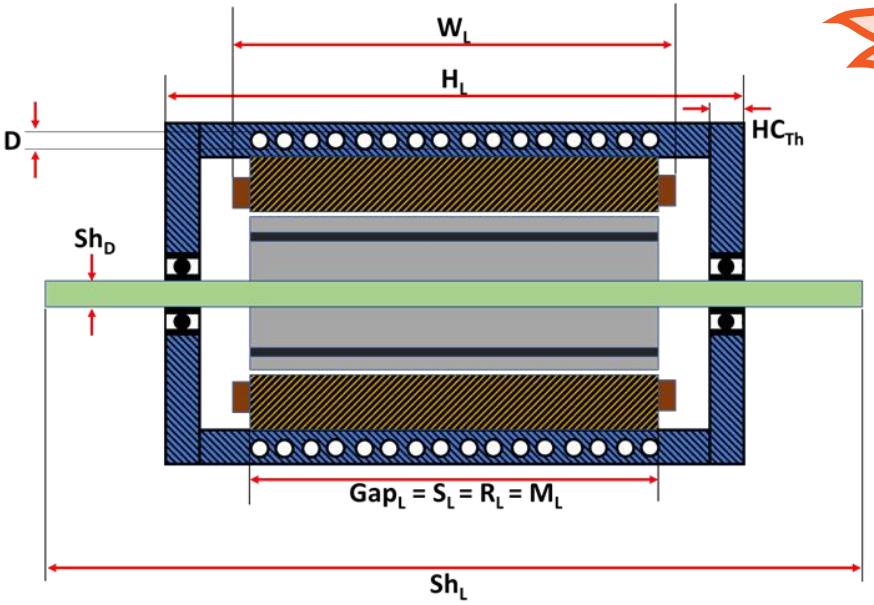
Electricalmagnetic

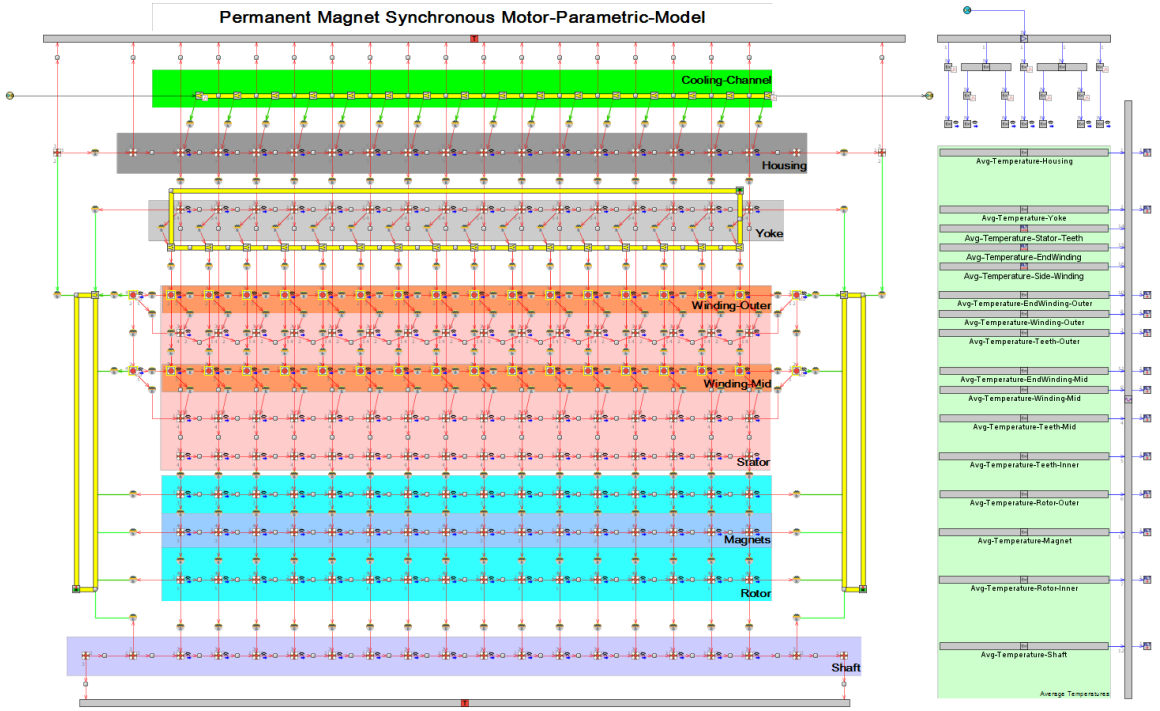
参数化电机模型

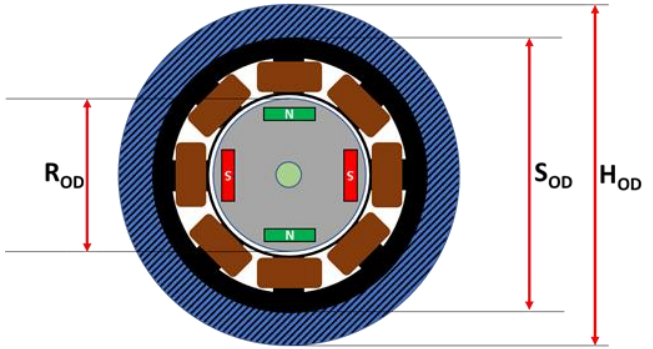
ACMachinePM
SynchThermal



New







H_L	-	Housing Outer Length
H_{OD}	-	Housing Outer Diameter
HC_{Th}	-	Housing Cover Thickness
S_L	-	Stator Length
S_{OD}	-	Stator Outer Diameter
W_L	-	Winding Axial Length
R_{OD}	-	Rotor Outer Diameter
R_L	-	Rotor Length
M_L	-	Magnet Length
Sh_L	-	Shaft Length
Sh_D	-	Shaft Diameter
D	-	Channel Diameter
GAP_L	-	Air Gap Length

参数化电机模型：参数化输入

外壳长度、直径、厚度

General | Housing | Stator and Winding | Rotor Components | Thermal

Attribute	Unit	Object Value
Housing Material Properties		Aluminum
Housing Outer Length	mm	250
Housing Outer Diameter	mm	216
Housing Cover Thickness	mm	10.1

定子长度、外径、
线圈体积、长度、数量

General | Housing | Stator and Winding | Rotor Components | Thermal Con

Attribute	Unit	Object Value
Stator		
Stator Material Properties		Iron
Stator Length	mm	175.5
Stator Outer Diameter	mm	180.7
Slot Filling Ratio	fraction	0.8623
Winding to Stator Volume Ratio	fraction	0.31
Windings		
Winding Material Properties		prop_wind
Winding Axial Length	mm	195
Number of Winding Slots		12

转子外径、磁钢体积、转轴长度、直径

General | Housing | Stator and Winding | Rotor Components | Thermal

Attribute	Unit	Object Value
Rotor		
Rotor Material Properties		Iron
Rotor Outer Diameter	mm	112
Magnets		
Magnet Material Properties		NbFeB
Magnet to Rotor Volume Ratio	fraction	0.19
Shaft		
Shaft Material Properties		StainlessSteel
Shaft Length	mm	343
Shaft Diameter	mm	22

热阻

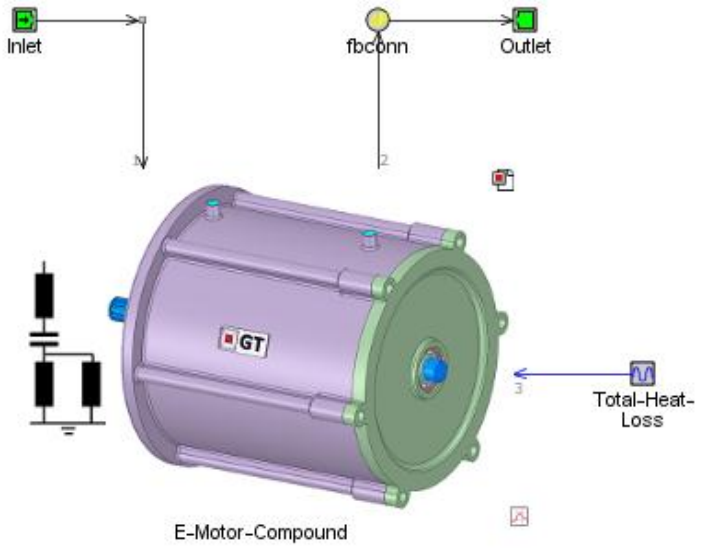
General | Housing | Stator and Winding | Rotor Components | Thermal Contact Resistance

Attribute	Unit	Object Value
Thermal Resistance: Housing to Cover	(m^2-...	def (=1E-8)
Thermal Resistance: Housing to Stator-Yoke	(m^2-...	def (=1E-8)
Thermal Resistance: Stator-Teeth to Rotor	(m^2-...	def (=1E-8)
Thermal Resistance: Rotor to Magnet	(m^2-...	def (=1E-8)
Thermal Resistance: Rotor to Shaft	(m^2-...	def (=1E-8)
Thermal Resistance: Winding (Axial)	(m^2-...	def (=1E-8)
Thermal Resistance: Winding (Radial)	(m^2-...	def (=1E-8)
Thermal Resistance: Winding (Angular)	(m^2-...	def (=1E-8)

参数化电机模型标定

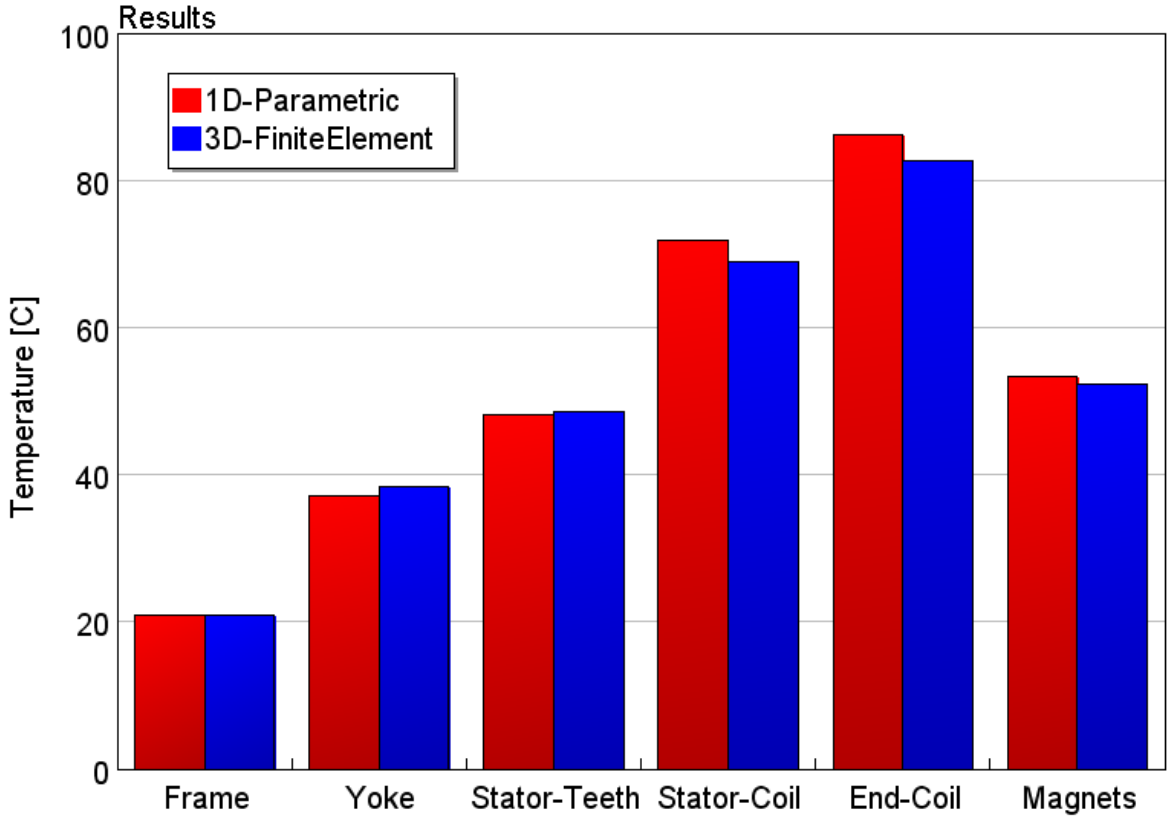
优化变量:

1. R_{th} Rotor-to-Stator
2. R_{th} Rotor-to-Magnet
3. R_{th} Winding-Axial
4. R_{th} Winding-Radial
5. R_{th} Winding-Angular
6. R_{th} Housing-to-Stator
7. HTM (Coolant)



优化目标:

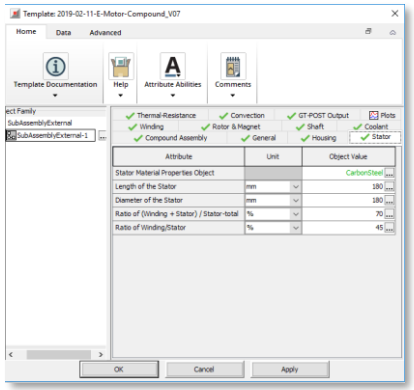
1. 线圈端部温度
2. 线圈边温度
3. 定子齿温度
4. 磁钢温度



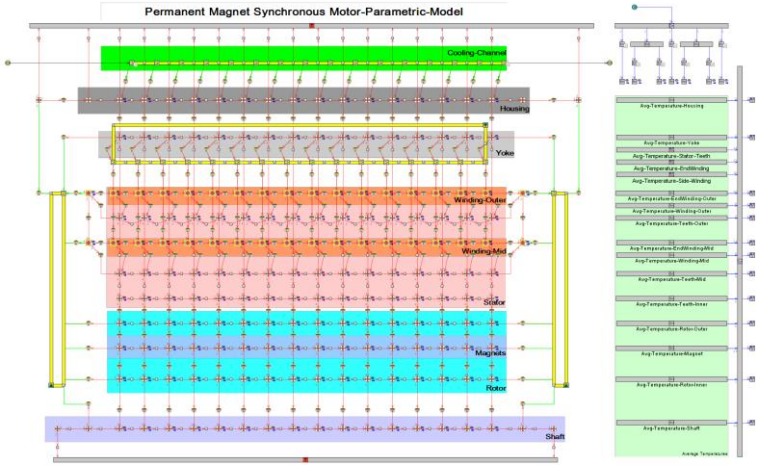
Load Torque = 80 Nm; Motor Speed = 6000 RPM
Coolant VFR = 8 L/min

参数化电机模型建模及标定流程

GT-SUITE
GT-ISE

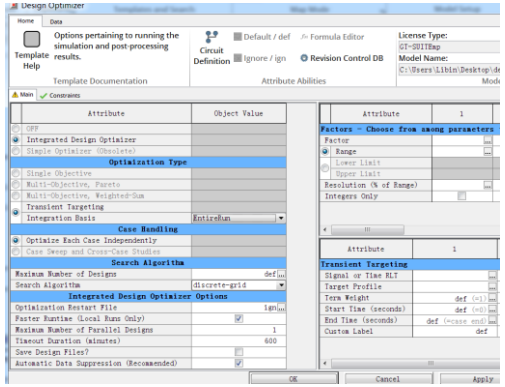


参数定义



GT-SUITE
Int. Design Optimizer

定义优化



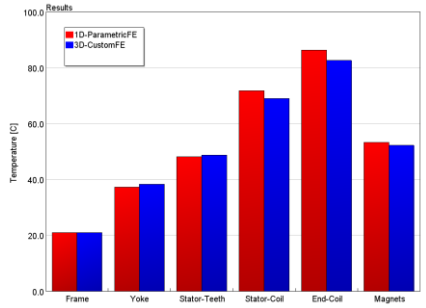
GT-SpaceClaim

=

尺寸测量

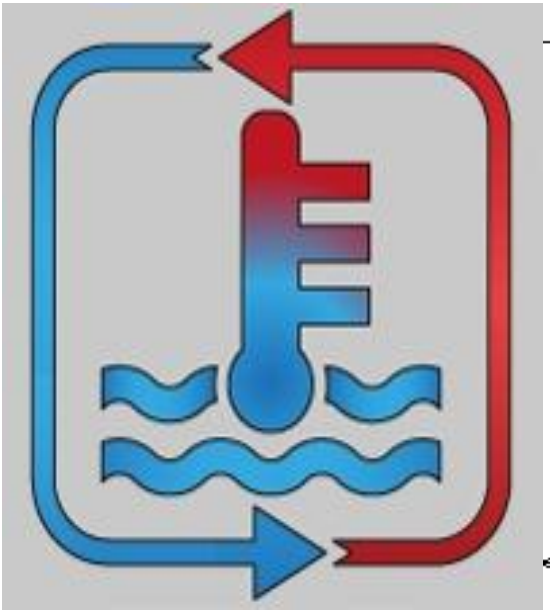
GT-SUITE
GT-POST

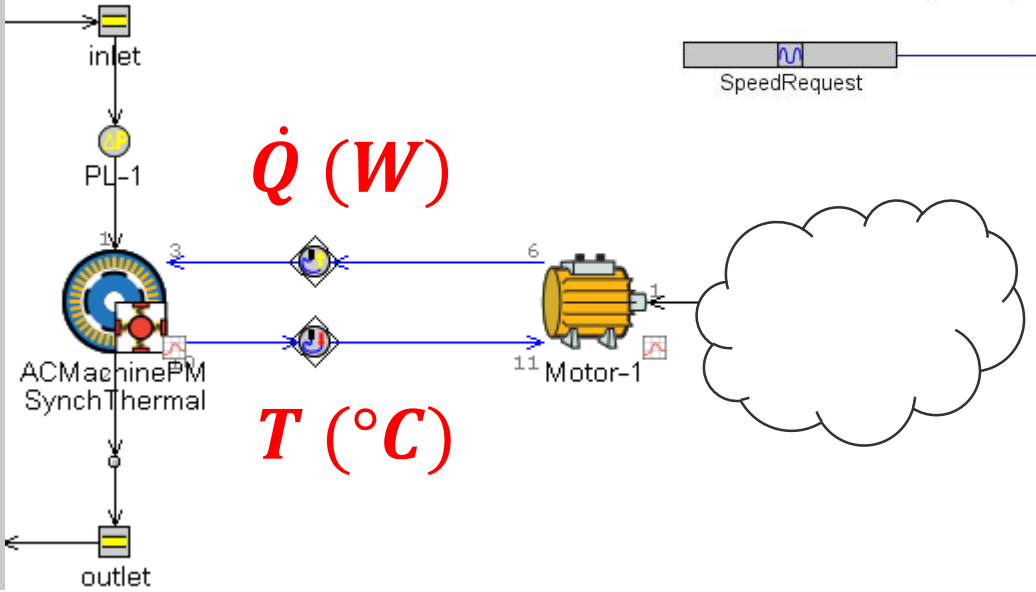
计算结果

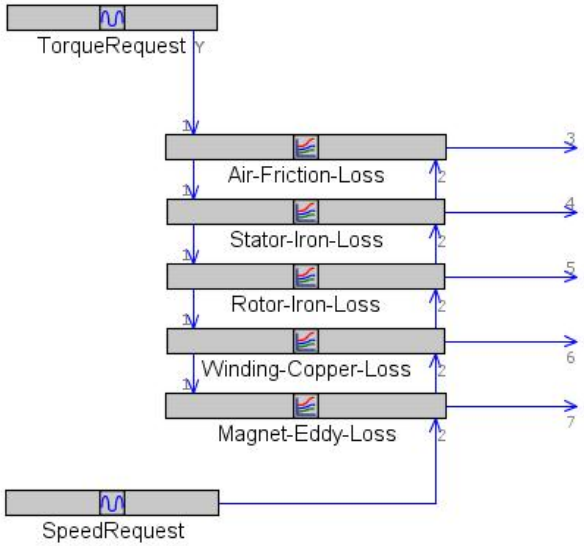


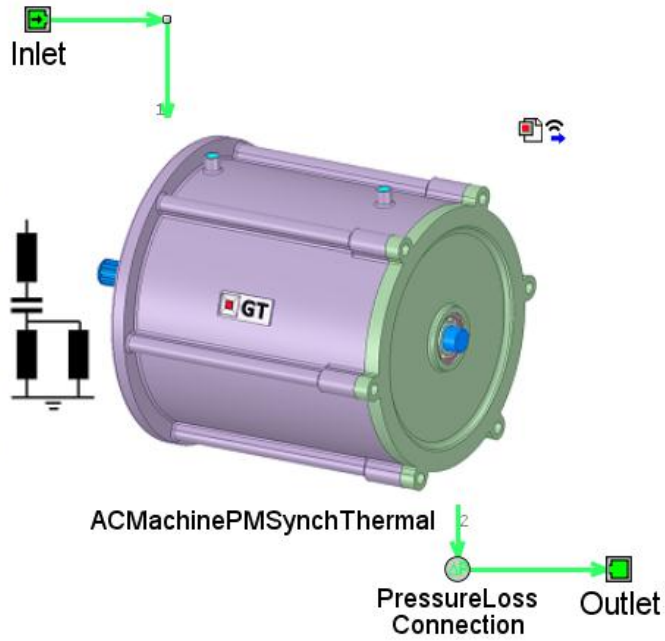
参数化电机的使用方法

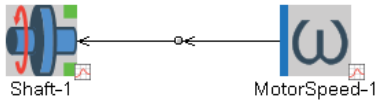
- 单一工况模拟
- 与电机联动
- 热源：总损失/损失分布



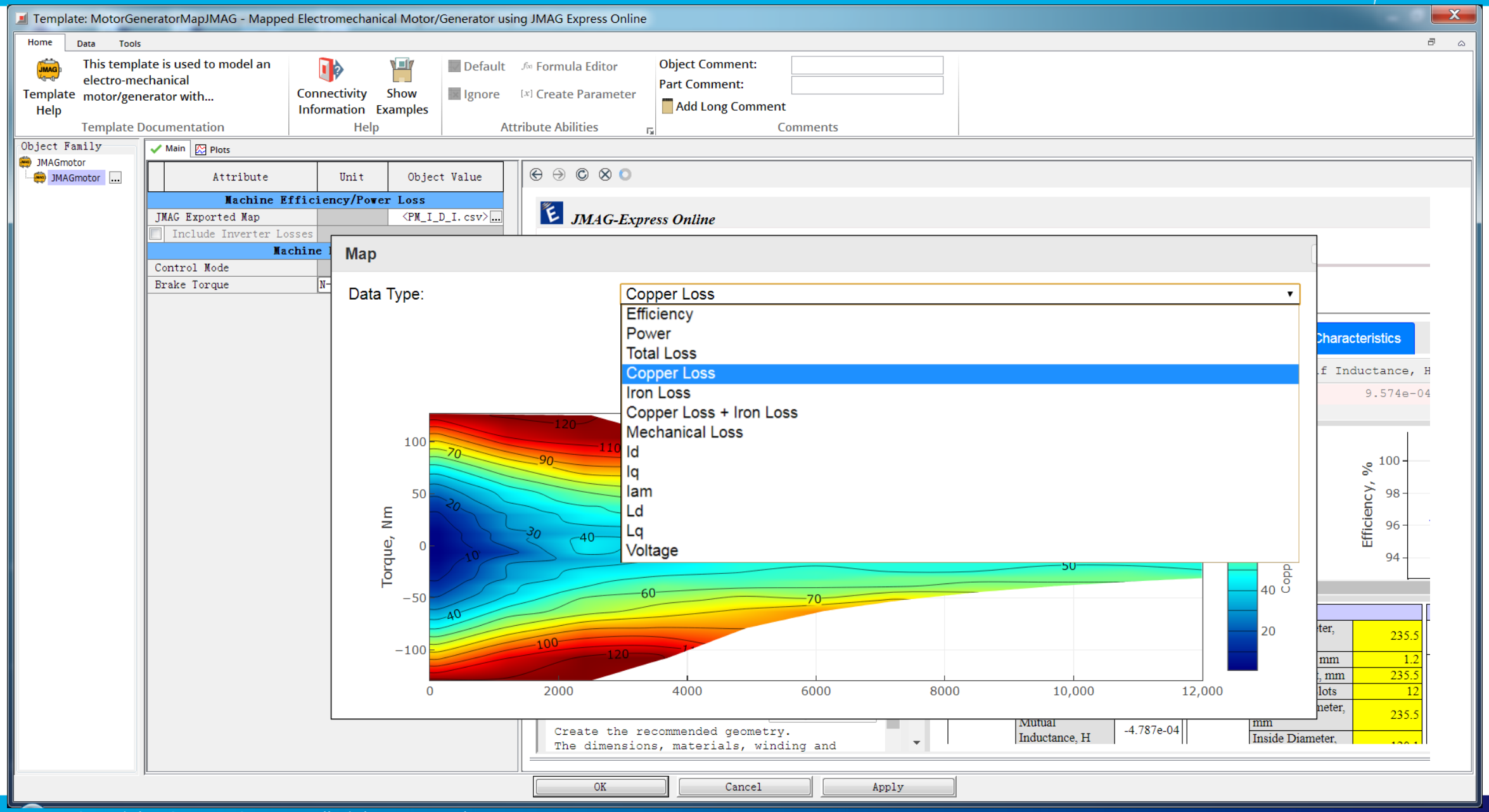




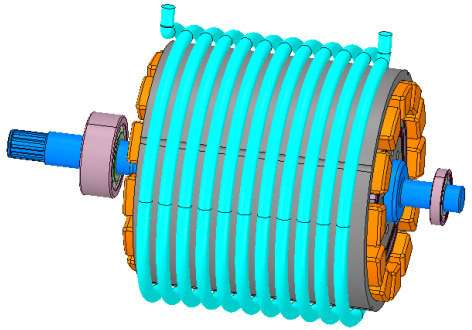




損失分布：JMAG Express Online



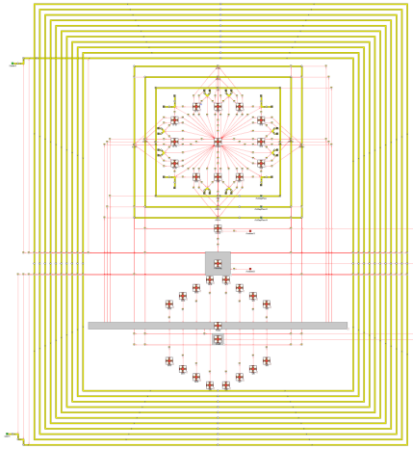
不同层级模型应用场合



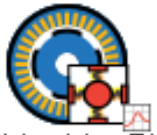
预测性

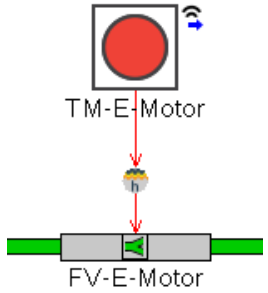
3D有限元模型

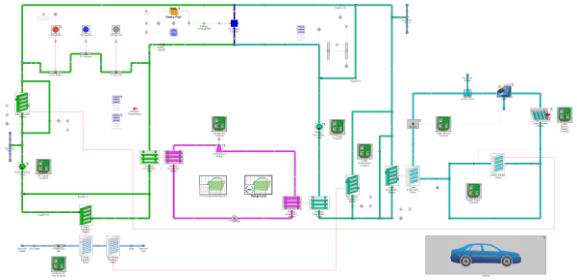
拟3D模型



集总参数模型

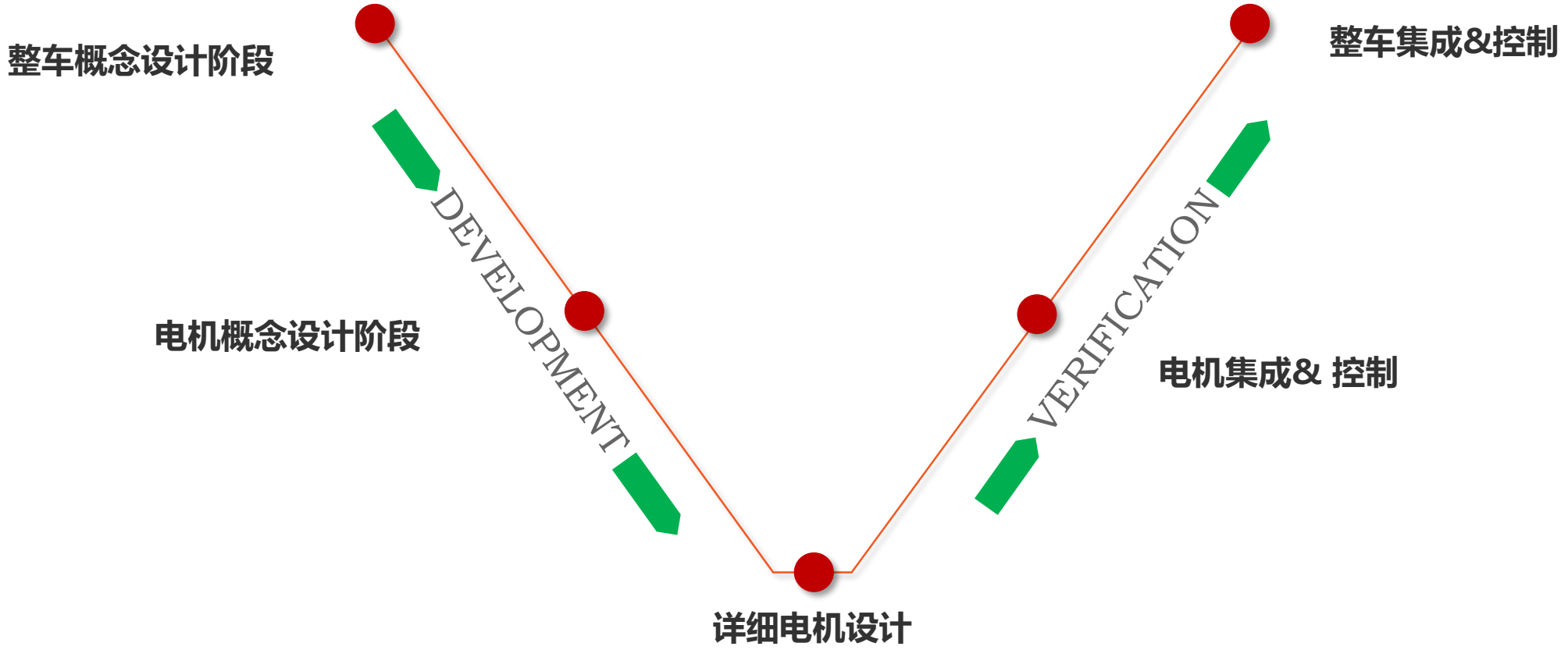




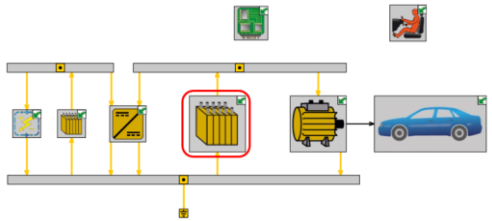


计算时间

整车开发流程



整车开发流程



整车概念设计阶段

电机概念设计阶段

DEVELOPMENT

详细电机设计

VERIFICATION

电机集成& 控制

整车集成&控制

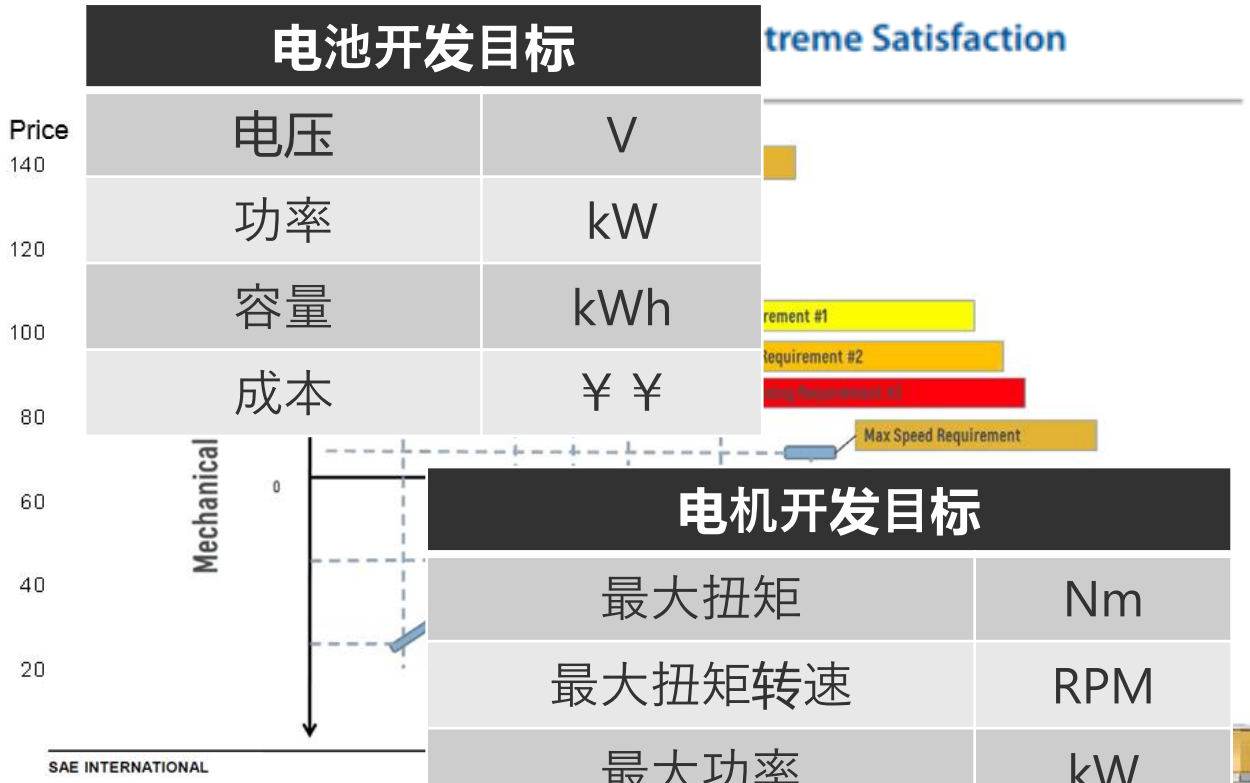
整车概念设计阶段

输入

整车开发目标:

- 续航里程
- 动力性
- 开发成本

电池开发目标	
电压	V
功率	kW
容量	kWh
成本	￥￥



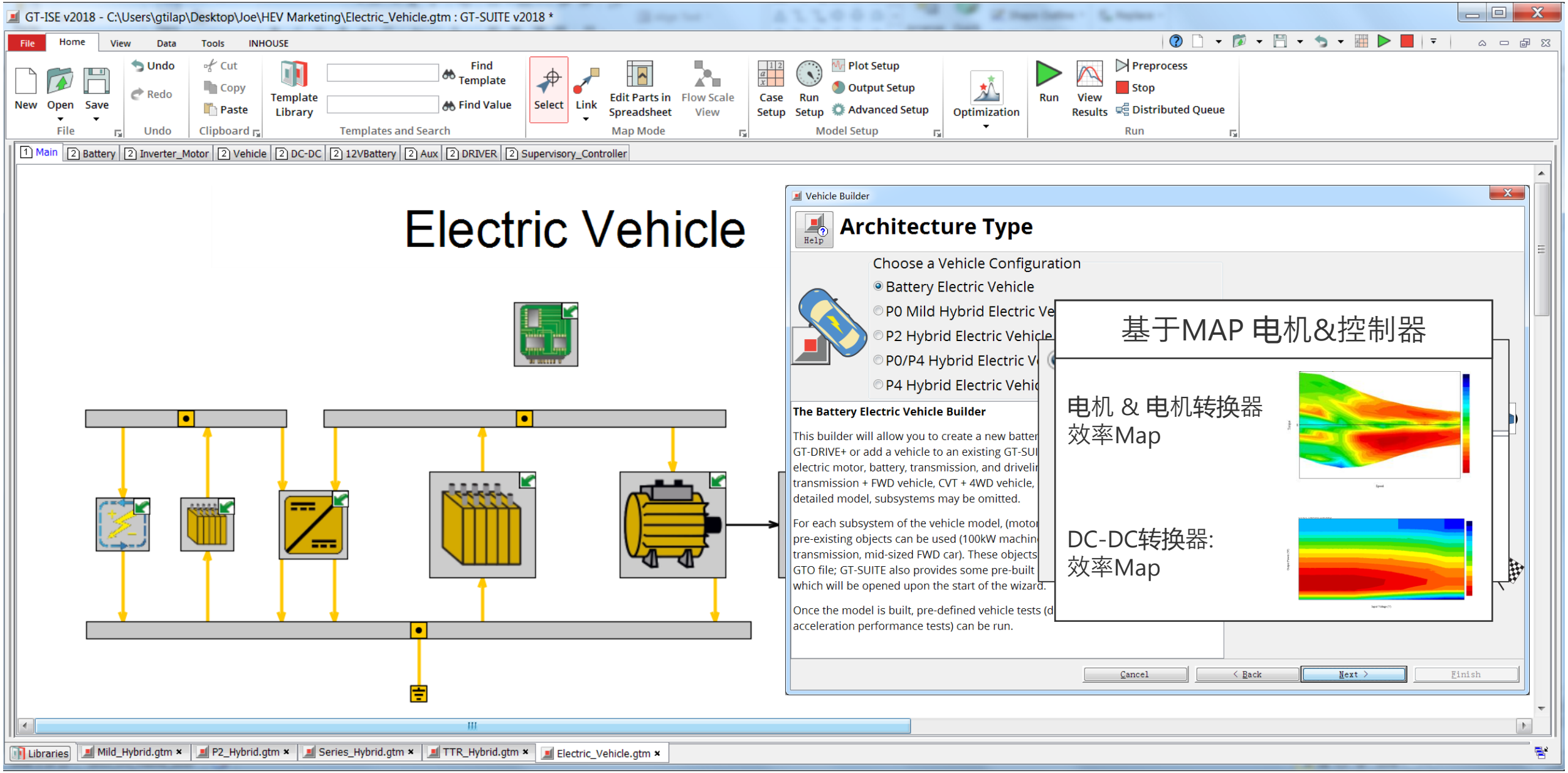
电机开发目标	
最大扭矩	Nm
最大扭矩转速	RPM
最大功率	kW
最高转速	RPM
效率	%
成本	￥￥

参考文献:
参考文献: SAE HEV Survey Result

输出

整车设计方案
电池开发目标
电机开发目标

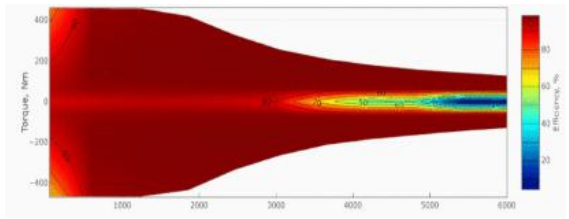
GT-SUITE在整车概念设计阶段的应用

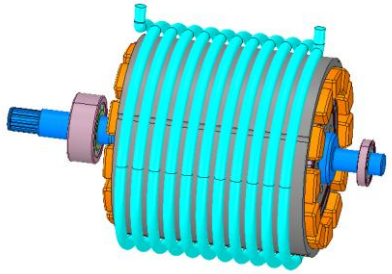


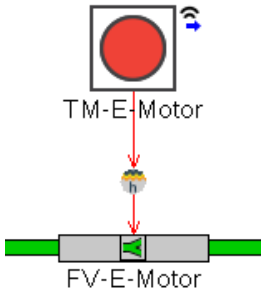
整车开发流程

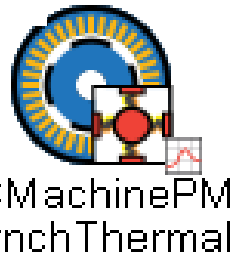
整车概念设计阶段

电机概念设计阶段









DEVELOPMENT

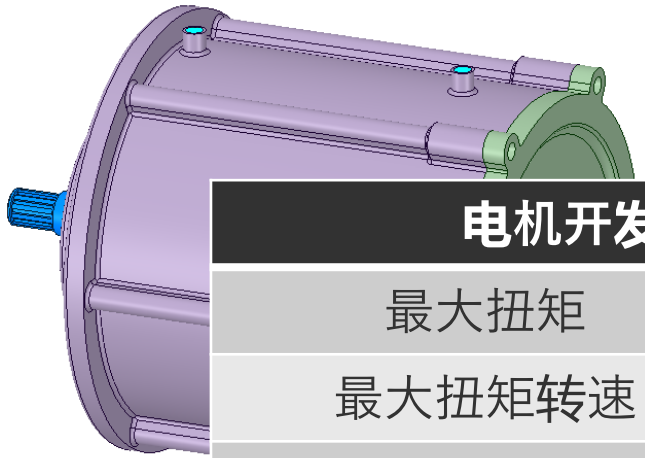
详细电机设计

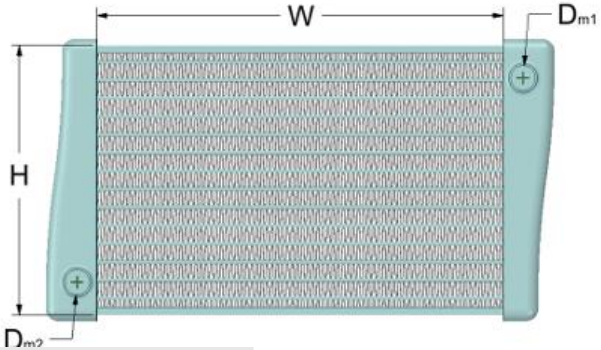
VERIFICATION

电机集成& 控制

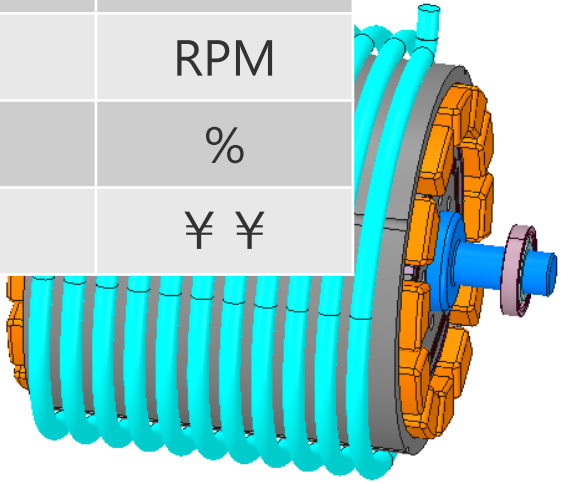
整车集成&控制

电机概念设计





电机开发目标	
最大扭矩	
最大扭矩转速	RPM
最大功率	kW
最高转速	RPM
效率	%
成本	￥￥



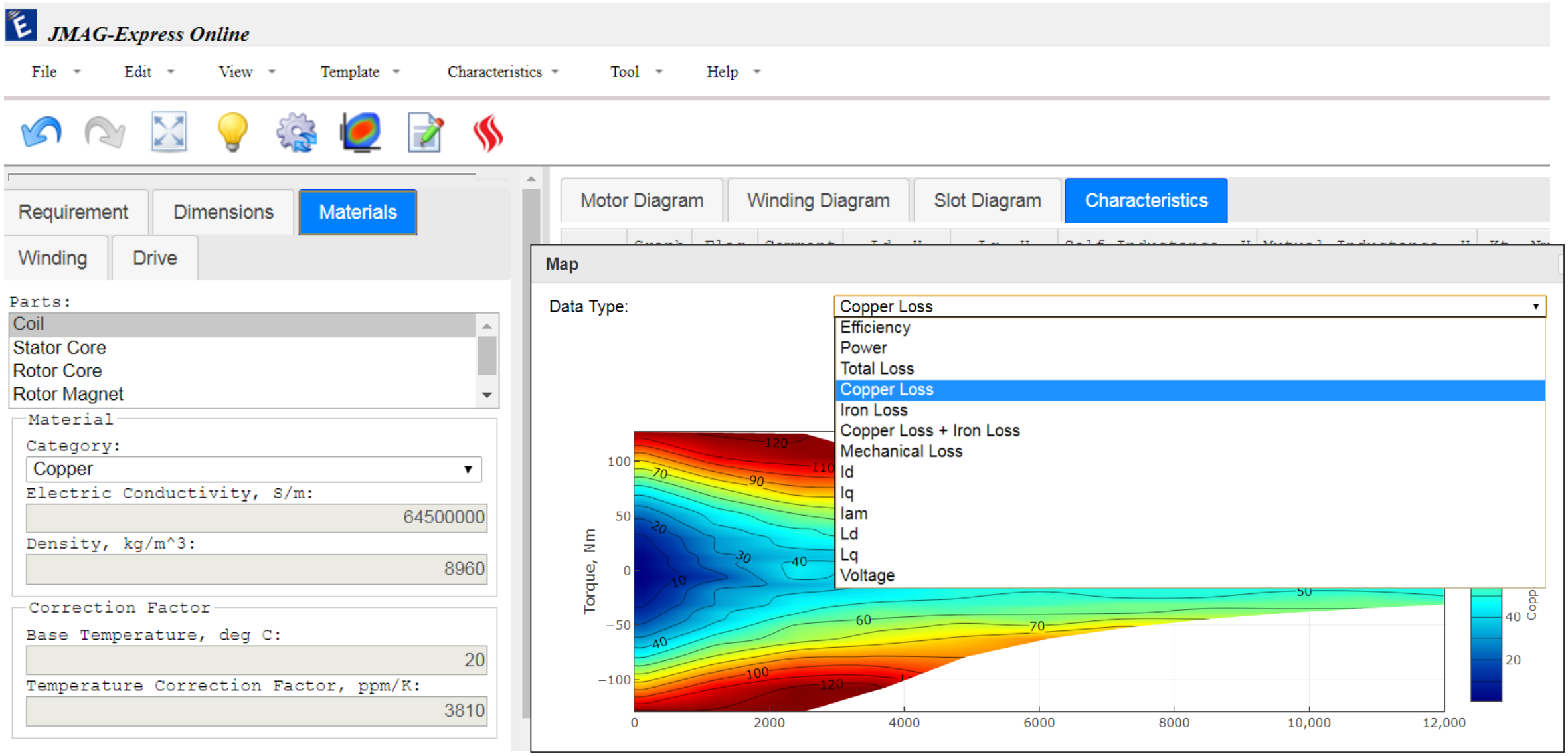
输入

电机设计要求
功率需求
温度要求

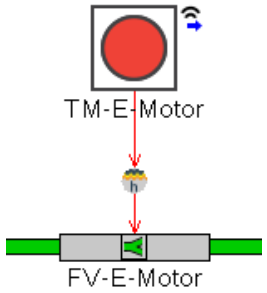
输出

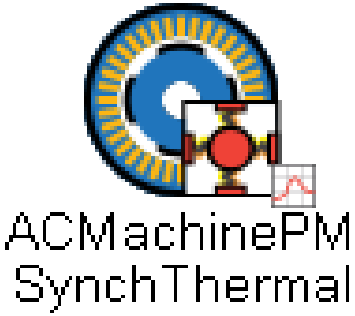
电机几何尺寸
电机效率
电机散热量
水泵流量

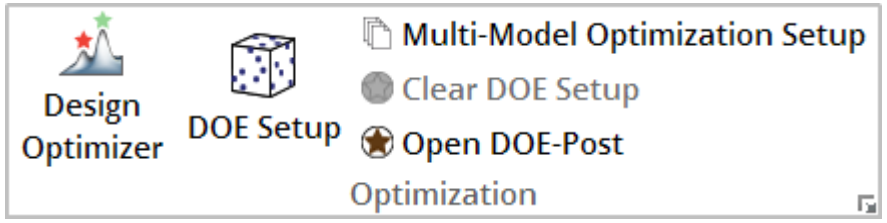
GT-SUITE在电机概念设计阶段的应用

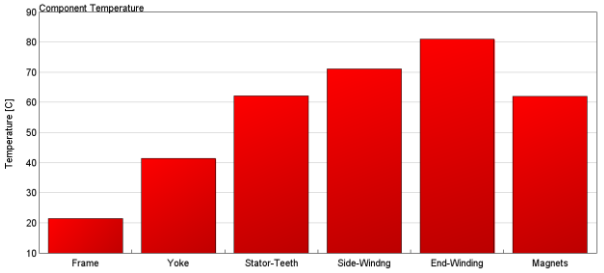


GT-SUITE在电机概念设计阶段的应用



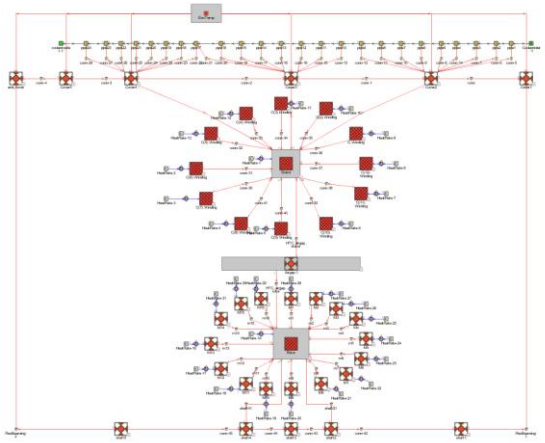


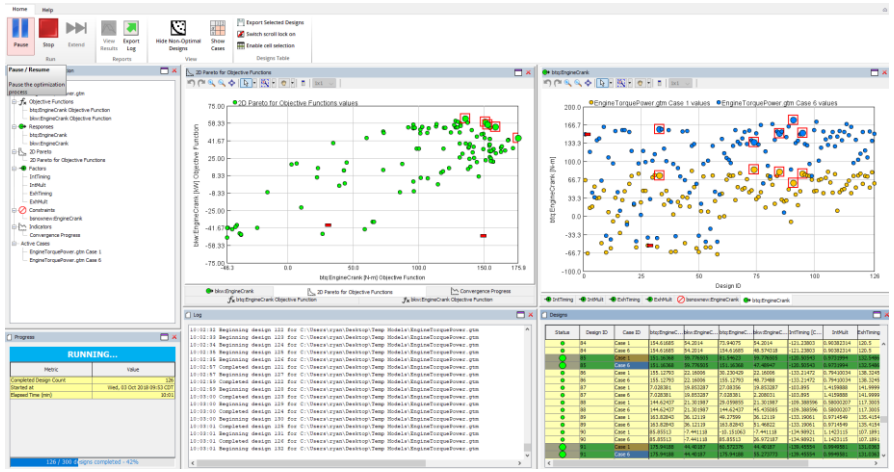


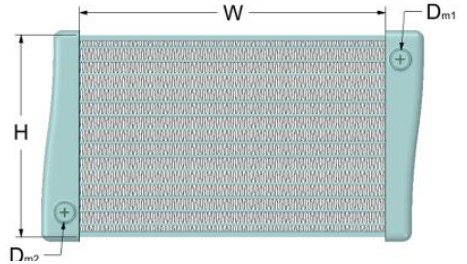


概念温度场

水泵规格







散热量

整车开发平台

整车概念设计阶段

电机概念设计阶段

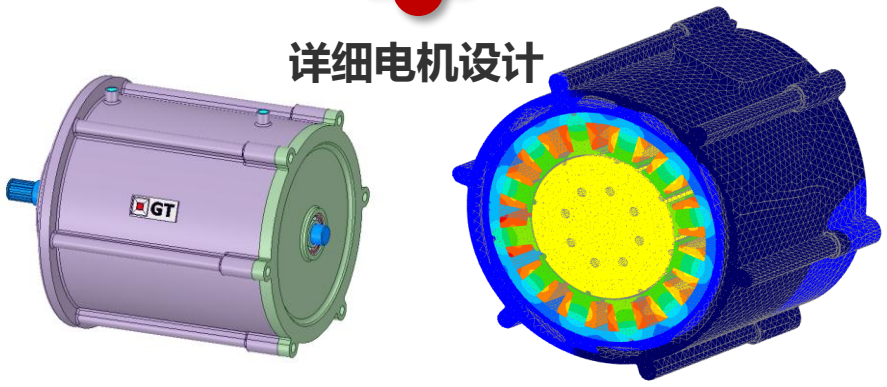
DEVELOPMENT

VERIFICATION

整车集成&控制

电机集成& 控制

详细电机设计



整车开发平台

整车概念设计阶段

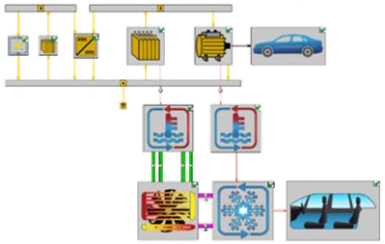
电机概念设计阶段

DEVELOPMENT

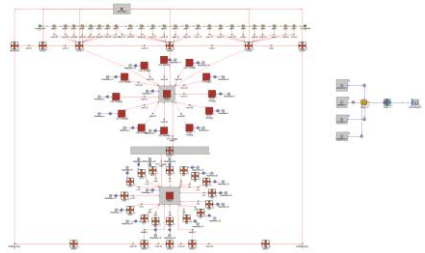
详细电机设计

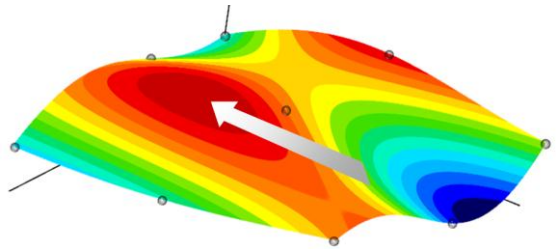
VERIFICATION

整车集成&控制

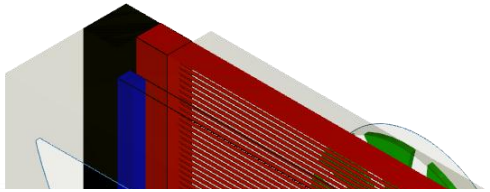


电机集成& 控制





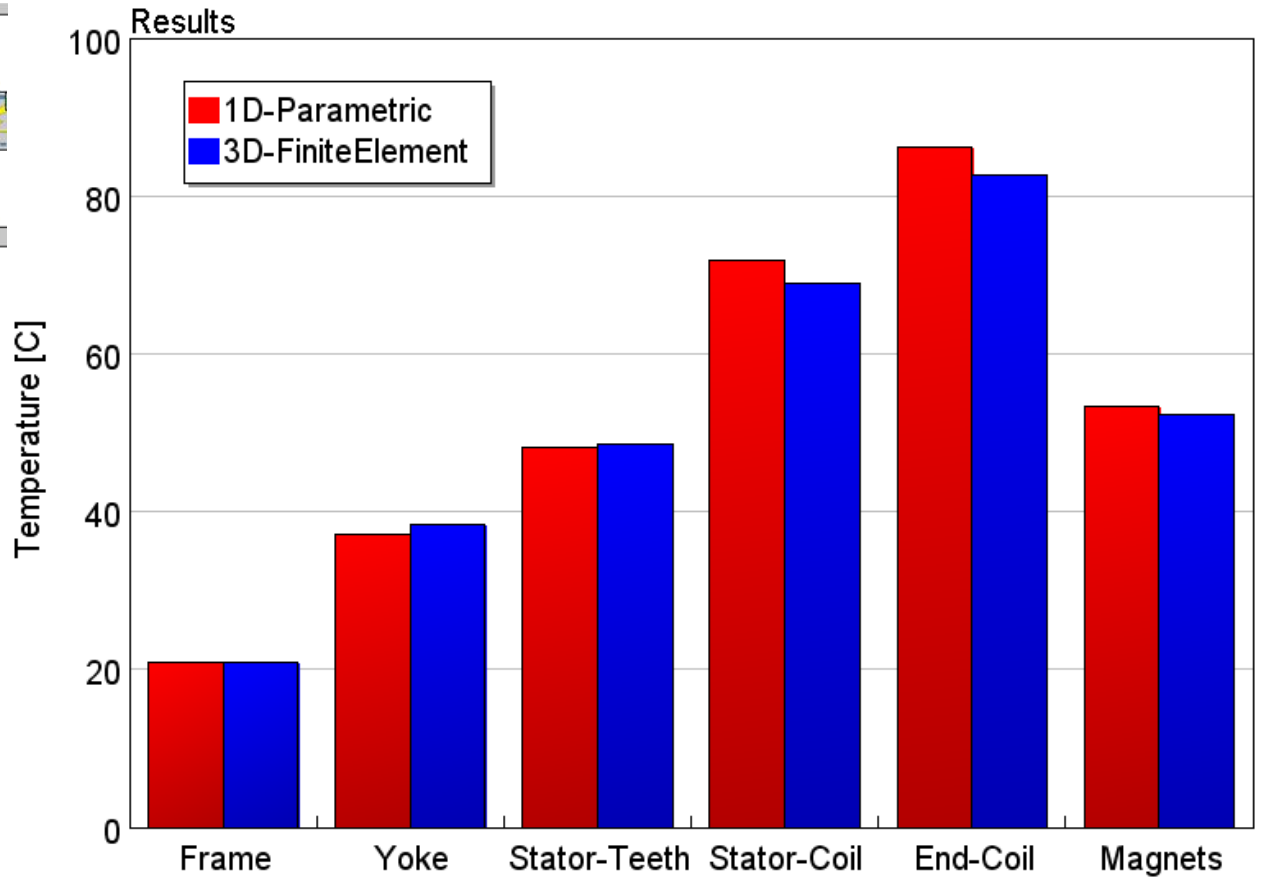
整车系统集成&控制



输入

快速计算3D/1D 模型

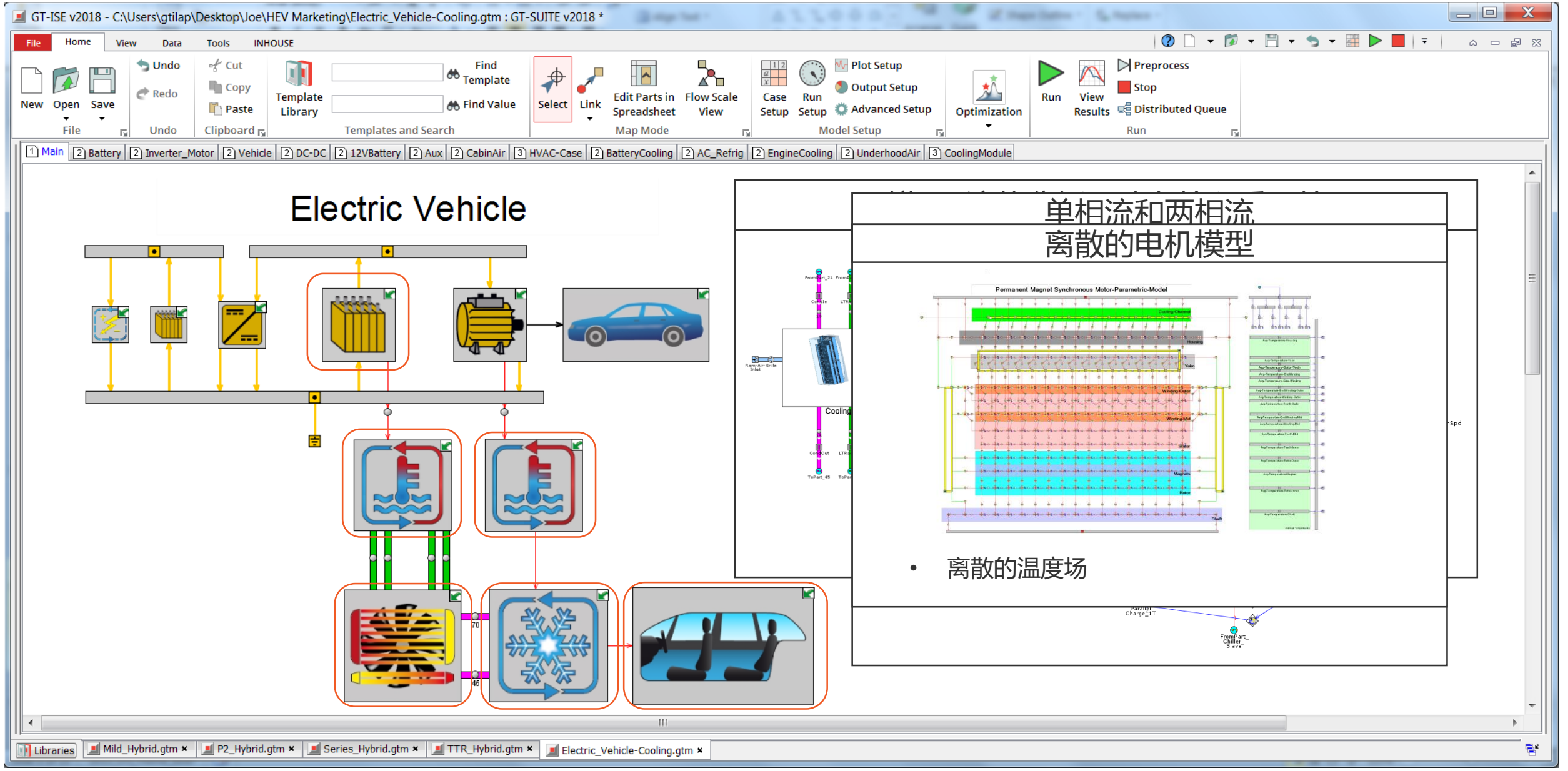
- 电池
- 电机
- 动力总成 & 整车
- 换热器
- 系统管路



输出

续航里程
控制策略优化
驾驶员舒适性
电机温度

GT-SUITE整车能量管理



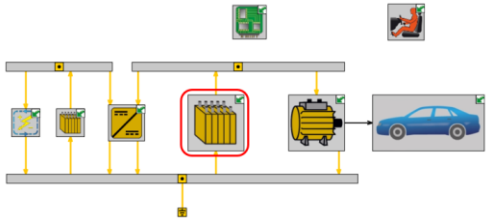
整车开发平台

Model Based Design

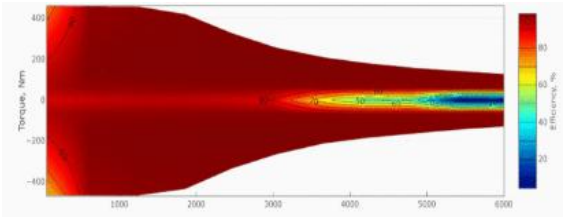
DEVELOPMENT

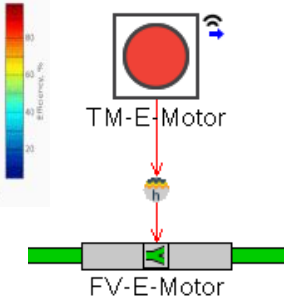
VERIFICATION

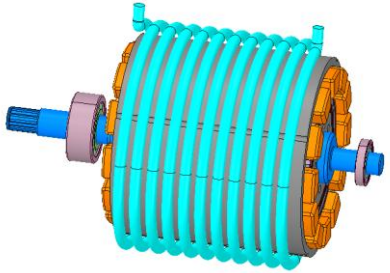
整车概念设计阶段

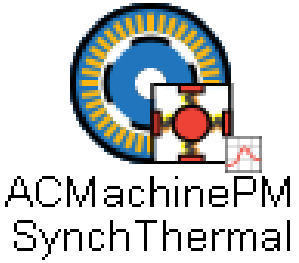


电机概念设计阶段

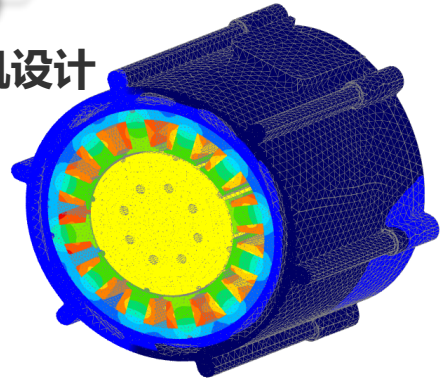




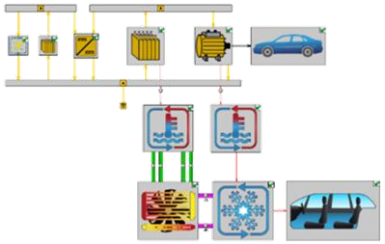




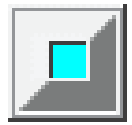
详细电机设计

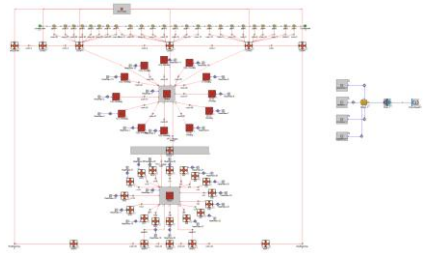


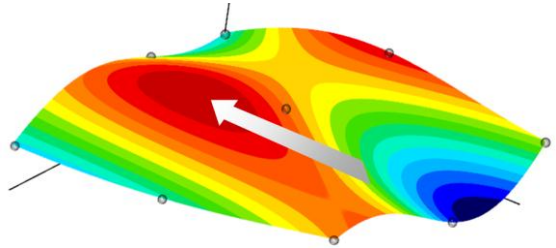
整车集成&控制



电机集成& 控制







要点总结

- 电机热管理系统在新能源汽车开发过程中尤为重要
- 针对不同的分析目的，需要使用不同层级的模型
- 拟3D电机热管理模型可有效应用于电机热管理系统开发
- GT-SUITE是电机-整车系统开发的理想工具
  - 具有完备的部件库
  - 快捷的前处理工具
  - 完整的整车能量管理平台
  - 优化和DOE

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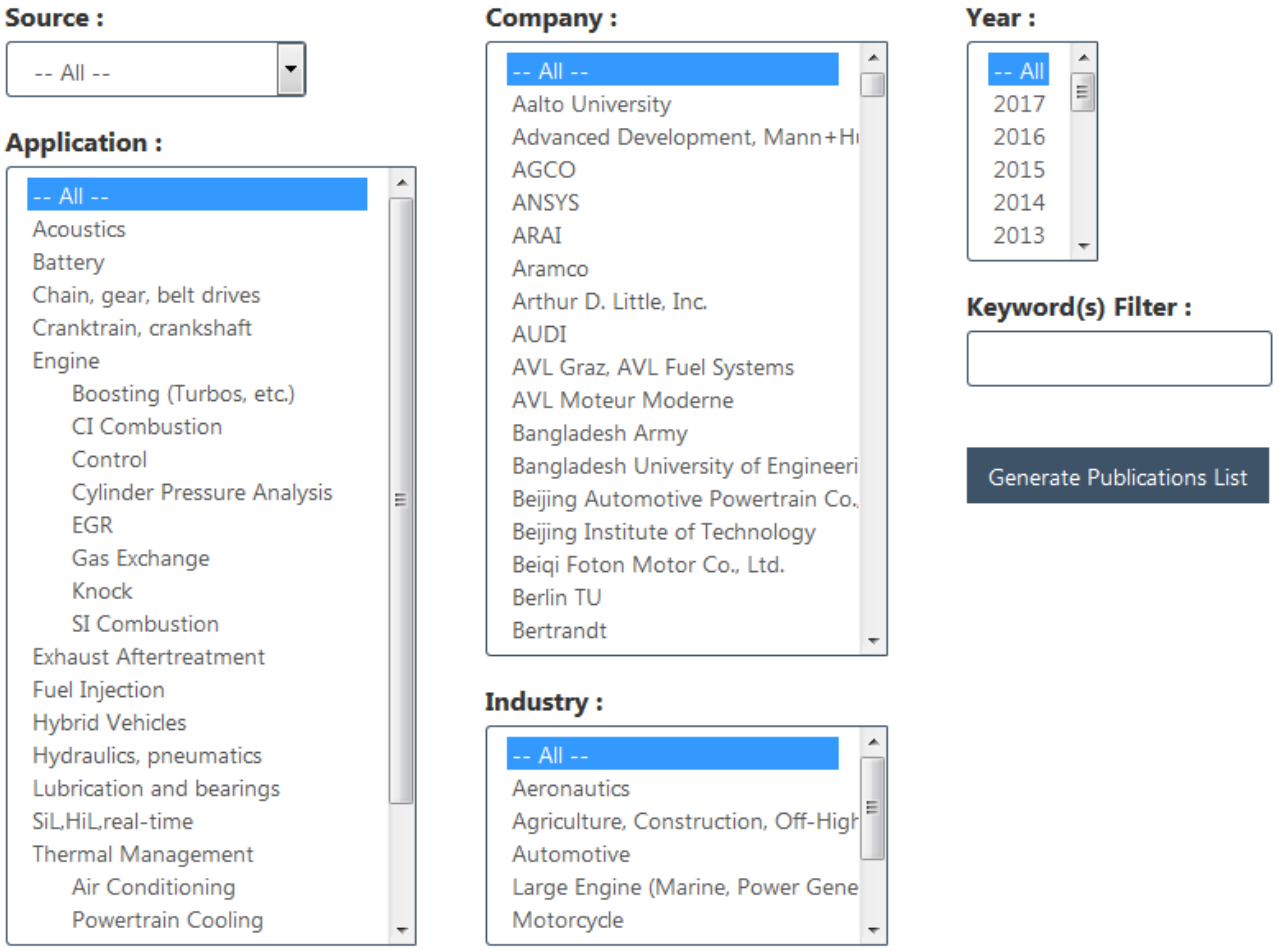

感谢倾听
期待与您的进一步合作 ☺

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