ARMEVA

Advanced Reluctance Motors for Electric Vehicle Applications

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GLOSSARY

ARMEVA	Advanced Reluctance Motors for Electric Vehicle Applications
BEM	Boundary element method
CAD	Computer aided design
dc	direct current
FEM	Finite element method
SRM	Switched reluctance motor
TEC	Thermal equivalent circuit
WP	Work package

1. PURPOSE AND SCOPE OF THE DOCUMENT

1.1 INTRODUCTION

Task 2.1 is the first task of work package 2 (WP2) in which three types of reluctance machines (ORSRM, DCE-FSM, VRSM) are being compared. Since only one of the three motor types will actually be built based on the results of a theoretical comparison, it is imperative to eliminate discrepancies in the outcomes on account of different model assumptions being adopted by the different designers in order to facilitate a fair comparison. Therefore, this document was created to serve as a baseline for the variables and parameters that are used for the model creation of each motor design.

It has to be noted that, apart from the requirements section, the actual values of many parameters which are described in this document are to be defined throughout WP2, since the quantification of these values and criteria will be the result of discussion between the consortium partners involved in the electromagnetic design of the three motors. Furthermore, some numerical values that are assigned to quantities and parameters are subject to change during the period of WP2 due to alterations in insight that might be the result of intermediate findings and evaluations.

Since this document was listed as a deliverable to be submitted in the early stage of WP2, the document is created as a generic list, and therefore the actual values of all parameters are included in a separate list [T2.1_Data.xls] which is available for all consortium members through the internal Jira/Confluence portal.

The purpose of D2.1 is to introduce the requirements, related parameters, calculation methods and evaluation criteria and to serve as an overview. D2.1 should be used along with the corresponding data list for the actual values.

1.2 DOCUMENT OVERVIEW

A breakdown is made into requirements, fixed parameters, calculation methods and evaluation criteria. Furthermore, a last section describes the design documentation which needs to be generated and presented for each of the concepts. To that end, this document consists of the following parts:

- **Requirements**
  This part provides the requirements the machine has to meet. The requirements are predominantly determined by the work conducted by LMS Imagine as formulated in the outcome of work package 1; more specifically in deliverables D1.1 and subsequently D1.3.

- **Fixed Parameters**
  This part contains a list of physical and geometrical parameters that should be set equally in all three types of motors. The assignment of actual values to the parameters depends among others on the technical implementation and manufacturability.

- **Methods of Calculation**
  This part covers guidelines on the way the simulation models should be created and how certain physical aspects such as iron losses should be calculated.

- **Evaluation Criteria**

This provides an overview of the evaluation criteria that enable overall comparison between the different machine types.

- **Design documentation**
  This describes the data, documents and models which should be presented for each of the analyzed concepts, in order to verify consistency with the requirements and to be able to make the assessment.

2 REQUIREMENTS

The outcome of work package 1 has resulted in the requirements as given in this section. Obviously, all final designs should meet these requirements.

2.1 TORQUE-SPEED CHARACTERISTIC

The basic speed-torque characteristic is shown in Figure 1. The numerical values that define the shape of the torque-speed characteristic follow from work package 1 and are tabulated in Table 1. It has to be noted that the torque values, *M*, given in Figure 1 are ***average*** torque values, torque ripple is averaged out. Hence, the values for *M* are denoted with a bar.

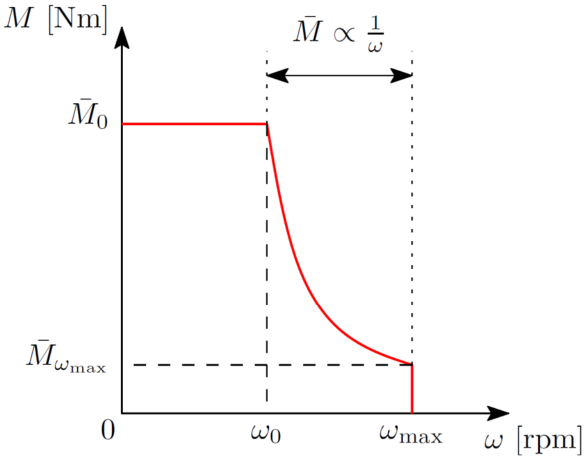

Figure 1: Speed-torque characteristic.

Quantity	Value	Unit
$\overline{M}_0$		Nm
$\overline{M}_{\omega_{\max}}$		Nm
ω_0		Rpm
$\omega_{\max}$		Rpm

Table 1: Defining parameters for the speed-torque characteristic

2.2 STALL CONDITIONS

At standstill the vehicle has to be able to overcome obstacles such as curbs. Hence a minimal torque, known as stall torque, has to be defined. The motor should be able to minimally provide this torque from standstill at any arbitrary relative position of the rotor with respect to the stator. Therefore, at a worst-case position where the torque of the motor is minimal it should still be able to deliver this stall torque. In other words, the torque of the minimal value of the torque ripple profile for $\omega = 0$ rpm should be greater than the stall torque. Moreover, the stall torque should last for at least a given period of time while the rotor is at standstill. During the stall time overheating of the motor and semiconductor switches must be avoided. The values for the stall torque and stall time are listed in Table 2.

Quantity	Value	Unit
M_{stall}		Nm
t_{stall}		s

Table 2: Stall conditions

2.3 CONTINUOUS POWER

The continuous power rating is the maximum mechanical power which can be sustained by the motor in continuous running duty. is needed to cover load cases such as top speed driving and driving up long slopes. This type of duty differs from other load cases in the sense that the thermal capacity of the motor is not used.The motor will reach a maximum temperature not higher than the specified temperature limits, and stay on that temperature as long as the load is applied.

The continuous power rating of a machine depends on its efficiency and the performance of the cooling system.

For the development in WP2 and WP3, the initial design is based on assumptions for the cooling system. For the initial design, the requirement of continuous power is expressed as a simple requirement of continuous power in a part of the speed range.

In a later stage when the cooling system is more accurately defined, a thermal model of the motor will be loaded into the vehicle model, allowing a simulation of the motor temperature during entire drive cycles.

The speed ω_{con} is the minimum rotational speed from which the continuous power should be delivered.

Quantity	Value	Unit
P_{con}		**W**
ω_{con}		**rpm**

Table 3: Continuous power requirement

2.4 TORQUE RIPPLE

An upper value on the absolute peak-to-peak torque ripple has to be defined to prevent undesired vibrations from being injected into the powertrain. On account of the filtering effect of the inertia the torque ripple requirement could be chosen to vary with the frequency of the torque ripple, i.e. the torque ripple requirement can be less stringent for higher speeds and/or motors with a higher number of poles.

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Frequency torque ripple (Hz)	**Quantity**	**value**	**unit**
100	ΔM_{pp}		Nm
200	ΔM_{pp}		Nm
300	ΔM_{pp}		Nm
$\vdots$	ΔM_{pp}		Nm
f_{max}	ΔM_{pp}		Nm

Table 4: Torque ripple

2.5 THERMAL ENVIRONMENT

The chosen cooling technology stipulates how much heat can be removed from the motor. At the initial stage of the electromagnetic motor-design the exact configuration and implementation of the cooling system are not yet known. Based on an envisioned cooling technology a conservative estimate has to be made of the equivalent convection coefficient and the thermal environment in which the powertrain is disposed. A conservative estimate of the convection coefficient is necessary to include a safety margin as result of a simplified model representation of both the cooling system and thermal environment. The quantification of the thermal convection coefficient is done in chapter 5, since it is not considered a requirement. The thermal environment, however, is a requirement and the quantities that determine it are tabulated in Table 5. Moreover, the thermal class of the material defines the maximum temperature of the hotspot in the machine. Figure 2 can assist in determining the maximum temperatures based on the thermal class and expected lifetime.

description	**Class**	**quantity**	**value**	**unit**
Maximum ambient temp.	-	$T_{\mathrm{amb,min}}$		K
Minimum ambient temp.	-	$T_{\mathrm{amb,max}}$		K
Continuous temperature of the hotspot (drive cycle dependent)	A	$T_{\mathrm{con,A}}$		K
	B	$T_{\mathrm{con,B}}$		K

	F	$T_{\mathrm{con,F}}$		K
	H	$T_{\mathrm{con,H}}$		K
Max. allowable over temperature of the hotspot	A	$T_{\mathrm{max,A}}$		K
	B	$T_{\mathrm{max,B}}$		K
	F	$T_{\mathrm{max,F}}$		K
	H	$T_{\mathrm{max,H}}$		K
Max. allowable time for over temperature	A	$t_{\mathrm{Tmax,A}}$		s
	B	$t_{\mathrm{Tmax,B}}$		s
	F	$t_{\mathrm{Tmax,F}}$		s
	H	$t_{\mathrm{Tmax,H}}$		s

Table 5: Thermal environment

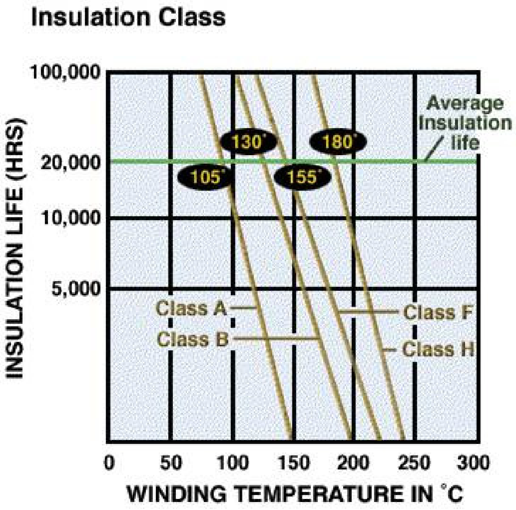

Figure 2 : Lifetime expectancy for different thermal classes

2.6 MAXIMUM MECHANICAL STRESS IN THE SHAFT

The radius of the solid or hollow shaft in itself is not constrained by a requirement; however, the dimensions of the shaft have to be such that it is able to transfer the torque without deformation. To that end, the maximum Von Mises-stress in the shaft is constrained to the value in Table 6.

Quantity	Value	unit
σ		MPa

Table 6: Maximum Stress in the shaft

2.7 MINIMAL AIRGAP LENGTH

Limitations in regard to manufacturing and tolerances stipulate the minimal airgap length. The minimal airgap length is given in Table 7.

Quantity	Value	unit
g		mm

Table 7: Airgap length

2.8 STRAIN OF THE ROTOR ON ACCOUNT OF CENTRIFUGAL FORCES

A mechanical simulation must be conducted to verify whether the rotor is stiff enough to prevent the centrifugal forces at maximum speed from deforming or even destroying it. The mechanical integrity of the structure of the rotor must be guaranteed at the maximum rotational mechanical speed. Apart from the worst-case scenario where centrifugal forces could destroy the rotor, also the strain in combination with a small airgap can cause the rotor and stator to graze. The evaluated strains are tabulated in Table 8.

Strain	Value	unit
$\varepsilon_{\mathrm{rot,orsrm}}$		-
$\varepsilon_{\mathrm{rot,synrm}}$		-
$\varepsilon_{\mathrm{rot,fsm}}$		-

Table 8: Strain of the rotor

Note: the combination of thermal expansion and rotor strain should also be considered as a worst case situation.

2.9 MAXIMUM DC-RIPPLE

A maximum current ripple is set on the dc-current to prevent degradation in performance of the battery. The maximum current ripple is specified in Table 9. The constraint on the current ripple amongst others determines the value of the dc-bus capacitor. It has to be noted that this requirement may be easier to satisfy for a given motor type in combination with a drive than for others.

Quantity	Value	unit
ΔI_{dc}		A

Table 9: Maximum dc-ripple

2.10 RANGE OF THE DC-BUS VOLTAGE

The dc-bus voltage varies as function of the battery output voltage. The variation in battery output voltage in turn is a function of temperature differences, state of charge and dc-current level. Furthermore, the impedance of the connection from the battery to the terminals of the drive/dc-bus causes an additional voltage drop of the dc-bus voltage. As a result the required speed-torque characteristic has to be redefined by Punch for reduced battery voltage ranges. The adjusted values that determine the shape of the speed-torque curve of figure 1 for reduced battery voltages are listed in Table 10.

dc-bus voltage range	Speed-curve parameter	value	unit
$0.9 < \frac{V_{\mathrm{dc}}}{V_{\mathrm{dc,\,max}}} \leq 1$	$\overline{M}_0$		Nm
	$\overline{M}_{\omega_{\max}}$		Nm
	ω_0		rpm
	$\omega_{\max}$		rpm
$0.8 < \frac{V_{\mathrm{dc}}}{V_{\mathrm{dc,\,max}}} \leq 0.9$	$\overline{M}_0$		Nm
	$\overline{M}_{\omega_{\max}}$		Nm
	ω_0		rpm
	$\omega_{\max}$		rpm
$0.7 < \frac{V_{\mathrm{dc}}}{V_{\mathrm{dc,\,max}}} \leq 0.8$	$\overline{M}_0$		Nm
	$\overline{M}_{\omega_{\max}}$		Nm

	ω_0		rpm
	$\omega_{\max}$		rpm
$V_{\text{dc, max}}$	N/A		V

Table 10: DC-bus voltage range

2.11 GEOMETRICAL DIMENSIONS

Obviously, geometrical restrictions are imposed that define the dimensions of the machine. In Table 11 and Table 12 the active dimension of the machine are given. It has to be noted that by the active axial length is meant the total length of the sum of the lamination stack and **two** times the axial length occupied by the end windings. A function has to be defined that relates the axial length of the end turns to the dimensions and filling factor of the coils in the slots (see chapter 6). Furthermore, different geometrical dimensions apply for inner and outer rotor design

Description	Quantity	value	unit
Active axial length	z_{ax}	235	mm
Max. outer radius of the stack	r_{out}	102,5	mm

Table 11: Geometrical dimensions for inner rotor designs

Description	Quantity	value	unit
Axial length of the motor	z_{ax}	258	mm
Max. outer radius of the motor	r_{out}	120	mm

Table 12: Geometrical dimensions for outer rotor designs

2.12 TORQUE ACCURACY

Generally, the actual torque on the shaft is not measured for feedback control; instead only the current through the machine is measured. Moreover, manufacturing spread plays a role. Inherently, this leads to slight deviations between calculated and actual torque. The accuracy with which the torque has to be estimated under all operating conditions (temperature dependency, dc-bus voltage) is given by Table 13. For torque values higher than a certain threshold value the torque accuracy is relative with respect to the actual value and when it is lower it is expressed as an absolute value.

Description	Quantity	value	unit
Relative accuracy for $M \geq M_{\mathrm{th}}$	$\varepsilon_{\tau,\mathrm{rel}}$		%
Relative accuracy for $M < M_{\mathrm{th}}$	$\varepsilon_{\tau,\mathrm{abs}}$		Nm
Threshold value for the torque accuracy	M_{th}		Nm

Table 13: Torque accuracy

3 FIXED PARAMETERS

In this chapter an overview is given of parameters and coefficients that are assigned fixed values and apply for all machine types. The list is subject to change and to be extended, however, every change and additions should be communicated to all partners involved in the electromagnetic design of the motors!

3.1 STACKING FACTOR FOR LAMINATED STEEL STACKS

For different choices of lamination thicknesses a fixed stacking factor is defined in Table 14.

Lamination thickness (mm)	Stacking factor	unit
0.10		-
0.20		-
0.35		-
0.50		-

Table 14: Stacking factors

3.2 MAGNETIC PROPERTIES OF STEEL

For all magnetic steels that are considered as core material for the stack the exact same table of values that describe the *BH*-curve should be distributed among the partners in the format as suggested in Table 15. This enables all partners to design with exactly the same material and compare their results in a fair way. Changes in and additions to a *BH*-curve should always be communicated. Materials can be added provided that the addition is communicated to other partners. Furthermore, if extrapolation of the data of the *BH*-curve is required the extrapolation method should be discussed. Note: prices of steel per unit mass should also be communicated to other parties to allow cost models to be updated accordingly.

NAME OF THE STEEL	
H	***B***
0	0.0
2.36e2	0.1
⋮	⋮
1e5	2.15

Table 15: Format for the BH-curve data

3.3 FILLING FACTOR OF COILS

For different winding technologies of the coils different filling factors are obtained. For all winding technologies copper filling factors are defined. Hence, when the choice is made for a given winding technology the filling factors of Table 16 should be applied. As is the case for the magnetic properties addition and changes are allow if communicated to all parties.

Winding technology	Filling factor
Wound in slot by hand	
Pre-wound round wire	
Pre-wound rectangular wire	
Pre-wound tape wire	
Litz wire	
…	

Table 16: Filling factors of coils

3.4 SLOT INSULATION

The thickness of the layer of insulation between coils and the lamination stack has to be defined (Table 17).

Quantity	value	unit
h_{insul}		mm

Table 17: Insulation thickness.

3.5 MASS DENSITIES OF MATERIALS

A list of volumetric mass densities of all (bulk!) materials is provided to ensure that the comparison of the masses of the motor is fair. It has to be noted that stacking and/or filling factors are not taken into account in Table 18.

Material	**Mass density value (ρ)**	**unit**
Steel name 1		kg m^{-3}
Steel name 2		kg m^{-3}
Shaft material		kg m^{-3}
⋮		⋮
Copper (wire)		kg m^{-3}
Insulation layer		kg m^{-3}
Resin (potting)		kg m^{-3}

Table 18: Volumetric mass densities

3.6 ELECTRIC CONDUCTIVITY OF MATERIALS

A list of the bulk electric conductivity as function of temperature of current carrying materials (coils) is provided in Table 19. For fair comparison it is imperative that the electric resistance of coils is calculated at the proper operating temperature. Again filling factors of the coils have not been considered.

Material		**Value**	**unit**
Copper	**Conductivity @ T = 298 K**		S m^{-1}
	Temp. coefficient		K^{-1}
Aluminum	**Conductivity @ T = 298 K**		S m^{-1}
	Temp. coefficient		K^{-1}
⋮	**Conductivity @ T = 298 K**		S m^{-1}
	Temp. coefficient		K^{-1}

Table 19: Bulk electric conductivities

3.7 THERMAL PROPERTIES

A list of the bulk thermal conductivities and heat capacities of the components the machine consists of are listed in Table 20. It has to be noted that the bulk thermal conductivity of the coils depends on the chosen winding topology! In case representing the coil as a single bulk entity does not provide an accurate enough estimate of the temperature of the hotspot in the coil, improved methods for calculating the temperature distribution have to be defined (can be suggested by all parties). Additionally, the thermal resistances as a result of transitions between materials are defined in Table 21. Finally, the thermal environment the machine is placed is given by the maximum cooling fluid temperature (which is the assumed temperature on the outer diameter of the motor) and convection coefficient in Table 22.

Description		value	unit
phase coil (bulk)	**Conductivity**		W m^{-1} K^{-1}
	Capacity		J kg^{-1} K^{-1}
conductivity steel 1 (stack)	**Conductivity**		W m^{-1} K^{-1}
	Capacity		J kg^{-1} K^{-1}
conductivity steel 2 (stack)	**Conductivity**		W m^{-1} K^{-1}
	Capacity		J kg^{-1} K^{-1}
⋮	**Conductivity**		W m^{-1} K^{-1}
	Capacity		J kg^{-1} K^{-1}
Shaft	**Conductivity**		W m^{-1} K^{-1}
	Capacity		J kg^{-1} K^{-1}
Insulation	**Conductivity**		W m^{-1} K^{-1}
	Capacity		J kg^{-1} K^{-1}

Table 20: Thermal conductivities and heat capacitances

Material transition	quantity	value	unit
coil ↔ insulation	$A^{-1}R_{\mathrm{coil2insul}}$		K W^{-1}
stack ↔ insulation	$A^{-1}R_{\mathrm{core2insul}}$		K W^{-1}

Table 21: Thermal resistance at material transitions as function of the cross section (A)

Description	quantity	value	unit
convection coef. @ heat removal surface	h_{conv}		W $K^{-1}m^{-2}$
max. cooling fluid temperature	$T_{\mathrm{fluid,max}}$		K

Table 22: Thermal ambient and convection coefficient

3.8 CORE LOSS COEFFICIENTS OF STEEL

The quantification of the iron losses is determined by the calculation method applied. Preferably, the same method for determining the iron losses is used by all three machine designers. For this method de loss parameters for each type of electric steel are tabulated in Table 23. It has to be noted that for the time being it is assumed that the Steinmetz method is applied by all parties.

Material	Coef.	value	unit
Steel 1	Eddy current		
	Hysteresis		
	Excess		
Steel 2	Eddy current		
	Hysteresis		
	Excess		

Table 23: Iron loss coefficients (Steinmetz)

3.9 BATTERY MODEL PARAMETERS

To discount the effect of the electrical behavior of the battery under varying load and its impact on machine performance an electrical equivalent battery model as discussed in chapter 6 is applied. The values of the components in the equivalent are given in Table 24.

Description	quantity	Value	unit
Internal resistance	R_i		Ω
Internal voltage ⋮ *To be extended depending on the applicable battery model.*	V_i		V

Table 24: Parameters for the equivalent electric battery model

3.10 PROPERTIES OF SEMI-CONDUCTOR SWITCHES

For a full model containing the battery model, drive model and electric motor model the semi-conductor switches have to be characterized. Characteristics of the switches are given in Table 25.

Switch	quantity	value	unit
IGBT type 1	Forward voltage		V
	Reverse recovery time		s
	⋮		
Diode type 1	Forward voltage		V
	Conducting losses		W
	⋮		

Table 25: Semi-conductor switches characteristics

3.11 MECHANICAL MATERIAL PROPERTIES

For any given material the mechanical properties (Table 26) should be known to be able to conduct mechanical stress calculations.

Material	quantity	value	unit
Shaft material	E_{shaft}		MPa
Copper	E_{Cu}		MPa
Steel 1 (stack)	$E_{\text{steel 1}}$		MPa
Steel 2 (stack)	$E_{\text{steel 2}}$		MPa
⋮			

Table 26: Young moduli of applicable materials

4 METHODS OF CALCULATION

This chapter is a result of a discussion between parties after reaching consensus on calculation methods for quantification of several physical quantities of prime interest.

4.1 SYSTEM MODEL

To investigate how the whole drive behaves electrically as a system under varying drive cycles and different operating conditions, it is required that a system model is developed (e.g. Simulink). The intention is not to obtain a complete vehicle model, but to consider the mechanical output on the shaft of the motor only. It is desired that this system model is created in a simulation tool that is available to all parties (same version / release, add-ons, toolboxes, etc.), so that models can be exchanged. The system model should include:

- A battery model (will be prescribed);
- The power electronic drive;
- Controls strategy;
- Electric motor model.

4.2 EQUIVALENT ELECTRIC BATTERY MODEL

To estimate, among others, the overall efficiency and the dynamical electrical behavior of the drive under varying conditions and varying state of charge of the battery a system model (e.g. a Simulink model) has to be made. To that end, an equivalent electric network of the battery has to be defined. Furthermore, the values of the components the equivalent electric battery network consists of have to be fixed in advance (see 4.9).

4.3 COST MODEL

A cost model should be defined to calculate the cost of the machines and the drive as a whole. The model has to be defined to be able to estimate the cost of the key materials and components as function of physical quantities such as current, voltage and power levels, volume and mass. Cost equations have to be defined for:

- The raw materials of the motors (€/kg);
- For tooling of motor parts;
- Semi-conductor devices as function of power level and voltage;
- DC-bus capacitance as function of voltage and capacity;
- Cables and connectors as function of current and voltage level;
- Estimating the investment cost for setting up series production facilities .

4.4 IRON LOSS MODEL

For the calculation of the iron/core losses the Steinmetz method is proposed:

$$P_{Fe} = \int_V \left[\frac{1}{T} \int_0^T \left[\frac{\sigma d^2}{12} \left(\frac{\mathrm{d}B(t)}{\mathrm{d}t} \right)^{\alpha_{\mathrm{eddy}}} + k_{\mathrm{hys}} B^{\alpha_{\mathrm{hys}}} f^{\beta_{\mathrm{hys}}} + k_{\mathrm{exc}} \left(\frac{\mathrm{d}B(t)}{\mathrm{d}t} \right)^{\alpha_{\mathrm{exc}}} \right] \mathrm{d}t \right] \mathrm{d}V$$

In case the flux density fluctuation exhibits high harmonic content a modified version of the Steinmetz equation should be defined. Consensus should be reached on which method is to be used for the calculation of the iron losses.

4.5 PROXIMITY LOSS MODEL

Especially in SRM proximity losses contribute significantly to the total losses on account of the fringing flux penetrating the phase coils at unaligned positions. First, it has to be investigated to which extent proximity losses contribute to the total losses. If their contribution to the total losses cannot be neglected a model has to be defined on how the proximity losses are to be calculated or estimated. This model can then be used during the optimization of the motor topologies. For the final, optimized topologies FEM can be used.

4.6 THERMAL MODEL

Preferably, consensus is reached on the method for the thermal calculations (BEM, FEM, TEC, etc.) to determine the heat distribution in the motor structure as a result of the operating conditions. Although, every designer is in principle free to choose its own thermal model, differences in thermal models might lead to unfair comparison of the thermal results. Possible discrepancies on account of different models being used should be avoided.

4.7 EXTRAPOLATION METHOD FOR MATERIAL PROPERTIES OF ELECTRIC STEELS

Datasheets of electric steels do not always provide sufficient information on losses, e.g. a certain type of steel might (shortly) be used under electromagnetic conditions for which manufactures fail to provide any information. Especially, for losses at higher, non-sinusoidal flux density levels at high frequencies. In this case data has to be extrapolated. The manner adopted to extrapolate the data has to be the same for all parties.

4.8 OPTIMIZATION METHOD

It should be reported to other parties how optimal designs have been obtained. Using different optimization methods introduce different convergence issues problems. For gradient based optimizations the optimal topology depends on the initial starting point that was chosen (local optimum), whereas a parameter sweep ensures a global optimum to be found at the expense of increased computation effort. Convergence issues as a result of the applied method should be addressed.

4.9 END TURNS

An analytical equation has to be formulated that describes the dimensions of the end windings of the phase coils. By using the same equation for the end turn volume the active axial length is estimated in the same way for all three motor designers. It has to be noted that for different winding technologies different expressions can be used.

4.10 PRACTICAL LIMITATIONS WITH RESPECT TO SENSING AND DATA ACQUISITION

Finally, the impact of sensors being non-ideal, limited bandwidths, the sampling frequency amongst others has to be evaluated. The practical implementation has to be taken into account in the system model, i.e. limited bandwidths of sensors must be included in the system model.

5 EVALUATION CRITERIA

It is evident that all the requirements of the previous chapter should be met for all three designs. However, the choice for the motor type which will be selected for prototyping is predominantly dictated by additional distinctive characteristic and features that are evaluated for the final designs. These evaluation criteria are provided in this chapter.

5.1 EFFICIENCY MAP AND WEIGHTED EFFICIENCY

Due to the highly dynamical load profile it is not straightforward to define a required fixed efficiency or minimal efficiency map over the full operating range of the machine. Nor is it practical to design for a required efficiency map in combination with the required speed-torque curve. Therefore, the efficiency map is considered an evaluation criterion. The efficiency map should be evaluated for a fixed set of operating points within the speed-torque characteristic. The efficiency map allows the weighted efficiencies as result of different drive cycles to be calculated (done by LMS). The required resolution of the map and the evaluated weighted efficiency are given in Table 27 and Table 28, respectively.

Quantity	Value	unit
$\Delta\omega$		rpm
ΔM		Nm

Table 27: Resolution of the efficiency map

Quantity	value to be evaluated	unit
$\bar{\eta}_{\mathrm{orsrm}}$		%
$\bar{\eta}_{\mathrm{synrm}}$		%
$\bar{\eta}_{\mathrm{fsm}}$		%

Table 28: Evaluated average efficiency over the drive cycle

5.2 MASS AND/OR VOLUME OF THE MOTOR

Mass is a very important aspect in automotive applications, since each reduction in mass leads to an increased overall efficiency and, therefore, increased driving range. Furthermore, the cylindrical volume of the motor is also an important issue with respect to the amount of mounting space being available. The axial height of the cylinder is determined by the active length (including end-turns of the phase coils) of the motor stack. The evaluated mass and volume are respectively given in Table 29 and Table 30

Quantity	value to be evaluated	unit
m_{orsrm}		kg
m_{synrm}		kg
m_{fsm}		kg

Table 29: Evaluated motor mass

Quantity	value to be evaluated	unit
V_{orsrm}		m^3
V_{synrm}		m^3
V_{fsm}		m^3

Table 30: Evaluated motor volume

5.3 COSTS

In the automotive industry a less technical criterion, but crucial nonetheless, is the cost in euros of a specific technology. A distinction can be made between the total raw material costs based on the material costs per unit mass (Table 31), technological expenses for (series) manufacturing (Table 32) and costs for the drive (Table 33). Where the costs for materials and electric components can be relatively accurately determined in advance; the manufacturing cost, however, are much harder to predict. Still, it is desired to have a well-founded estimate of the production cost of each motor type. By mutual agreement a calculation method for estimating the total costs has to be defined in chapter 6. Moreover, an estimate of investment cost should be provided to enable an assessment to determine whether a certain technology is not only technically, but also economically viable (Table 34).

Quantity	value to be evaluated	unit
$C_{\mathrm{mat,orsrm}}$		€
$C_{\mathrm{mat,synrm}}$		€
$C_{\mathrm{mat,fsm}}$		€

Table 31: Estimated material costs

Quantity	value to be evaluated	unit
$C_{\mathrm{man,orsrm}}$		€
$C_{\mathrm{man,synrm}}$		€
$C_{\mathrm{man,fsm}}$		€

Table 32: Estimated manufacturing costs

Quantity	value to be evaluated	unit
$C_{\mathrm{drive,orsrm}}$		€
$C_{\mathrm{drive,synrm}}$		€
$C_{\mathrm{drive,fsm}}$		€

Table 33: Estimated costs of the drive

Quantity	value to be evaluated	unit
$C_{\text{inv,orsrm}}$		€
$C_{\text{inv,synrm}}$		€
$C_{\text{inv,fsm}}$		€

Table 34: Estimate of investment costs

5.4 ACOUSTIC NOISE

Currently, Punch Powertrain applies a switched reluctance machine in their electric and hybrid drive trains where the reduction of acoustic noise inherently poses a serious challenge. The complexity associated with calculating the acoustic noise emitted by a motor and the subjectivity with respect to the perception of noise by the human ear make the quantification of ‘how much noise is being emitted by the motor’ troublesome. Still, a comparison between the three topologies has to be conducted and quantified. For the final designs an elaborate acoustic analysis is conducted by LMS in work package 3. A reduced model – coarse model – should be provided by LMS that the machine designers can use during their optimization, in order to enable the machine designers to roughly quantify the acoustic noise levels. Details regarding this model are to be defined.

5.5 OBJECTIVE AND WEIGHTING FACTORS

Certain requirements might be easier met for a given motor topology than for another. Therefore, it is not evident to set the weighting factors of the objective to be optimized to equal numerical values. Instead the weighing factors are applied during the evaluation stage to compare the different machine types. Values for the weighting factors should be recorded in Table 35.

Weighting factor	Value
Efficiency	
Mass	
Volume	
System costs	
Investment costs	
Acoustic noise	

Table 35: Weighting factors

6 DESIGN DOCUMENTATION

To facilitate a quantitative comparison between machine types and a decent transfer of information some specific technical deliverables are to be provided by each of the partners

6.1 DATA WITH RESPECT TO KEY PERFORMANCE INDICATORS

The findings and conclusions of the evaluation stage have to be reported. The report must contain the findings in regard to all evaluation criteria mentioned in chapter 3, except for the evaluation criterion with respect to acoustic noise. The three individual reports will be merged into one report by Punch that afterwards will be distributed to all parties. Based on the contents of this report one of the three machine type will be selected for prototyping.

6.2 DESIGN AND SIMULATION MODELS

The following models that were used during the design of each motor type must be made available to all parties for verification purposes:

- The system model as discussed in section 4.1
- Final electromagnetic FEM model of all three optimized topologies
- The thermal model of each topology
- Cost information
- A list of electrical and mechanical key components

6.3 TRANSFER OF INFORMATION TO SUBSEQUENT WORK PACKAGES

To ensure a smooth exchange of essential data and information from one work package to the next, it is imperative that all relevant information obtained in a work package is neatly archived and being made available to the partners in charge of the work to be conducted in the next work package(s). The contents of the archive are to be determined on a mutual agreement between the parties delivering the data and the parties receiving it. For work package 2 specifically the following information is to be transferred to subsequent work packages:

- Requirements for power electronics (input for WP4)
  - Results of work in WP2;
  - What is the preferred form ProDrive needs to receive the information in.
- 3D CAD Model
- Specific requirements for mechanical integration (input for WP3)

7 LIST OF FILES

- T2.1_Data.xls