Design, manufacturing, and validation of ecocycle electric traction motor

Call topic: **HORIZON-CL5-2022-D5-01-09**

Grant Agreement n° **101096557**

Funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

D4.1: Preliminary motor specifications

Lead Author: **Antti Tarkiainen, DAN**

with contributions from: **Juha Pyrhönen, LUT,
Ilya Petrov, LUT,
Lasse Laurila, LUT,
Dieter Zeppei, BWSE,
Rok Podobnik, HIDRIA,
Damijan Miljavec, UL,
Sergii Shlyk, KRNU,
Mathieu Sarrazin, SISW,
Janne Keränen, VTT,
Jenni Pippuri-Mäkeläinen,
VTT**

Reviewed by Markus Brunk, BOSCH and Mehrnaz Farzam Far, VTT

Deliverable nature	R - Document, report
Dissemination level	PU - Public
Contractual delivery date	M3 / 30 Apr 2023
Actual delivery	M5 / 16 Jun 2023
version	v1.0

Version history

Version	Date	Editors	Description
v0	06 Apr 2023	Jenni Pippuri-Mäkeläinen, VTT	Template for the deliverable created
v0.1	18 Apr 2023	Juha Pyrhönen, LUT	Preliminarily filled template
v0.2	10 May 2023	Ilya Petrov, LUT	Various additions to, e.g., motor

		Lasse Laurila, LUT	specification
v0.2	10 May 2023	Antti Tarkiainen, DAN	Inverter data and considerations
v0.2	10 May 2023	Dieter Zeppei, BWSE	Various additions to, e.g., transmission
v0.2	10 May 2023	Rok Podobnik, HIDRIA	Amendments to electrical steel sheets and lamination stacks
v0.2	10 May 2023	Damijan Miljavec, UL	Amendments and comments on electrical motor requirements and specifications
v0.2	10 May 2023	Sergii Shlyk, KRNU	Amendments to the cooling system
v0.2	10 May 2023	Mathieu Sarrazin, SISW	Driving cycle and NVH information
v0.3	16 May 2023	Janne Keränen, VTT	Version of consortium internal review
v0.3	24 May 2023	Jenni Pippuri-Mäkeläinen, VTT	Small amendments before consortium internal review
v0.3	01 Jun 2023	Markus Brunk, BOSCH	Internal review
v0.4	12 Jun 2023	Mehrnaz Farzam Far, VTT	Internal review and updated template
v1.0	16 Jun 2023	Jenni Pippuri-Mäkeläinen, VTT	Update on first three pages, final check, and submission in the commission portal

Abstract

The key features of the VOLTCAR traction motor are described in the document. First, we summarise the general drive train requirements stemming from the application of passenger cars or vans. Next, we present the requirements and detailed specifications and characteristics for the VOLTCAR traction motor. This document will be a living document that is updated frequently during the project's lifetime. It was not possible to define the numeric values of some of the key features at this point since the project started in Feb 2023 and the work is very much in progress between the different consortium partners.

The original submission deadline for this deliverable was at the end of Apr 2023. The small delay in the actual delivery, in the middle of Jun 2023, is not expected to impact the project execution onwards.

Publishable Summary

A high specific-power (7 kW/kg) and power-density (>23 kW/l) traction motor with minimum or no rare earth materials is designed to be applied in passenger cars or light commercial vehicles (vans). The motor rated power will be 120 kW. Its total mass including housing can therefore be maximally 17.14 kg. Its volume must be below approx. 5 litres. The motor is based on the synchronous reluctance motor principle with some (or possibly no) permanent magnet assistance.

To achieve the high specific power target, a higher rated speed is needed, resulting in the motor operating at a speed higher than what has been observed in commercial vehicles thus far. The motor rated speed is expected to be in the range of 10-12 krpm, with a maximum speed below 24 krpm for a permanent magnet assisted synchronous reluctance machine. The high-power density of the motor calls for a very effective cooling. A direct oil cooling system will be developed for the stator core and stator winding. If no magnets are finally used, the speeds of the machine must most likely be increased.

Despite the stand-alone prototype machine, the target is that the motor could later after the project be integrated with a step-down gearbox and with a converter so that a common bearing system and common cooling system can be based on circulating the gear lubrication via a heat exchanger, power electronic converter, electrical motor, and the gear itself.

<u>This deliverable presents the key features of the VOLTCAR motor, from the requirements of the vehicle applications to the requirements and specifications of the motor itself. This document will be a living document that is frequently updated during the project execution.</u>

Table of Contents

Table of Figures

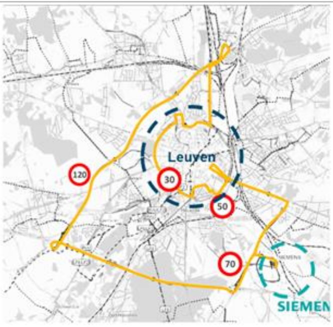
Table of Tables

1 Introduction

The main objective of this document is to bring all consortium members on the same line and increase mutual understanding of the project targets. This document will serve as a guideline for all developments. In case needed, it will be updated and amended during the project execution to present the latest status and targets. The document is composed of five main sections: drive train requirements, electrical motor (E-Motor) requirements and specifications, subcomponent requirements, interfaces to external components, and additional requirements mandatory for serial production.

2 Drive train requirements

Action	Response
Analysing the performance requirements of selected representative pure electric vehicles (EVs) to define the torque and power needed from the electrical machine.	Grant Agreement (GA) specifies the power range for the VOLTCAR electrical motor. Tesla Model 3 motor has been chosen as a reference. Motor rated power is 120 kW (at rated speed 10-12 krpm) and maximum power ca. 200 kW for a few seconds operation at the rated speed. The machine should be capable to provide power needed for traction at the maximum speed, e.g., 24 krpm.
Defining the requirements for the peak and continuous torque, along with gear ratios for a drive module (motor and gear) and basic requirements for the converter.	The rated torque of the motor is T_n = (95.5-114.5 Nm) depending on the rated speed. The maximum short-time operating torque at low speeds is ca. 2 x T_n. The gear ratio will define the torque at wheels and the maximum vehicle speed. Adaptation to the vehicle maximum speed depends on the maximum targeted vehicle speed. There may be different alternatives of the motor, one for max 160 km/h speed and another for max 200 km/h speed. The maximum speed affects the mechanical design of the rotor.
Defining the selected duty cycle for a detailed evaluation of the integrated drive module design.	Typical driving cycles (e.g., ECE-15 (NEDC part 1), EUDC (NEDC part 2), and HWYCOL (Highway Fuel Economy Test)) have been shared and can be used. In the past, SISW has measured realistic EV driving cycles with different slopes, curves, and speed limitations:

	 BWSE, DAN, LUT, HIDRIA, UL, KRNU, SISW, and VTT will select the most representative duty cycles from a pool of standardised and realistic terrain driving cycles (resting on, e.g., typical operating range of light-duty vehicle, slope curvature, speed limitations). Results of this work will be reported in deliverable D4.2. The motor performance will be checked for the selected duty cycle(s) when the feasible motor design is approved.

3 E-Motor requirements and specifications

3.1 General definitions

3.1.1 Physical elements

The VOLTCAR prototype E-Motor shall as a minimum include the following features/parts:

a) E-Motor active hardware (stator stack, stator windings, permanent magnet assisted synchronous reluctance machine, PMaSynRM, (or synchronous reluctance machine, SynRM) rotor, electrical connections).
b) Housing to enclose E-Motor, containing cooling arrangement and means for mounting.
c) Bearings to support the rotor.
d) E-Motor rotor shaft including transmission coupling interface.
e) Resolver and connector.
f) Stator winding temperature sensors and connector.
g) Three-phase AC power cable connection harness for the prototype from the project, later direct connection to the inverter can be considered.
h) Three-phase mobile cable directly attached to the motor non-drive (ND) end in the prototype from the project, later direct connection of the three phases to an integrated converter.
i) ¾” threads for cooling oil input and output in the prototype from the project. Later, integrated conduits to conduct oil via the power electronics cool plate, through the motor stator, and via the rotor shaft to the gearbox, pump, and heat exchanger.
j) Warning and identifications markings and labels according to automotive standards.

3.1.2 Physical appearance

The initial prototype should be a standalone motor (without integration options). Therefore, the housing structure should be simple and lightweight, e.g., made of aluminium (to fit the weight requirements). It can be in the form of a cylinder. One side of the machine should include the position sensor. Since the hollow shaft and the main machine body are going to have oil circulation (for cooling and lubrication purposes), the complete motor body is going to be sealed and enclosed by an oil circulating system.

3.1.3 Functional elements

The E-Motor subsystem shall provide the following functions:

a. Convert electric energy, applying three-phase AC current, into mechanical energy by producing desired torque at desired speed keeping the E-Motor temperature at acceptable levels. The motor shall be capable of providing high-enough excess torque during accelerating and braking, i.e., ca. 2 x T_n.
b. Convert mechanical energy back to electrical energy through regenerative braking.
c. Include in- and outlets for liquid cooling.
d. Provide adequate stator winding insulation from the stator stack according to IEC 60034-1 and 60349-2 / 60439-4.
e. Provide adequate insulation between the stator winding potential and the temperature sensors according to IEC 60034-1 and 60349-2 / 60439-4.
f. Provide adequate insulation of the core from the E-Motor temperature sensors according to IEC 60034-1 and 60349-2 / 60439-4.
g. Indicate stator windings temperature by using at least three PT100 sensors next to the stator winding by arranging a suitable cavity in three stator teeth outside the mainwall insulation.
h. Indicate rotor to stator orientation with a resolver, however, this machine should enable high accuracy also with signal injection method because of the high saliency.
i. Provide structural support for the E-Motor to be able to couple it to BWSE (BorgWarner) gear or to a test stand. In the future, in possible post-VOLTCAR project, all parts should be integrated into one unit. In that case, the unit needs supporting parts so that it can be assembled in an EV.
j. Thermal, speed, and balance levels should be agreed upon by WPs. The first estimates are: 1) Stator insulation class 180 Degrees C is required; 2) motor rated speed 10 000 – 12 000 rpm and max operating speed 20 000 rpm or 24 000 rpm resulting in vehicle maximum speed of 160 km/h and 200 km/h, respectively; 3) rotor balancing better than 1g.

3.2 Mechanical specifications

3.2.1 Package dimensions

Table 1. Package dimensions.

	Unit	Requirement	Comment
Housing outer diameter	mm	≤ 150	The housing is simplified (stator cooling is arranged in the lamination) to occupy less space. In case of SynRM, < 160 mm.
Housing total length	mm	≤ 270	

3.2.2 Speed limits

Table 2. Speed limits.

	Unit	Requirement	Comment
Max. speed for full performance	rpm	24 000 (n_{max})	Full operation, no deformations allowed, failure not allowed. Can be higher in case of SynRM.
Spinning speed	rpm	($n_{max} \cdot 1.2$)	No permanent deformations and influence on performance allowed between max. speed and spinning speed

3.2.3 Mass specification

The motor operates at a max speed of 20 000 or 24 000 rpm depending on the version. This dictates that the mechanical design of the rotor must be optimised to ensure that the stresses due to centrifugal forces are kept at a minimum without detrimental effects to the motor mechanical performance. The need to recycle the magnets requires that aluminium or other applicable material is used to encapsulate the magnets to allow easy recyclability. Despite their benefits, allowing encapsulated magnets in the motor brings challenges in minimising stress concentrations at the rotor lamination support. Using alternative means of recycling the magnets will ensure improving the mechanical integrity of the rotor.

Table 3. Mass specifications.

	Unit	Requirement	Comment
Max. mass of stator assembly	kg	TBD	Incl. lamination, copper, insulation system (papers, tubes, impregnation resin, potting material, etc.), terminal lugs, etc.
Max. mass of rotor assembly	kg	TBD	Incl. lamination, magnets, mechanical parts (e.g., press ring, safety ring, end caps) for fixation and balancing, without shaft
Max. inertia of rotor	kgm^2	TBD	Complete rotor assembly
Max. mass of active parts	kg	12	Containing rotor and stator assemblies
Max. total mass of E-Motor	kg	17	Active parts plus shaft, housing, and cooling parts inside the motor. Dry mass without cooling liquid. Derived from continuous specific power requirement of >7 kW/kg and continuous power rate (min. duration of ~30 mins) of 120 kW.

3.3 Performance specifications

3.3.1 Power limits

The motor must be capable of providing:

- 120 kW constant power for a minimum duration of ~30 min.
- 200 kW peak power in the rated speed region for 30 s.

3.3.2 Thermal limits

At continuous rated operational mode, the winding hot-spot temperature is expected to be in the range of 170 °C and having rotor maximum temperature below this value (in the range between 140 °C and 160 °C). At peak power operation, these temperatures could exceed for a short period of time.

At least during the early phases of the stator winding design, the following values could also be considered to have some margin: varnish 180 °C / slot 220 °C / wire 240 °C. A proper winding insulation class and permanent magnet grade must be chosen by considering these temperature ranges. The demagnetisation properties of rotor magnets at low temperature down to −40°C and hot temperature up to 150°C must be respected.

3.3.3 Short circuit condition

The short-circuit current is limited as the permanent magnet (PM) flux is very low.

3.3.4 Efficiency requirements

The motor can deliver efficiency higher than 93% within the high-power operating range.

3.3.4.1 Torque density

>23 Nm/litre.

3.3.4.2 Specific power

>7 kW/kg continuous 11.6 kW/kg peak.

3.3.5 Cogging torque

Lower than 1% of the peak torque.

3.3.6 Torque ripple

1st order torque ripple should be lower than 5% of the peak torque. Higher orders lower than 10% of peak torque.

3.3.7 Service life

Passenger car motor service life is 5 000 hours. Light-duty vehicle motor service life is 10 000 hours. The service life of the VOLTCAR E-Motor will settle between these values.

3.4 Active short circuit

3.4.1 General

Due to the limited PM material used in the rotor, at rated-speed and no-load, PM-induced phase back-EMF (BEMF) is quite limited and much smaller than the supply voltage (e.g., E_{PM} = 81 V).

The BEMF limit at max speed, under extreme (low) temperature condition, should not be higher than 1 200 VpeakAC in the worst-case scenario (no stator current).

3.4.2 Short circuit persistency

Steady state short circuit current less than the peak current and the transient short circuit current less than 2x of the peak current are allowed for the motor.

3.4.3 E-Motor component protection

To be defined later.

3.5 Electrical boundaries

The E-Motor shall be a 3-phase motor driven by an inverter with sinusoidal space vector pulse width modulation (SVPWM) (modulation index < TBD; end of linear area with blanking time; modulation index < TBD) and field-oriented control (FOC) with implemented maximum torque per ampere (MTPA) motor control algorithm.

The following table shows the electrical boundaries to achieve the required full performance.

Table 4. Electrical boundaries.

	Unit	Requirement	Comment
E-Motor max. fundamental frequency	Hz	1 600	Depending on maximum speed and pole number of E-Motor
Inverter max. PWM frequency	kHz	30	
Max. line-to-line voltage	V_{rms}	TBD	at minimal DC link voltage (TBD VDC)
		TBD	at minimal DC link voltage for full performance (TBD VDC)
		TBD	at nominal DC link voltage (TBD VDC)
		520	at maximal DC link voltage (796 VDC)
E-Motor phase current, maximum	A_{rms}	500	For 30 sec
E-Motor phase current. continuous	A_{rms}	300	
dV/dt	kV/µs	TBD	Voltage switching speed, insulation quality has to withstand (with higher frequency losses in inverter can be reduced)

3.6 Environmental boundaries

3.6.1 Ambient environment

The motor must be capable of operating between −40 °C and +50 °C at sea level in normal air pressure and high humidity. The IP67 protection class should tolerate even short-term immersion in shallow water. Relevant standards include IEC 60034-1 and 60349-2 / 60439-4.

3.6.1.1 Altitude

The motor must be capable of operating in environments up to 3 km altitude. In this case, the higher operating temperature is limited to +30 °C.

3.6.2 Normal operating environment

The optimal operating environment is between −30 °C and +40 °C in normal air pressure at altitudes lower than 1000 m.

3.6.3 Extreme operating environment

Operating outside the normal operating temperature between −30 °C and +40 °C or at altitude higher than 3 000 m.

3.6.4 Non-operating environment temperature

When temperature is not in the range between −40 °C and +50 °C the motor torque and speed are limited to 70% of the rated values.

3.7 Ingress protection (IP-Code)

In automotive applications, the ingress protection code and classification IP67 is the most common one as it provides sufficient protection against dust and water. The first number 6 refers to "dust-tight" meaning "No ingress of dust; complete protection against contact (dust-tight)."; the second number 7 refers to "immersion, up to 1 meter (3 ft 3 in) depth" meaning "Ingress of water in harmful quantity shall not be possible when the enclosure is immersed in water under defined conditions of pressure and time (up to 1 meter (3 ft 3 in) of submersion)."

3.8 Corrosion protection

The motor housing will be built from an aluminium alloy, which itself is corrosion resistant but does not tolerate highly corroding environments like salty water. Therefore, the housing must be painted with two-component epoxy varnish. The bearing shields will be equipped with O-rings to make the whole housing fluid tight as of ISO 20653 IP67.

3.9 Tolerances

The housing must be manufactured accurate enough to enable high-speed spinning of the bearings. The bearings will most probably be angular-contact ball bearings that need very accurate alignment of the bearing housing and correct pre-tensioning to enable safe operation at a high speed.

4 Sub-components requirements

4.1 Permanent magnets

The permanent magnets should sustain high and low temperatures and demagnetising fields without being partially or totally demagnetised. The magnets should also have high intrinsic coercivity (Hci) preventing the demagnetisation from the stator side by electric currents. Magnets should be protected to withstand dismantling forces to enable the reuse of magnets.

4.2 Lamination

When it comes to the lamination for the E-Motor's rotor and stator, the consortium must address two issues:

1) Motor magnetic circuit lamination materials must be selected according to manufacturing capabilities and loss performance to enable low-cost manufacturing and acceptable low losses during operation.

2) Bonding/gluing techniques need to be chosen to achieve the desired stack properties – especially regarding rotor stack properties – to meet the operational mechanical and structural properties of the motor.

LAMINATION ELECTRICAL STEEL:

HIDRIA sources el. steel lamination from multiple suppliers. El. steel has various properties which are usually considered when choosing the specific steel type and supplier, i.e., 1) el. steel thickness, 2) el. steel material type (usually NO20, NO27), el. steel mechanical properties (el. resistivity, thermal conductivity, etc.), and 3) el. steel magnetic properties (specific total loss, peak magnetisation, etc.).

Some industrially used el. steel considered suitable for VOLTCAR rotors includes:

SUPPLIER	Steel type	El. steel thickness	Max. total losses at 1.0 T and 400 Hz
ThyssenKrupp	Powercore® 020-130Y320	0.20 mm	Max. 13 W/kg
ThyssenKrupp	Powercore® traction 027-140Y420	0.27 mm	Max. 14 W/kg
Tata Steel	Hi-Lite grade NO20-1200H	0.20 mm	Max. 12 W/kg
Tata Steel	Hi-Lite grade NO20-1400H	0.20 mm	Max. 14 W/kg
Arcelor Mittal	Save 27-14	0.27 mm	Max. 15 W/kg
C.D. Waelzholz	NO20-13	0.20 mm	Max. 13 W/kg
Voestalpine	Isovac high-perm NO27-14 Y420	0.27 mm	Max. 14 W/kg

BACKPLATE:

A 3D design of the rotor is to be done. The rotor consists in principle of modules that have flux guides and backplates to support them. The backplate material must be non-magnetic and have high yield stress. One possible strong backplate material is Outokumpu's Forta H 1000.

BONDING/GLUING:

When discussing different technologies used for joining separate rotor/stator laminations to form a stack, three technologies are possible that HIDRIA usually uses in EV/heavy electric vehicle (HEV) applications:

Technology type	Technology description	Advantage	Disadvantage

Backlack	Self-bonding technology based on a specialised varnish surface of electrical steel, which enables the joining of laminations into a stack through thermal curing.	Industrial standard in automotive, very reliable, very high mechanical stability, high magnetic properties (high saturation magnetic flux density, low magnetic coercivity), high thermal conductivity.	A bit pricier than older metal-rivet-based interlocking solutions.
Gluing	Hidria Bond®: bonding of lamination using glue added to each separate lamination.	Exceptional magnetic properties, high thermal conductivity.	Very pricy, not an industrial standard in automotive yet.
Interlocking	Joining of rotor/stator laminations using an array of metal rivets.	Very cheap, good mechanical stability.	Lower thermal conductivity, lower magnetic properties, high losses.

<u>ROTOR STACK PROPERTIES:</u>

In VOLTCAR, HIDRIA will produce stator and rotor stacks. While stator stacks usually follow a more standardised design, rotor stacks need to meet specifically designed limits. These are known as 'stacking factor' measurements, in which a rotor stack needs to clear certain thresholds to ensure its mechanical stability at high speed.

HIDRIA has an established stacking factor measurement standard with an established measurement process that meets the criteria set in the automotive supply chain and complies with HIDRIA's EV/HEV customers' demands.

Height measurement (credit HIDRIA).

Locations of height measurement (credit HIDRIA).

Tensile compression machine load cell (credit HIDRIA).

$$Sf = 1 - \left(\frac{dH}{H_0}\right)$$

Where $dH = H_0 - H$

H_0…Segment height

H… Segment height after 1 min of applying 10 kN of load

Equation used to calculate the stacking factor (credit HIDRIA).

Figure 1. Stacking factor measurements by HIDRIA. Pictures credit HIDRIA.

4.3 Insulation

a) The insulation shall be correctly dimensioned to ensure the reliability of the E-Motor over its entire service life (including being powered on the high voltage side).

b) Insulation system design requirements are described in standards IEC 60664-1 and ISO 6469-3:2011.

c) Class H 180°C (or higher) insulation material and varnish shall be used in the insulation of the E-Motor.

d) Insulation system qualification procedures are described in IEC 60034-18-42 “Partial discharge resistant electrical insulation systems (Type II) used in rotating electrical machines fed from voltage converters - Qualification tests”

e) The insulation system should withstand a voltage of at least 1.5x operating voltage, TBD kV

f) The insulation resistance should be at least TBD MΩ.

g) The E-Motor should use barriers and enclosures to prevent access to high voltage. These barriers and enclosures should have a minimum protection degree of IP67, as defined by ISO 20653:2013 - Degrees of protection (IP code).

4.4 High voltage grounding

The E-motor housing is reliably connected to protective earth (PE) with 50 mm^2 yellow-green grounding cable in lab tests and car chassis in the case of automotive use. Relevant standards include ICS 29.160.01 “Rotating machinery in general” and UN ECE R100 and ISO 6469.

For mitigating shaft currents and for bearing protection, the option of a shaft grounding ring must be considered. The shaft grounding ring will connect to the shaft of the motor via carbon brush contact. Typically, the axial and radial fibre frictional pressure are very low and not easily measurable. While selecting the shaft grounding ring, the materials and oil compatibility need to be ensured, based on the requirements of the sealing concept.

4.5 Electrical terminals and connectors

No terminals will be provided in the prototype. Later, if developed into an integrated unit, the motor will be directly connected to frequency converter.

4.6 Instrumentation

4.6.1 Position sensor

A position sensor is needed in the prototype E-Motor. End shaft magnetic encoder is proposed. The encoder resolution must be compatible with the variable frequency drive/inverter having a reasonable resolution per one shaft revolution. The encoder will be positioned on the non-drive end (NDE) outside the housing. The sensor should have enough pulses to detect torsional vibrations.

More detailed specifications of the sensor and its requirements and signals required for the appropriate sensor connection to the inverter will be added later.

4.6.2 Temperature sensors

For a productised E-Motor, at least three PT100 sensors must be embedded in the stator winding to measure the temperature distribution within the winding. Preferable is to have at least one at each end-winding and if possible, at least one in the stator slot. All positions must be clearly marked in the drawings.

In the VOLTCAR prototypes, at least six pieces of PT100 sensors will be installed in the stator winding (two pieces per stator phase). At least one PT100 sensor will be embedded inside the stator slot and one mounted for the stator core. Ways to measure the rotor temperature will be considered, too.

More detailed specifications of the sensors and their requirements and the signals required for the appropriate sensor connection to the inverter will be added later.

4.6.3 Extra sensors for prototype demonstrator

In the demonstrator, we need PT100 sensors also inside both end windings, i.e., 2 x 3 additional sensors to provide a good view of the temperature distribution in the end-winding region as a hot-spot area. Also, at least one sensor should be placed inside the stator slot and one for the stator core. All these sensors will allow us to properly control the motor in terms of load-ability and over-load-ability as well as to validate the motor’s digital twin. Additional sensors (acceleration sensors, microphones, thermal sensors, voltage and current sensors, laser-based sensors) will be mounted on the motor during the experimental testing.

4.6.3.1 Sensors for validation of the digital twin

Additional sensors (acceleration sensors, microphone, voltage and current sensors, thermal sensors, laser-based sensors) will be mounted on the motor during the experimental testing (static, dynamic, transient, operational...), also for the purpose to validate the E-Motor digital twin.

5 Interfaces to external components

5.1 Interfaces E-Motor to transmission

The prototype E-Motor will be attached to a gearbox. There will be a mechanical high-speed coupling between the motor shaft and the gearbox input. BWSE must provide exact data about the connection to its gearbox. Both units, E-Motor and gearbox, will have their own housing, bearings, lubrication, and cooling.

The E-Motor will have two bearings, one at the drive side and one for the non-drive end in the case of the prototype. Later, in post-VOLTCAR project, integrating motor housing and gearbox into a same unit might enable using just two bearings for the whole high-speed shaft including both the E-Motor rotor and the high-speed cogwheel of the gear.

The BWSE gearbox has a ratio of 11.7, max input torque 385 Nm, max speed 24 000 rpm (limited by bearings and seal).

5.1.1 Flange connection

The E-Motor shall have a flange connection to the transmission. BWSE will provide the dimensions of the gearbox connection.

5.1.2 Shaft connection

BWSE will provide the dimensions of the gearbox connection. The dimensions of the shafts and connections shall match.

5.2 Interfaces E-Motor to inverter

5.2.1 AC phases

To summarise, the following aspects need to be considered in regards of the AC phases:

a) Three-phase mobile cables will be installed between the variable frequency drive/inverter and the prototype E-Motor. For instance, 3x95 mm^2 Shielded HV Copper Core Cable could be used with a pressure contact system with bus bars pressed on contact areas of the inverter.
b) The maximum E-Motor phase current shall be fixed later. Current estimate 500 Arms.
c) The continuous E-Motor phase current shall be fixed later. Current estimate 300 Arms.
d) The maximum E-Motor phase voltage phase to phase shall be defined later. Maximum inverter operation voltage given shall be defined later.

e) The width of the contact area shall be defined later.
f) The length of the contact area shall be defined later.
g) The height tolerance of the connection shall be defined later.
h) The IP class of the mounted connection shall be IP67, IP6K9K to support the vehicle integration.
i) The IP class of the unmounted connection shall be IP00.
j) The protection measures shall be defined later.

Later, in post-VOLTCAR project, direct connection of the E-Motor windings into the converter terminals can be considered.

5.2.2 Mechanical interfaces

Inverter will be a standalone component, not integrated with the E-Motor. Integration of the inverter and E-Motor shall be considered after the project if productised further.

5.3 Interface E-Motor to cooling circuit

In short, the following requirements need to be taken into in the E-Motor cooling circuit development:

a) The E-Motor will be cooled with an oil coolant medium.
b) The E-Motor shall operate at continuous operating performance with nominal coolant inlet temperature and flow rate.
c) The nominal coolant inlet temperature shall be defined later.
d) The nominal coolant flow rate shall be defined later.
e) There will be ¾"oil connections at both ends of the motor.
f) More detailed specifications of the connectors will be specified later.
g) The pressure drop of the E-Motor shall be defined later.
h) Details of the heat extraction from the cooling medium will be defined later.
i) Based on the results obtained, a system of climatic zones acceptable for the normal operation of the E-Motor will be developed.

Later, in post-VOLTCAR project, full integration of the cooling fluid flow in the system shall be considered.

5.4 Interface E-Motor to powertrain cradle or frame

During the VOLTCAR project, the E-Motor system will be connected to the BWSE gearbox and a test bench for conducting the different measurements. The motor stand-alone measuring test rig should be prepared to validate the developed E-Motor performance.

Later, in post-VOLTCAR project, full integration in a car/van shall be implemented.

6 Additional requirements (only mandatory for serial production)

This section presents the requirements that are mandatory only for serial production, as a reference and guidelines for the E-Motor development. However, for instance, the testing regimes involved will not be followed to the letter during the VOLTCAR project. If serial production is entered after the project, they naturally need to be followed.

6.1 Electromagnetic Compatibility (EMC)

The motor design should provide acceptable operating conditions for the bearings from the bearing currents perspective. However, the 5 000-h lifetime may be so short that no special means to prevent bearing currents are needed. The fluid-tight housing and normal mobile cables with concentric protective earth and 360-degree grounding should guarantee inherent EMC compatibility of the motor.

With respect to regulations and standards, as a reference, if serial production is entered after the project:

a) The European directive UN ECE R10 and the requirements listed in CISPR 12 should be followed.
b) In addition, the following standards should be followed for components connected to the high-voltage power system:
    - ISO 7637-4 Road Vehicles – Electrical disturbance by conduction and coupling – Part 4: Electrical transient conduction along shielded high voltage supply lines only.
    - CISPR/D/425A Test method for shielded power supply systems for high voltages in electric and hybrid vehicles.
    - GB/T 18387 Limits and Test Method of Magnetic and Electric Field Strength from Electric Vehicles, Broadband, 9 kHz to 30 MHz.

6.2 Noise, Vibration, and Harshness (NVH)

Audible E-Motor noise and vibrations highly influence the perceived vehicle quality and comfort inside an EV. Thus, the noise and vibration profiles should be measured and reviewed focussing on, e.g., resonance frequencies, magnetic noise depending on the air gap, noise related to stator rotor motor slot design, and torsional vibrations. Different techniques and sensors exist to perform those assessments. The best sensor can be selected for each individual case based on the physical quantity, the type of analysis, the accessibility of the shaft, the ease of instrumentation, and the required accuracy or level of detail.

An example of a final classification that could be used in a subjective evaluation of noise and vibration is presented in Table 5.

Table 5. Example of classification of subjective evaluation of noise and vibration.[1]

Level	1	2	3	4	5	6	7	8	9	10
Opinion	Unacceptable				Acceptable transition stage		Acceptable			
Accepted object	All customers	Majority of customers			Critical customers			Trained people		

To be able to judge this subjective evaluation, sound quality metrics can be used. This allows you to make an analysis in terms of loudness, sharpness, tonality, or modulation in order to understand and quantify sound.

Additionally, as high efficiency and low noise radiation do not always go hand in hand, an ideal trade-off between the two is necessary.

Finally, a lot depends also on how the E-Motor will be integrated into the drivetrain (mainly in combination with an inverter that generates pulse width modulation (PWM) noise) and inside the vehicle. Structural and acoustical paths are important.

6.2.1 Noise

As noise is closely connected to vibration, coupled analyses (electromagnetic, structural, and emitted air pressure from housing) should be done in combination with real measurements. In general,

a) Noise and sound from the E-Motor should follow the European directives UN ECE R51 and 540/2014.
b) Noise emitted from the E-Motor should be limited as specified in ISO 362-1.
c) The E-Motor should not produce any audible transient or impulsive noises or characteristic tones that the customer would consider unusual, objectionable, or a cause for concern about the vehicle integrity. Unusual noises should not get a subjective rating lower than 7 (Table 5) under all driving conditions.
d) Care should be taken that the E-Motor excited noise does not radiate via the housing structure.

6.2.2 Vibration

Coupled electromagnetic and structural optimisation should be intensively executed by using 2D/3D finite element calculations during the motor design process. High electromagnetic forces are expected due to high phase currents in relatively small volume, leading to a high-power density of the designed motor. Natural frequencies should be analysed due to possible interaction with electromagnetic

[1] Jian Qiang Xiong, Research on Subjective Rating Attenuation Analysis of Automobile NVH Characteristics, Procedia Computer Science, Volume 154, 2019, Pages 383-388, ISSN 1877-0509, https://doi.org/10.1016/j.procs.2019.06.055.

excitations. The influence of other motor's components (shaft, housing, windings...) should be analysed in terms of vibration. In short,

a) The E-Motor should not produce any transient, impulsive, annoying, or steady state vibration disturbances that the customer would consider unusual or a cause for concern about the vehicle integrity. Vibration levels should not get a subjective rating lower than 7 (Table 5) under all driving conditions.
b) The attachment of the E-Motor to the supporting cradle or mount brackets should be such that the E-Motor vibration is not amplified when transmitting to the surrounding structure. It should neither allow vibration modes where the main strain region is found around the attachment. To achieve this, the stiffness should be as high as possible, and the attachment footprint should be distributed in an appropriate way.
c) The E-Motor should be designed to minimise the risk of rattle, however considering the overall intent.
d) Radiation of E-Motor should not only be checked on a component level but also how it will be implemented in a (sub) system.

Measurement validation is required to reduce the gap between simulations and reality.

6.2.3 Harshness

Harshness is a subjective assessment that refers to the quality of being unkind or severe. To enhance consumer satisfaction, sound quality metric analyses are required in such a way that it not only satisfies 'noise' legislation. Psychoacoustic measurements enable both objective and subjective assessments. Even at the same sound pressure levels, microphone recordings can be very different from the levels perceived by the human ear. A microphone can measure the sound pressure levels (SPL) but will not consider the subjective preference of a human brain. Words such as whine, squeak or rattle are rarely associated with a robust and good quality item, regardless of if it is a white good or a car.

6.3 Safety

6.3.1 General safety

The prototype E-Motor shall create no mechanical threat to testing personnel or human beings in, e.g., a car or van. After the project, if serial production is entered

a) The E-Motor should meet the safety inspection requirements stated in EU Directive 2014/45/EU and 2014/47/EU.
b) The E-Motor should fulfil the post-crash safety requirements specified in ISO 6469-4.

6.3.2 Electrical safety

No electric shock danger shall be created by the motor for testing personnel, users, or maintenance personnel. In more detail, the relevant regulations and concerns include:

a) The E-Motor should meet the safety requirements specified in ICS 29.160.01 and EC regulation UN ECE R100 and 661/2009.

b) The High Voltage Interlock (HVIL) signal connections should withstand at least 1 A current and 12–14 V voltage.
c) The E-Motor should loop the HVIL internally, only a disconnected HV connector should break the HVIL.
d) High voltage shall not be accessible without removal of covers.
e) Unplugged high voltage connectors should have a minimum protection of IP 23 according to IEC 529 (no direct access with finger) on the power source end.
f) Any high voltage cabling in the design (DC or AC) shall meet the requirements in ISO 6722 and 14572.

6.3.3 Functional safety

The motor must tolerate all stresses caused by operating it in a car or a van. Specifically, Automotive Safety Integrity Level (ASIL C) classification according to ISO 26262 is required.

6.4 Reliability requirements

The planned mean time before failure should be in the range of the expected lifetime of the motor in car operation, i.e., mean time between failures (MTBF) = 5 000 - 10 000 h. In more detail, for instance, the following procedure could be followed:

a) Reliability assessments shall be done for a defined Reliability Evaluation Point (REP). REP can be expressed by kilometres driven by a customer and hours of environmental exposure.
b) Customer usage profile shall be defined and used together with REP for analysis. This customer usage profile can be characterised by, e.g., the number of start-up events and the total run time in hours.
c) Reliability demonstration profiles shall be consistent with the chosen customer usage profile (loads, cycles, etc.).
d) E-Motor shall have a demonstrated test reliability of TBD% or greater under the REP of the chosen customer profile.
e) The test reliability shall be demonstrated at a confidence level of TBD%.
f) The E-Motor reliability shall be tested according to ISO/CD 21782-6.

7 Conclusions

The ambitious targets of VOLTCAR, providing a prototype of a compact, energy-efficient, and affordable motor, with a very low amount of recyclable permanent magnet material, require balancing between partly contradicting aspects. In this deliverable, the latest status of the VOLTCAR electrical motor requirements and specifications is presented. This document is a living document and will be updated frequently as the project progresses. Further, together with an associated consortium confidential Excel, it will be the main guideline for the VOLTCAR motor developments. All targets listed will always be in line with the Grant Agreement.