Rare Earth Free e-Drives Featuring Low Cost Manufacturing

ReFreeDrive

Collaborative Project
Grant Agreement Number 770143

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Document version	**Date**	***Modified sections - Details***
V1.0	25.03.2021	First draft
V2.0	16.04.2021	Rework following the technical and quality review
V3.0	07.05.2021	Rework following PO feedback
V4.0	27.07.2021	Update with FR IM motor testing progress
V5.0	03.09.2021	Update with FR IM motor testing progress

Table of Contents

Abbreviations

GA: Grant Agreement

WP: Work Package

RFD: ReFreeDrive

KPI: Key Performance Indicators

PMa-SynRel: Permanent Magnet (ferrite) assisted Synchronous-Reluctance motor

Pure-SynRel: Pure Synchronous-Reluctance motor

FR-IM: Fabricated Rotor Induction Motor

DC-IM: Die Casted rotor Induction Motor

SiC: Silicon Carbide

PE: Power Electronics

JLR: Jaguar Land Rover

UAQ: University of L'Aquila

MDL: Motor Design LTD

Back-EMF: Back Electromotive Force

rpm: Revolution Per Minute

WBG: Wide Band Gap

WLTC: Worldwide Harmonized Light Vehicles Test Cycles

DoA: Deed of Agreement

1 Executive Summary

The current report relates to the activity carried out in Work Package 7 - Task 7.1 aiming at characterizing 4 motor topologies associated to Silicon Carbide (SiC) module-based power electronics in 2 track forms: medium and high-power range each.

According to the ReFreeDrive Grant Agreement (GA) document, the main objective of the Task 7.1 is to validate and characterize at IFP Energies nouvelles (IFPEN) bench 8 motors with associated Power Electronics (PE), control and cooling systems manufactured within the Work Package (WP) 6 framework. This experimental activity is supported by University of L'Aquila (UAQ) for the control of Pure Synchronous-Reluctance motor (Pure-SynRel), Fabricated (FR-IM) and Die-cast (DC-IM) rotor Induction Motor, while Permanent Magnet (ferrite) assisted Synchronous-Reluctance motor (PMa-SynRel) control is implemented by IFPEN. This in order to provide experimental evidence of the developed technologies, validating the followed design methodologies and proving the motors performance (Key Performance Indicators (KPI) and results in accordance with Jaguar Land Rover (JLR) requirements).

COVID pandemics have had an impact on the task 7.1 with namely WP6 induced delays and impossible partner travel in order to support mid power range PE validation, DC-IM and Pure-SynRel motor testing. In agreement with CIDAUT (CID) and partners a plan B was activated with IFPEN assuming complementary activities to minimize the deviation in time and content.

With respect to items listed in the GA and considering Jaguar Land Rover (JLR) recommendations, the work carried out during the task includes:

- Validation and characterization of 3 high power and 3 medium power range motors out of 4 with their cooling systems.
    - The 4th motor (FR IM) is installed in the bench and about to be tested in the United Kingdom (Cummins R&T Lab, Peterborough) at the time of the current report submission.

- Validation and characterization of the High-power range PE with dedicated control to each motor topology and track (350 V-75 kW and 750 V-200 kW). Medium power range PE was tested at UAQ and CID facility.
- Experimental results analysis and share with the partners.

Thus, task 7.1 provides experimental evidence of the developed technologies, validating the followed design methodologies and demonstrating the motors performance.
Medium and high-power range motor KPI compliance and overall performances are given in Table 1, Table 2 and Table 4 respectively. PE KPI are given in Table 3.
The most of KPI are met with the 1st prototypes validating the chosen approaches to meet the requirements (Motor, PE and software). PMaSynRel motor achieved the highest torque (364 Nm)

and efficiency (96.4 %), Pure-SynRel motors have produced the highest peak power (218 kW) while DC-IM reached the highest high-speed power (128 kW).

Some exceptions leading to performance deviation were observed, analyzed and explained. None of those exceptions lead to technological locks which would question the developed technologies and should be corrected for production phase with limited engineering effort.

Table 1. Medium power range motors KPI

Parameter	Unit	PMa- SynRel 75 kW		Pure-SynRel 75 kW		DC IM 75 kW		FR IM 75 kW	
		Spec	Achiev	Spec	Achiev	Spec	Achiev	Spec	Achiev
Specific peak power	kW/kg	>3.1	3.6	>1.6	3.9	>1.6	2.2	>1.6	In progress
Peak power density	kW/L	>5	13.8	>3	13.6	>5.4	12.6	>5.4	
Specific peak torque	Nm/kg	>5	7	>3	8.6	>2.5	5.1	>2.5	
Peak torque density	Nm/L	>9	26.5	>6	29.9	>8	29.1	>8	
Active parts weight	kg	<47	19.5	<47	20.4	<47	40	<47	
Peak efficiency	%	>96	96.3	>96	94.2	>96	94	>96	
Maximal speed	krpm	15-22	12/17.5[1]	15-22	12/16[1]	15-22	12/15[1]	15-22	12/15[1]

More particularly, high power range motors have all a deviation in mass torque density compared to the target. This deviation is due to the cooling system (DC-IM), necessary current and phase cable temperature (Pure-SynRel) and ferrite performances deviation in comparison with the datasheet (PMa-SynRel) which should be corrected for B-sample specimens in the production phase. Though, volume performance densities are met by all tested motors.

The scalability of the developed technology in terms of power range keeping the same industrial tooling was as well proven with complete performance KPI compliance except for peak efficiency. (Pure-SynRel and DC-IM). 75 kW motors maximal speed is given at 12000 rpm because of the vehicle demonstrator maximal speed requirement and the geartrain limitation. Nevertheless 75 kW motor rotors are identical to 200 kW motors and share the same maximal achievable speed.

Table 2 : High power range motors KPI

Parameter	Unit	Target	Achieved			
			PMa-SynRel 200	Pure-SynRel 200	DC-IM 200	FR-IM 200
Specific peak power	kW/kg	>4.3	3.8	5	5.4	In progress
Peak power density	kW/L	>8	17.7	22.1	30.6	
Specific peak torque	Nm/kg	>8.2	7.9	6.9	7.7	
Peak torque density	Nm/L	>15.4	36.8	30.9	43.6	
Active parts weight	kg	<47	46.3	44.1	40	
Peak efficiency	%	>96	96.4	96	92.7[2]	

[1] Rotor designed and manufactured for the same speed as for the high-power range. Though the vehicle application gearbox max speed is 12krpm.
[2] Software parameters impact on the efficiency. Expected efficiency for high power range IM is at least equivalent to medium power range IM (>94 % peak).

Maximal speed	krpm	15-22	**17.5**	**16**	**15**	**15**

PE benefiting from the high-power density Mitsubishi Full-SiC modules and a very compact electronics and mechatronics design, achieves the expected performances with 45% better power mass density and 100% better power volume density. 99 % efficiency target being asymptotic was achieved (measured on each tested motor). SiC power modules which were used within the project are expected to start mass production in 2022 making this technology cost compliant with PE cost targets.

Table 3. PE KPIs

PE KPIs	**RFD goals**	**200kW inverter**
Specific Power (kW/kg)	13.7	20
Power density (kW/liter)	12.9	27
Efficiency (%)	98-99	99.2

Finally, Task 7.1 tests served to identify early in the project the prototype related problems and correct them upstream integrated e-Drive tests (Task 7.2) and in vehicle Technology Validation (Task 7.3).

Table 4. Main motor performances

Parameter	**Unit**	**PMa-SynRel 75**	**Pure-SynRel 75**	**DC IM 75**	**FR IM 75**	**PMa-SynRel 200**	**Pure-SynRel 200**	**DC IM 200**	**FR IM 200**
Peak torque	Nm	136	176.4	204.6	In progress	363.9	305.7	306	In progress
Peak power	kW	71	80.2	88.4		174.8	218.3	214.6	
Maximal speed	krpm	12	12	12		17.5	16	15	
Power at max speed	kW	34	22.3	27.7		57	58.7	127.9	
Motor peak efficiency	%	96.3	94.2	94		96.3	96	92.7	
System eff. on driv. cycle	%	90.6	87.5	86.4		89.8	87.6	79.2	

This task was achieved with time and content deviation from the Deed of Agreement (DoA). The task 7.1 planning was affected:

- First by the WP6 progress and then by the COVID lockdown which occurred at the beginning of the testing phase (March 17th, 2020). In agreement with the Project Officer, deliverable 7.1 was rescheduled from 31/12/2019 to 31/05/2020, and then to 28/02/2021 respectively.
- Bearing in mind the post lockdown restriction,
  - Medium power range PE was not tested on the IFPEN bench and was replaced by high power rage PE for medium power range motor testing. The medium power PE was tested directly at UAQ and CID.

- In what software support is concerned, UAQ has provided the software for DC-IM which was integrated in high power range PE and operated by IFPEN. For Pure-SynRel motors, IFPEN software solution was exploited based on UAQ motor maps.
- Finally, COVID impact on FR-IM manufacturer (until the project end and beyond), associated to the rotor manufacturing high challenges, resulted in a motor delivery planning deviation. Despite the efforts of the designer Motor Design LTD (MDL), the coordinator (Alicia Rodriguez Carrascal) and the motor manufacturer (Denis Ferranti Group) the motor was not available for testing before the end of the project.

To limit the impact of the task 7.1 delay on the following activities, and namely the eDrive testing and in vehicle technology validation, medium power motors tests were given the priority. Thus, the first medium power motor with power electronics was tested and sent to the partners for the eDrive validation (task 7.2) on June 16th, 2020. Also, the delay was minimized through IFPEN contribution reinforcement in order to ensure all 6 motor testing in autonomy. Finally, parts redundancy was setup to avoid delays due to COVID impact on WP6 partner suppliers. Considering the last IM unavailability specific mechanical coupling parts are sent to partners to accelerate eDrive testing.

After the end of the project and in agreement with the PO, the partners have pursued the efforts to test FR-IM and prove the validity of the proposed technology. After FR-IM has been shipped from the manufacturer (United Kingdom), it was blocked during 8 weeks at the shipping company's facilities for administrative reasons. Consequently, and to avoid further transport delays, partners took the decision to test the motor directly in the United Kingdom (Peterborough) at Cummins R&T lab. At the time of the current report submission:

- All bench adaptation parts have been designed and manufactured
- Motor has been installed in the bench
- FR-IM successfully accomplished preliminary tests on cooling system and hairpin stator for medium and high-power levels. The results are consistent with previous tests done at IFPEN.
- Characterization phase of the motor is starting in parallel to the current report submission.

This report is organized as follows:

- Section 2 presents the experimental facility at IFPEN (Figure 1)
- Section 3 is dedicated to PE experimentally validated performances and KPIs
- Section 4 concern motors experimental results and KPIs

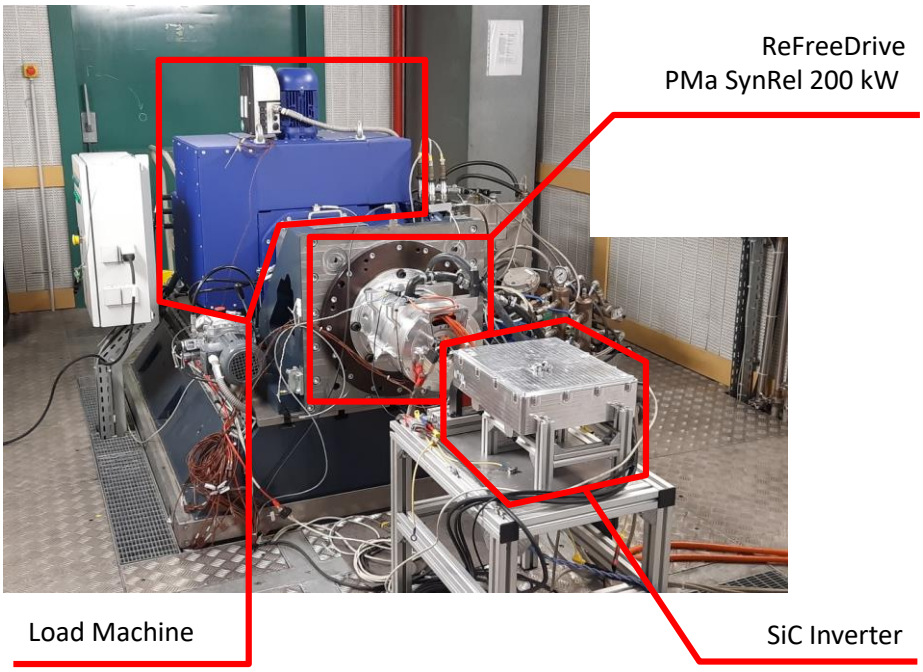

Figure 1. Hi-Power test bench overview

2 General Conclusion

Task 7.1 was achieved despite deviation in time due to COVID lockdown. A complete set of 6 out of 8 motors was characterized providing experimental evidence of the developed technologies, validating the followed design methodologies and demonstrating the motors performance.
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Motors and PE were tested considering GA engagements as well as following JLR recommendations. Medium and high-power range motor KPI compliance and overall performances are given in Table 1, Table 2 and Table 4 respectively. PE KPI are given in Table 3.
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More particularly, high power range motors have all a deviation in mass torque density compared to the target. This deviation is due to cooling and ferrite performances (in comparison with the datasheet) related limitations which should be corrected for B-sample specimens (afterward the current project). Volume performances densities are met by all the motors.

The scalability of the developed technology in terms of power range keeping the same industrial tooling was as well proven with complete performance KPI compliance except for peak efficiency.

PE benefiting from the high power density Mitsubishi Full-SiC modules and a very compact electronics and mechatronics design, achieves the expected performances with 45% better power mass density and 100% power volume density. 99 % efficiency target being asymptotic was achieved. SiC power modules which were used within the project is expected to start mass production in 2022 making this technology cost compliant with PE cost targets.

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