FABRIC

Feasibility analysis and development of on-road charging solutions for future electric vehicles

Analysis of Results and Recommendations

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LIST OF ABBREVIATIONS

ABBREVIATION	DESCRIPTION
AC	Alternating Current
DC	Direct Current
DSO	Distribution System Operator
EMC	Electromagnetic Compatibility
EMF	Electromagnetic field
HSE	Health, Safety and Environment
ICNRP	International Commission on Non-Ionizing Radiation Protection
IEC	International Electro technical Commission
OEM	Original Equipment Manufacturers
PCC	Point of Common Coupling
PWM	Pulse Width Modulation
THD	Total Harmonic Distortion
WP	Work Package
WPT	Wireless Power Transfer

REVISION CHART AND HISTORY LOG

REV	DATE	REASON
1	23/03/2017	First Draft
2	15/15/2017	Second Draft
3	06/06/2017	Final Draft
4	20/06/2017	Final Draft V1.1
5	19/09/2017	Technical review
6	25/09/2017	Final for internal review
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EXECUTIVE SUMMARY

The objective of the FABRIC project is to investigate the technological feasibility, economic viability and socio-environmental feasibility of dynamic on-road charging of electric vehicles. The project aimed to develop and test a number of dynamic on-road charging solutions. These involve the inductive transfer of power from primary coils embedded in the road to secondary coils fitted in the vehicles. High frequency inverters fed by the rectified mains supply are used to drive the primary coil and rectifiers in the vehicle convert the received AC power into DC to charge the battery. The FABRIC project also investigates dynamic conductive power transfer solutions, though only as desk analysis. The scope includes a review of the technology, interoperability, specification, design, testing and development of dynamic on-road wireless power transfer solutions.

This report is deliverable D3.72: “The analysis of results and recommendations”. It presents results of verification tests carried out on wireless power transfer systems provided by POLITO, SAET and CIRCE. The results for the verification tests for the VEDECOM solution are subject to commercial confidentiality agreements and are presented in a separate confidential annex to this deliverable. This report also provides recommendations on possible further improvements for the solutions in order to meet the specifications in D.3.4.1: Specification Document.

Maximum power transfer efficiency requires the correct alignment of primary and secondary coils. The verification test consists of five test conditions and 16 different test setups, where each test condition defines a horizontal (y-axis) or vertical (z-axis) offset position of the secondary coil relative to the primary coil. A detailed set of raw data was captured by all manufacturers (POLITO, SAET, VEDECOM and CIRCE) for all test conditions. The POLITO and SAET solutions were tested in the same laboratory in Italy using the same methodology and equipment. The Qualcomm tests were carried out in a laboratory in Germany and the CIRCE solution was tested in Spain.

Key Findings

POLITO and SAET

- The POLITO and SAET solutions were tested at 11kW as opposed to the specified value of 20kW; this was due to the inability of the primary rectifiers (AC-DC) to provide such power. The rectifiers on the primary side require further development and modification in order to ensure that the solution is capable of providing 20kW at the DC out on the vehicle.
- The efficiency of the POLITO solution was greater than 80% for the majority of the test setups, apart from those where the horizontal offset was 200mm.
- The efficiency of the SAET solution was below 80% for the majority of the test setups, apart from those where the vertical offset was -50mm and horizontal offset was 0mm. The results showed that the SAET solution require further improvements in order to achieve at least 80% efficiency when the solution is perfectly aligned at nominal airgap.
- The results show that the Total Harmonic Distortion (Voltage) at the input was below 8% for all test setups. The voltage total harmonic distortion meets the specifications.
- The Total Harmonic Distortion (Current) was very high for both solutions; the current harmonics were high as 61.9% for perfect horizontal alignment at the nominal air gap. The reason for these high current harmonics is due to the use of a six-pulse rectifier, which distorts the current waveform at the input (Primary). Both solutions were under development at the time when tests were conducted; therefore meeting current harmonics requirements was not seen as priority at this stage. However, the solutions are expected to meet all

harmonic requirements during the validation tests in SP4, a 12-pulse rectifier will be employed at the test site.
- The power factor for POLITO solution was 0.84 and for SAET solution was 0.87, when both solutions were perfectly aligned at nominal airgap. Both solutions were therefore below the specification level of 0.95. The low power factor is due to the high current harmonics recorded; therefore improving the current harmonics could significantly increase the power factor, but this cannot be achieved while simple diode rectifiers are used.
- Voltage fluctuations on the grid side are expected to be 5% of the nominal voltage, according to EN50160. No abnormal fluctuations were observed during testing.
- The EM field for the POLITO solution was 7.02 uT and 12.96 uT for the SAET solution at nominal airgap with no misalignment. The results were therefore below the limit of 27 uT recommended by ICNIRP 2010 for all the test setups. However, the exposure level was very close to 27uT when the horizontal offset was 200mm and the vertical offset was +50mm. Note that these tests were carried out in laboratory conditions where there was no equivalent vehicle body to act as a shield. Since the EM field for both solutions were well below the specified value (27 uT), the EM field levels are expected to be below ICNIRP 2010 specification for the fully developed solutions.

CIRCE

- The CIRCE solution was tested at 50 kW; the power transfer efficiency was over 80% in most of the operating conditions except for maximum x-displacement (1000 mm), where the secondary coil was partly outside of the primary coil.
- The voltage and current Total Harmonic Distortion for the CIRCE solution was below 2%; the Total Harmonic Distortion was very low even when supraharmonics were considered.
- The power factor of the CIRCE solution is fully controllable, because of the Pulse Width Modulation multi-level converter employed. Therefore, if unity power factor is desired, this can be met at any operational conditions.
- EM field levels were tested with the secondary coil installed under an actual bus over the primary coil, so that the EM readings were realistic. Results showed that in all test setups the EM field was below 27 uT, as recommended by ICNIRP 2010.

1. INTRODUCTION

Deliverable D.3.7.2 presents results of and recommendations arising from verification tests carried out on the VEDECOM, POLITO, SAET and CIRCE solutions. TRL helped to set up and carry out testing of POLITO and SAET solutions. The verification tests carried out were based on the verification methodology set out in D.3.7.1. Figure 1 shows the main tasks within Work Package 3.7. Data were collected during the verification tests, which was analysed to assess the solutions ability to meet the specifications (set in D.3.4.1) and also to provide recommendations on further improvements and modifications in order to meet the specifications. The output from analysis of raw data was compared with the success criteria in order to understand whether the solutions meet the requirements based on the specification deliverable (D.3.4.1). Finally, recommendations were made to the solution providers based on the analysis of results and success criteria.

Note that while VEDECOM have carried out verification tests and produced a report on analysis of results and recommendations, the findings cannot be shared publicly because of commercial sensitivity, and therefore are reported separately as a confidential appendix. The European Commission, coordinator and SP leader have agreed on this arrangement. Therefore the present report is focused on analysis of the POLITO and SAET solutions. The results from tests with the CIRCE solution are also presented, as agreed with the project officer/.

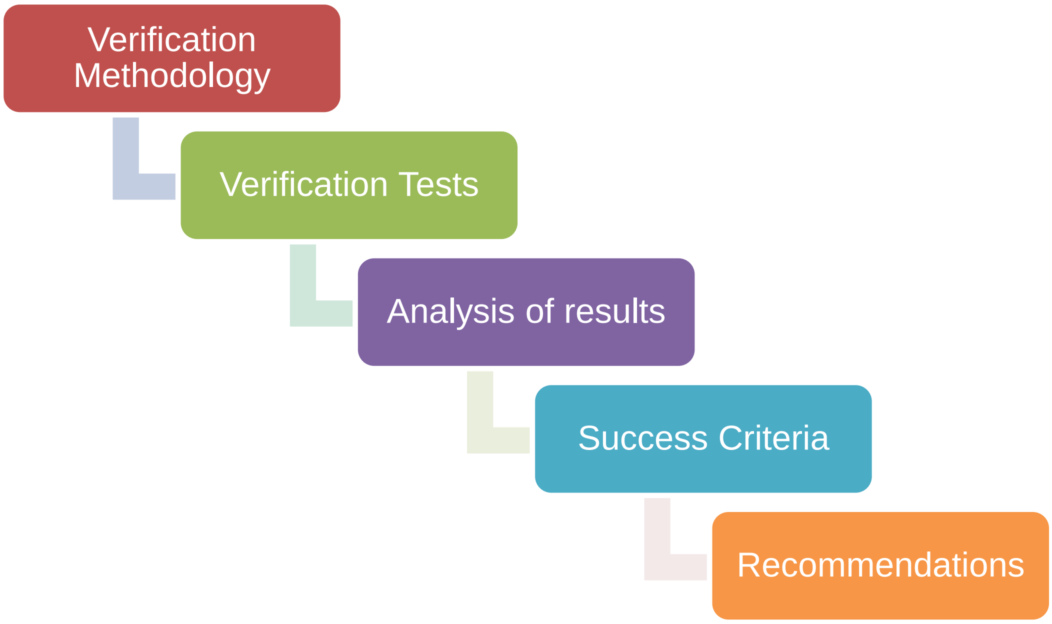

Figure 1: Work Package 3.7 tasks and process

In this report each verification test section presents conclusions on whether the solution being tested meets the requirement. Each verification test section also provides recommendations on potential improvements before validation tests.

2. METHODOLOGY

Figure 2 shows the test process, as presented in Deliverable 7.1. Each verification test applies to five test conditions, as explained below. The detailed raw data was captured for all solution providers (POLITO, SAET, VEDECOM) for all test conditions. Additionally, results by CIRCE from tests with a dynamic charging system of the VICTORIA project are presented. The tests of CIRCE for VICTORIA project were slightly different, as they were started under the VICTORIA project before the FABRIC verification methodology was defined. Nevertheless, the results can be considered as complementary to those of the other 3 solutions.

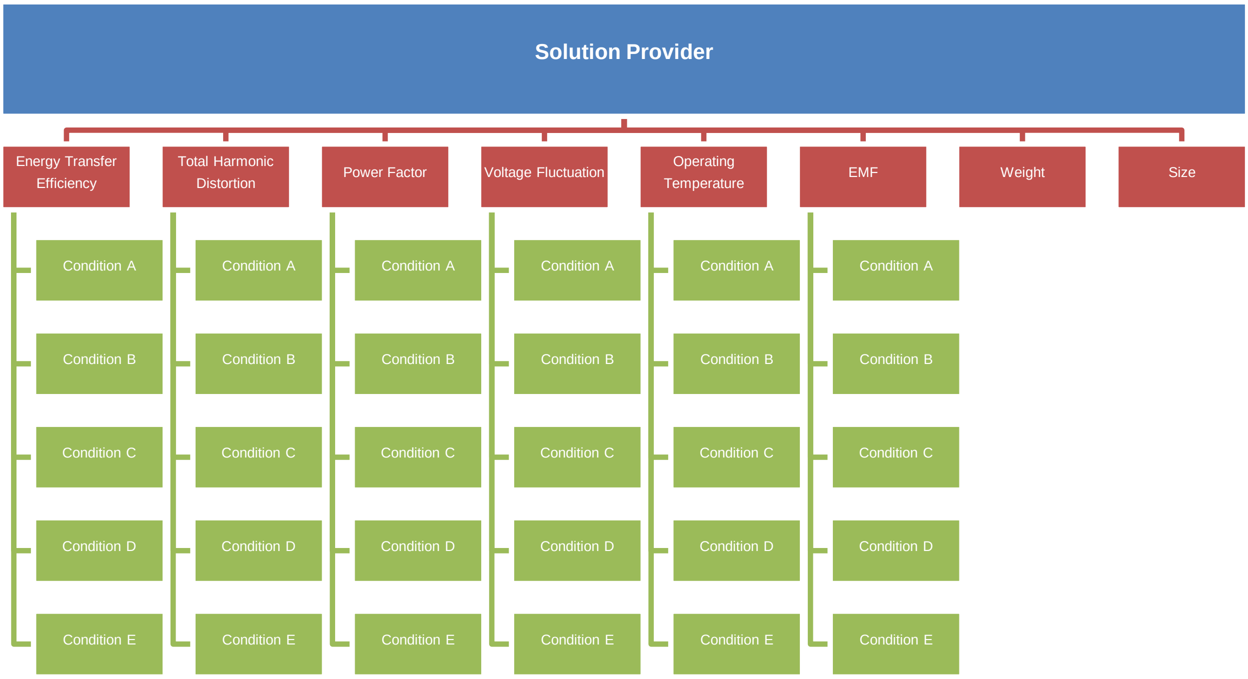

Figure 2: Verification tests

The manufacturers were responsible for developing the test rigs, performing tests and monitoring relevant data for all the test conditions. TRL was present during POLITO and SAET verification tests. As presented in Deliverable 3.7.1, the test conditions were:

A. **Nominal value of parameter at static charging:** Initially, the nominal value of each parameter, for example efficiency, was measured. In nominal condition, the primary and secondary devices were static, at ideal alignment conditions (0mm offset), at their nominal air gap (e.g. 150mm) and at nominal power level.
B. **Impact of misalignment:** Each parameter was then measured during wireless power transfer while the primary and secondary devices were misaligned in the y axis. For this condition, the secondary coil was offset in the y-axis (laterally, i.e. perpendicular to the direction the vehicle would travel) at 50 mm intervals, until a maximum of +-200 mm. In each test, air gap and power level were constant
C. **Impact of air gap:** Each parameter was measured during wireless power transfer while the airgap was varied, i.e. the secondary device was offset in the z-axis. (i.e. height) Measurements were taken at +- 50 mm around the nominal air gap for each y-axis offset

(i.e. the tests in condition B were repeated with new airgap values). In each test, the x offset and power level remained constant at their nominal values.

D. **Impact of power level:** The values of parameters were measured during wireless power transfer at partial values of the nominal power level, for example at 60%. In this condition, the primary and secondary devices were fixed at their ideal alignment condition (x=y=0) and at nominal air gap.

E. **Moving secondary:** The values of parameters were measured during wireless power transfer, while the secondary was moving at a steady speed with respect to the primary. Since the tests were done in laboratory environment, this movement was at low speed; however they may give an indication of what can be expected in real operating conditions. In this condition, the primary and secondary devices were held at ideal y alignment, at nominal air gap and at nominal power level. Note that the POLITO and SAET solutions were not tested at this condition; because of limited space in the laboratories and the safety risk. Moving the test rig required human force, which meant someone had to be too close to the coils whilst in operation; which was not considered to be safe.

Figure 3 presents the layout of a generic WPT system according to IEC 61980-1. The IEC 61980-1 standard defines the system efficiency as being calculated between the AC power supply, Energy $_{in}$ at grid connection point, and the DC vehicle side, Energy E_{out} at battery or other device.

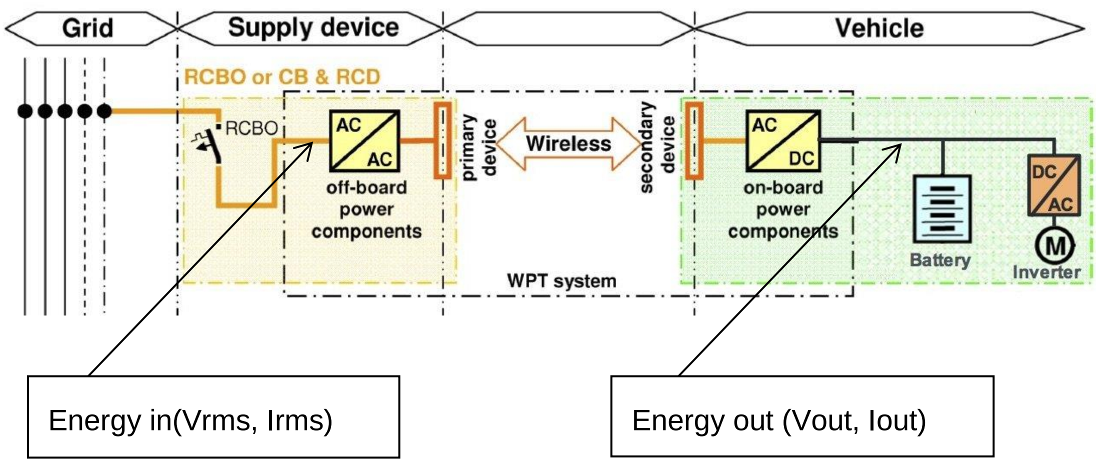

Figure 3: General WPT System (Source: IEC 61980-1), input power (Pin) and output power (Pout) are indicated.

2.1 POLITO and SAET

There were 92 tests for the POLITO and SAET solutions; however, the data required for these tests could be collected from 16 test setups (Table 1); as the data required for different tests can be recorded at the same time. Table 1 shows the test number and test condition. There are three different air gaps (vertical offsets) and each vertical offset was tested under 5 different horizontal (y) offset conditions.

Table 1: POLITO and SAET Verification Tests

Test ID	Air Gap Z (vertical displacement) (mm)	Alignment Y (lateral displacement) (mm)
T.1.1	0	0
T.1.2.1	0	50
T.1.2.2	0	100
T.1.2.3	0	150
T.1.2.4	0	200
T.1.3.1	-50	0
T.1.3.1.1	-50	50
T.1.3.1.2	-50	100
T.1.3.1.3	-50	150
T.1.3.1.4	-50	200
T.1.3.2	50	0
T.1.3.2.1	50	50
T.1.3.2.2	50	100
T.1.3.2.3	50	150
T.1.3.2.4	50	200
T.1.4 (60% power)	0	0

2.2 CIRCE

The CIRCE verification tests concentrated on the x-direction (displacement of natural movement of the vehicle). CIRCE's secondary coil is longer than primary coils, which results in different coupling set up depending on the vehicle position. Therefore, in contrast to the setups defined in FABRIC D3.7.1, the CIRCE verification tests focussed more on the longitudinal displacement (as the vehicle moves naturally forwards in the x-direction) and not so much on lateral displacement (y-direction). Table 2 shows the test setups; lateral displacement (Y-direction) offset by 5 and 10 cm; as the tolerance of the self-guided system is 5 cm. The nominal air gap is

20 cm; the solution was tested at 15 cm (-5 cm) air gap as well, which represents the expected variation with and without passengers on board.

Table 2: CIRCE verification tests

Test	Air gap Z (vertical displacement) (mm)	Y (lateral displacement) (mm)	X (longitudinal displacement) (mm)
0	0	0	0
1	0	0	600
2	0	0	700
3	0	0	850
4	0	0	925
5	0	0	1000
6	0	50	850
7	0	100	0
8	0	100	850
9	0	100	1000
10	-50	0	850

Figure 4 shows the positioning between primary and secondary coil. Tests were carried out up to a longitudinal displacement of 1000 mm. At this position, the secondary coil is 150 mm outside of the primary coil and at this point the control system switches off in order to limit currents.

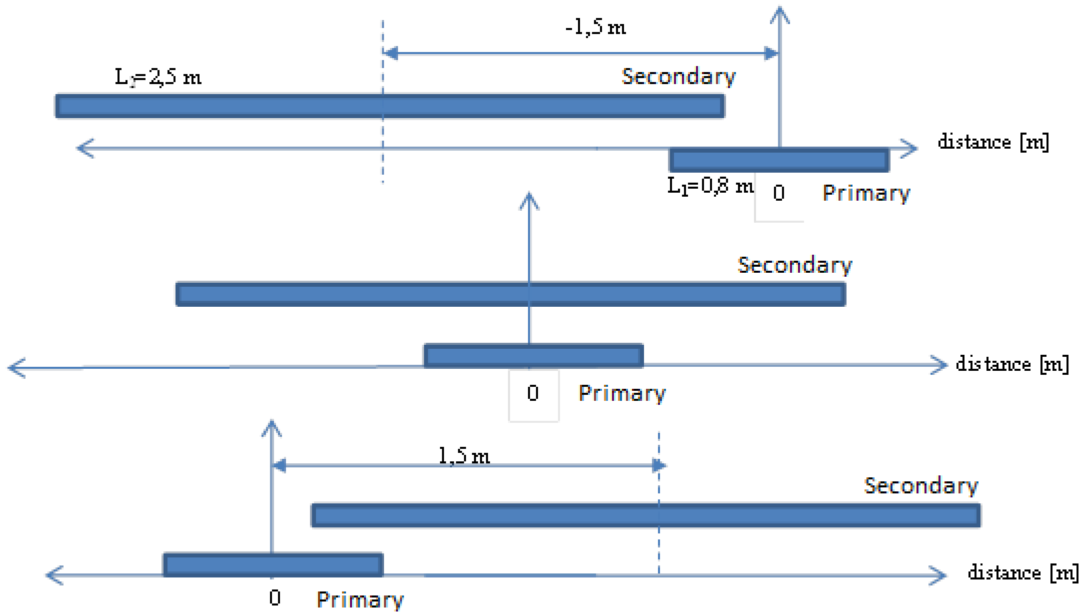

Figure 4 Definition of positions between coils for the CIRCE tests

The raw data was provided. The first task was to briefly describe and validate the raw data to ensure that the collected data was in the correct format and was collected at the correct test point. Table 3 shows what data was recorded during verification testing, and whether it was measured or calculated. These datasets were used to verify each solution against the success criteria defined in D.3.7.1. The harmonics were calculated from waveform seen on the oscilloscope.

Table 3: Measured or Calculated Data

Parameter	Unit	SAET	POLITO	CIRCE
Input Real Power	W	Calculated	Calculated	Calculated
Input Apparent Power	VA	Calculated	Calculated	Calculated
Input Reactive Power	VAr	Calculated	Calculated	Calculated
Phase Shift	φ	Calculated	Calculated	Calculated
V_{ac} RMS (Voltage phase a-c)	V_{rms}	Measured	Measured	Measured
V_{bc} RMS (Voltage phase b-c)	V_{rms}	Measured	Measured	Measured
V_{ca} RMS (Voltage phase c-a)	V_{rms}	Calculated	Calculated	Measured
I_a RMS (Current phase a)	I_{rms}	Measured	Measured	Measured

I_b RMS (Current phase b)	I_{rms}	Measured	Measured	Measured
I_c RMS (Current phase c)	I_{rms}	Calculated	Calculated	Measured
V_{out} (Output Voltage)	V	Measured	Measured	Measured
I_{out} (Output Current)	I	Measured	Measured	Measured
Fundamental Current	I_1	Calculated	Calculated	Calculated
Current Odd Harmonics: up to 21	I_k	Calculated	Calculated	Calculated
Current Even Harmonics: up to 24	I_k	Calculated	Calculated	Calculated
Fundamental Voltage	V_1	Calculated	Calculated	Calculated
Voltage Odd Harmonics: up to 21	V_k	Calculated	Calculated	Calculated
Voltage Even Harmonics: up to 24	V_k	Calculated	Calculated	Calculated
Temperature Primary	^{0}C	Measured	Measured	Measured
Temperature Secondary	^{0}C	Measured	Measured	Measured
Magnetic Field	T	Measured	Measured	Measured
Equipment size (LxWxD)	mm	Measured	Measured	Measured
Equipment weight	kg	Measured	Measured	Measured

The second task was to use the raw data to calculate the verification test parameters by using the equations provided in Deliverable 3.7.1. The values of the parameters were compared against the benchmark criteria in order to determine whether each solution met that specific requirement. .

Thirdly, further analysis was carried out on the solutions that did not meet a specific requirement in order to understand the reasons for not meeting the requirements. Finally, recommendations on further developments were presented for the systems that did not meet the requirement or the value was too close to the limit.

As stated earlier, POLITO, SAET and VEDECOM were the FABRIC solution providers and responsible parties to carry out tests and record raw data, with CIRCE offering data from tests with the VICTORIA project solution. TRL was the data analysis leader supported by FKA for vehicle requirements and CIRCE for EMF and grid requirements. The results were reviewed by ICCS, CRF, VEDECOM and Scania, who provided feedback on any necessary modifications to the existing solutions.

Figure 5: POLITO and SAET verification test rig.

Figure 6: Laboratory test setup for CIRCE solution (VICTORIA)

3. POWER TRANSFER SYSTEM ANALYSIS

This section presents the nominal efficiency analysis, the calculations were based on the D.3.71 methodology.

3.1 POLITO and SAET

The plan was to test the POLITO and SAET solutions at 20 kW. However, these two solutions were tested at 11kW at the secondary coil DC output. The reason was that the AC/DC (rectifier) converter, that converts AC power from the grid to DC, was not able to provide power at the levels that would provide 20kW at the secondary output. POLITO and SAET were working to resolve this issue at the time of writing of this report to ensure that the solutions provide 20kW power during the validation testing in SP4. However, the coils were optimised to operate at 20kW; therefore the efficiency is expected to be higher when the power transfer rate is increased to 20kW.

Figure 7 and Figure 8 shows the efficiency of the POLITO and SAET solutions at various vertical and lateral offset levels. The results show that the efficiency reduces as the lateral and vertical offset increase. The efficiency was 89% for 0 mm vertical and 0 mm horizontal offset for the POLITO solution. The efficiency fell below 80% for the POLITO solution only when lateral offset was greater than 150 mm and vertical offset was greater than 50 mm.

The results show that the SAET solution was less efficient than the POLITO solution; the efficiency of SAET was only above 80% when the horizontal offset was zero and vertical offset was -50mm. The significant source of the losses was between primary and secondary coils, the efficiency between grid to primary coil and secondary coil to battery was as expected (above 95%). However, the efficiency between primary coil and secondary coil was below 90%. The efficiency of the SAET solution can be increased by improving the coupling between primary and secondary. The primary coil is a loop of wire on a platform; even small changes in the shape of the loops could have a significant effect on the power transfer rate. Therefore using a rigid frame to ensure that the primary coil is securely mounted could increase the efficiency of the system. Note that the first point (lateral=0 vertical=0) in Figure 7 and Figure 8 is the efficiency at 60% power (6.6kW) with no x, y and z misalignment, the remaining points are the efficiency results for 100% power (11kW).

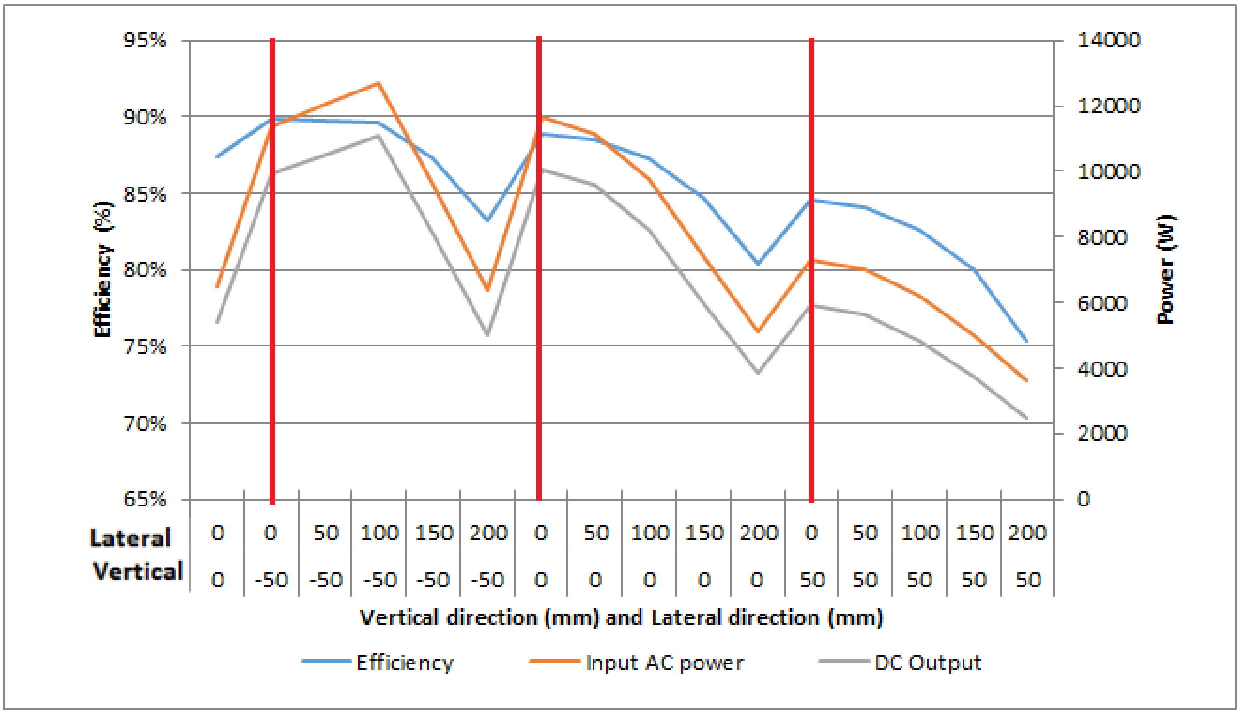

Figure 7: POLITO system Efficiency

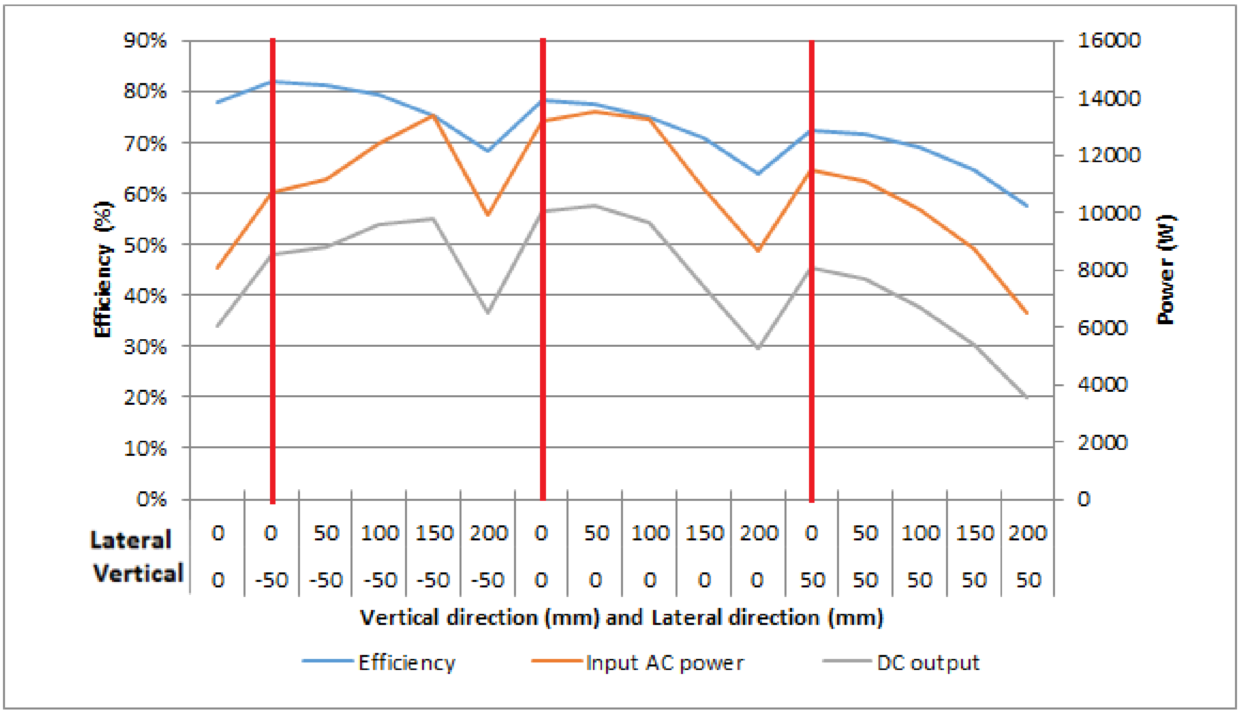

Figure 8: SAET system efficiency

3.2 CIRCE

Figure 9 shows the input power at the grid, output DC power on the vehicle and the transfer efficiency of the CIRCE solution at various offsets in vertical (z), lateral (y) and longitudinal (x) -directions. The efficiency increases as the longitudinal (x) position reaches 850 mm; the efficiency value at this point was 84.9%. The efficiency was maintained up to approximately 900 mm of displacement, after which point the efficiency started to reduce and the power at the grid side started to increase, until the system switched the power transfer off in order to avoid over-current.

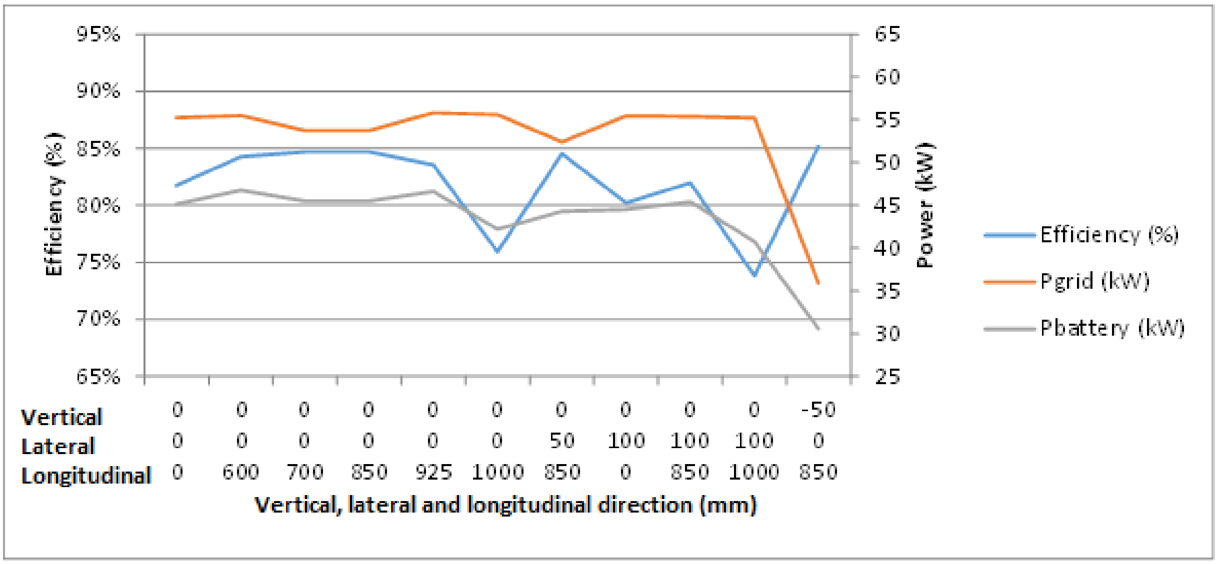

Figure 9 Power input from the grid, power supplied to the battery and efficiency in different positions between coils for the CIRCE system

Lateral displacement (y-direction) of 50 mm did not result in significant decrease in efficiency, while at 100 mm the efficiency decreased to 82%. The tested vertical offset of -50 mm did not provide any noticeable change in power transfer efficiency, but the transferred power decreases drastically due to the fact that the system moves slightly out of the resonance conditions.

Efficiency results show that the efficiency of the CIRCE solution was above 80% for all test conditions, except for maximum longitudinal (x) displacement (1000 mm), where the receiver coil was already partly outside of the emitter coil (by 150 mm), which is equivalent to 18.8% of the receiver coil surface.

Figure 10 shows the efficiency of CIRCE solution at various power transfer levels; at nominal airgap and perfect alignment. Results show that the efficiency was above 80% when the power transfer to the battery was more than 25 kW or 50% of the nominal power of the system.

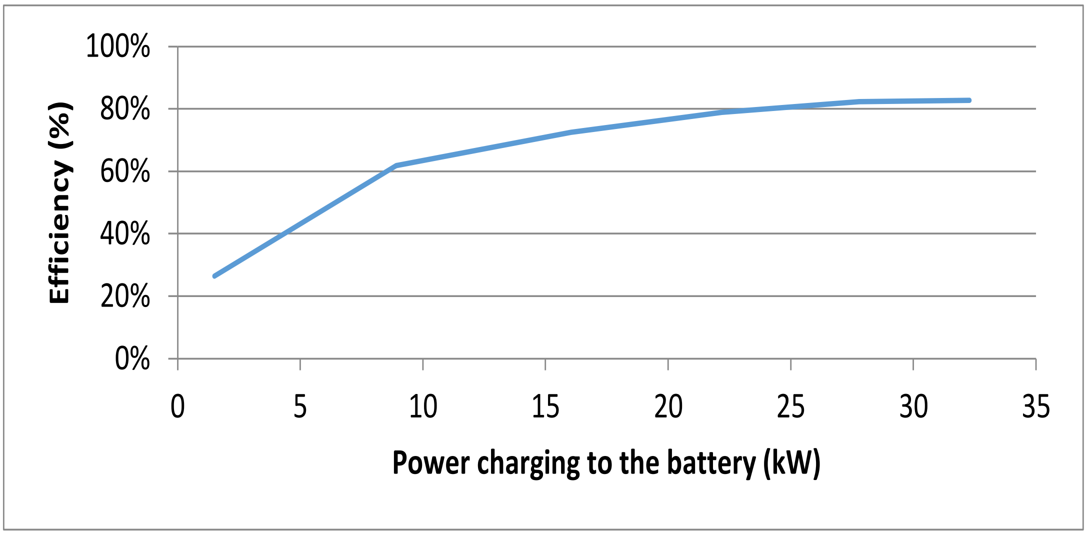

Figure 10: CIRCE system efficiency vs. charging power

Additionally, dynamic tests were carried out at the laboratory and registered by oscilloscope measurements for the CIRCE solution. Figure 11 shows an example of the results for a test run with 40 A battery current, which is approximately 30% of nominal power. Figure 11 presents the whole charging process as the bus drives over one of the primary coils. The graph presents wave forms for primary current (yellow), primary voltage (pink), secondary current (green) and battery current (blue).

Figure 12 shows the current at the grid side, I_1 (left chart) and battery charging current, I_2 (right chart) for the whole range of displacement in longitudinal (x) direction between -1500 and 1500 mm according to the convention explained in Figure 4. It is important to note that the charger uses active limitation of the primary voltage to keep current within limits. This can be observed in the charts: the supply current is 10% above the nominal current of 95 A as the secondary coil starts to move over the primary coil, and then drops rapidly as it comes into alignment. On the other hand, battery charging current was controlled perfectly. In most systems the primary is a short-circuit if not aligned (current run-away) as it is out of resonance. That means, absorbed current increases, but transferred power is reduced; however CIRCE adopted Series-Parallel-Series compensation to minimise the variation in primary voltage and current when compared with other compensation methods such as series-series or series-parallel.

These are preliminary tests which will be extended during the final validation tests which will be reported in FABRIC D4.7.2.

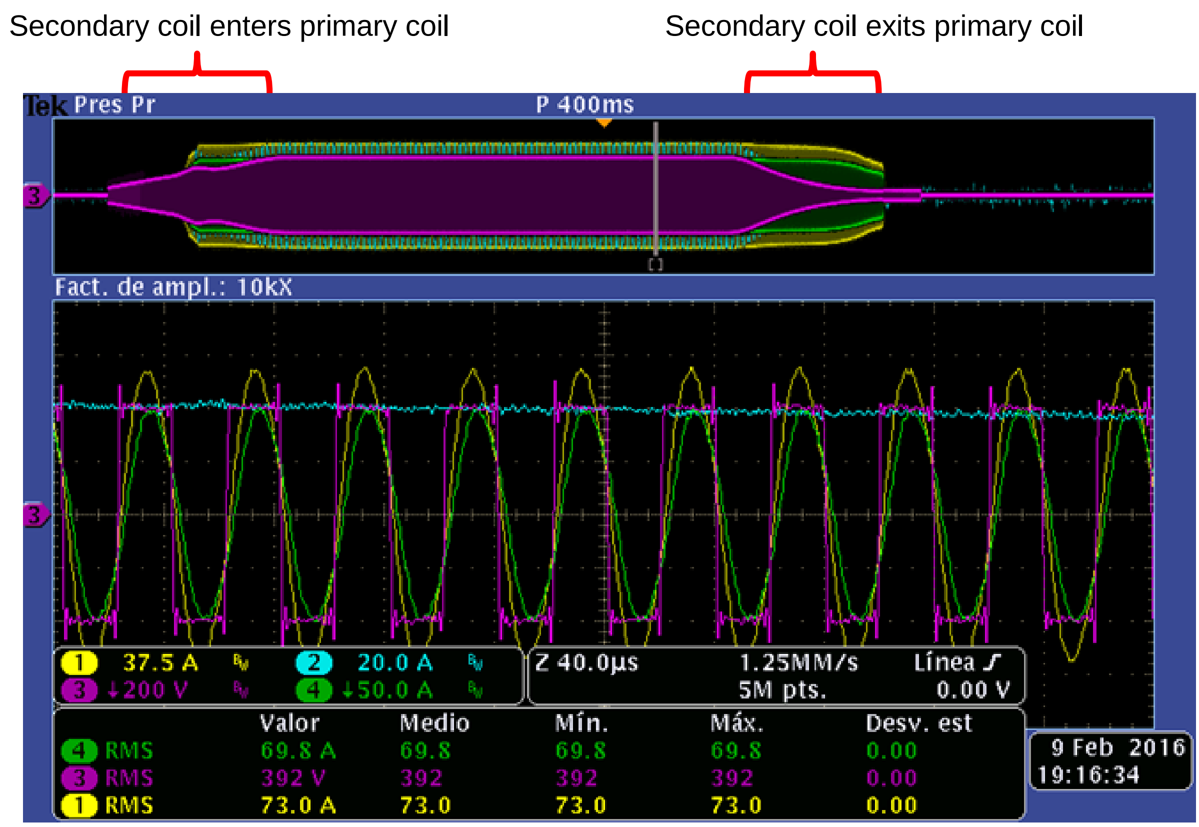

Figure 11: Dynamic test charge with 40 A battery current. Primary current (yellow), primary voltage (pink), secondary current (green) and battery current (blue)

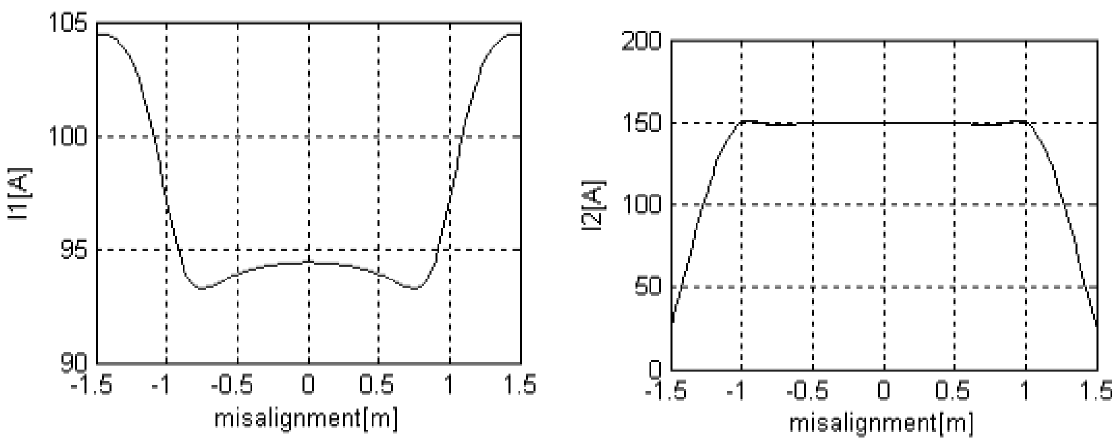

Figure 12 CIRCE tests: Current at the grid side, I1 (left) and battery charging current, I2 (right)

4. GRID INTERFACE ANALYSIS

4.1 Harmonics

Voltage harmonics are defined for the grid connection point and represent the possible impact of the equipment to the grid, arising from distortion of the grid voltage waveform. Table 4 from D3.4.1 shows the voltage harmonic limits according to EN 50160 (LV and MV grids). Maximum voltage Total Harmonic Distortion (THD) is established at 8% for 95% of the time and voltage THD should be below the limits established in the table below, which applies to low and medium voltage grids.

Table 4: Limits for single voltage harmonics in the supply points for LV and MV grids according to EN 50160

Odd harmonics				Even harmonics	
Non multiples of 3		Multiples of 3			
h order	Relative amplitude, u_h	h order	Relative amplitude, u_h	h order	Relative amplitude, u_h
5	6.0 %	3	5.0 %*	2	2.0 %
7	5.0 %	9	1.5 %	4	1.0 %
11	3.5 %	15	0.5 %	6 … 24	0.5 %
13	3.0 %	21	0.5 %		
17	2.0 %				
19	1.5 %				
23	1.5 %				
25	1.5 %				

Harmonics order higher than 25 are not shown in this table as they usually are weak and very unpredictable.

* For MV grids, depending on the grid design, the order 3 harmonic could be lower.

Current harmonics are defined as a requirement of the equipment connected to the grid (IEC 61000-3-12 (>16 A, ≤75 A/phase)), as shown in Table 5. Note that the reference of the equipment power is dependent on the grid strength (expressed as short circuit power at the PCC) $R_{SCe} = S_{sc}/S_{equ}$. The greater the value of Rsce, the lower the power supplied to the equipment, assuming a constant grid supply

Table 5: Limits for current emissions for equilibrated 3-phase equipment according to IEC 61000-3-12

minimum $R_{SCe} = S_{sc}/S_{equ}$	Allowed individual harmonic current I_h/I_{ref} (%)				THD (%)
	I_5	I_7	I_{11}	I_{13}	THC/I_{ref}

33	10.7	7.2	3.1	2	13
66	14	9	5	3	16
120	19	12	7	4	22
250	31	20	12	7	37
≥350	40	25	15	10	48
Even harmonics of order $h \leq 12$ cannot surpass $16/h$ %. Even and odd harmonics of order $h > 12$ are included in THC.					
R_{sce}: Relation between equipment power and grid connection strength, S_{sc}: Short circuit power at grid connection point (PCC), S_{equ}: Nominal apparent power of the equipment, I_{ref}: Reference current (fundamental current), I_h: Harmonic current component					
Linear interpolation R_{SCe} is permitted					

4.1.1 POLITO AND SAET

Table 6 and Table 7 show the current and voltage harmonics for POLITO and SAET solutions; the harmonics were calculated by using waveform seen by oscilloscope. The voltage harmonics were below 8% (limit) for the POLITO and SAET solutions. The results show that the voltage harmonics are approximately 6% at nominal air gap and zero lateral offset. The voltage harmonics were lower when the power transfer rate was 60% of full load when compared with the full load; this could potentially result in voltage harmonics being exceeded when the power transfer rate is increased to the target value of 20kW. Also, voltage harmonics reduced as lateral and vertical offset increased.

The current harmonics for POLITO and SAET solutions were very high. Even though a 1kHz low pass filter was applied, the distorted waveform at the input resulted in high current harmonics. The current harmonics were as high as 61.9% at perfect alignment and nominal airgap for the POLITO solution. The current harmonics were high due to the use of a six pulse rectifier which distorted the current waveform at the input. Since the solutions were laboratory test solutions at the moment of conducting the verification tests, meeting the current harmonics requirements was not seen as priority. However, the solutions are expected to meet all harmonics requirements during validation tests in SP4.

The results show that there is the need for further harmonics treatment such as introduction of 12-pulse rectification in the solution, which should lead to a better current waveform hence improved THD. This has been already applied for SAET at the test site and the solution will be tested during the validation work package (W4.7).

A second improvement would be an AC/DC converter with unity power factor. These improvements should completely solve the THD problem but would increase the cost.

A third improvement could be an active filter shared among all the users of the connected substation. Note that the first point (Test 0) in Table 6 and Table 7 is the 60% power mark 6.6 kW, the remaining points are the results for 100% power (11 kW).

Table 6: POLITO Harmonics

Test	Z (vertical direction) (mm)	Y (lateral direction) (mm)	THD I_a (%)	THD I_b (%)	THD I_c (%)	THD V_{ab} (%)	THD V_{bc} (%)	THD V_{ca} (%)
0	*0*	*0*	76.56	73.66	72.08	4.37	4.77	4.62
1	*0*	*0*	61.90	54.74	55.73	5.62	6.06	6.08
2	*0*	*50*	62.61	55.29	56.05	5.58	6.02	6.05
3	*0*	*100*	66.29	60.55	60.68	5.28	5.75	5.70
4	*0*	*150*	73.22	70.17	68.42	4.76	5.23	5.14
5	*0*	*200*	82.44	78.67	77.50	4.03	4.45	4.16
6	*-50*	*0*	61.78	54.98	55.65	5.62	6.06	6.10
7	*-50*	*50*	59.78	53.01	53.63	5.75	6.19	6.25
8	*-50*	*100*	57.64	51.38	52.27	5.84	6.26	6.32
9	*-50*	*150*	66.52	61.06	61.02	5.29	5.75	5.71
10	*-50*	*200*	77.02	74.11	72.17	4.37	4.85	4.69
11	*50*	*0*	73.20	70.43	69.14	4.76	5.17	5.08
12	*50*	*50*	73.94	70.98	69.83	4.67	5.10	5.00
13	*50*	*100*	77.19	74.19	72.72	4.37	4.80	4.63
14	*50*	*150*	82.52	78.94	77.94	3.94	4.35	4.11
15	*50*	*200*	90.08	85.96	85.26	3.47	3.86	3.61

Table 7: SAET Harmonics

Test	Z (vertical direction) (mm)	Y (horizontal direction) (mm)	THD I_a (%)	THD I_b (%)	THD I_c (%)	THD V_{ab} (%)	THD V_{bc} (%)	THD V_{ca} (%)
0	*0*	*0*	69.42	66.49	65.22	5.10	5.45	5.45
1	*0*	*0*	54.49	48.44	50.37	6.07	6.32	6.44

2	*0*	*50*	54.47	48.78	50.05	6.08	6.34	6.49
3	*0*	*100*	54.79	49.00	50.46	6.08	6.34	6.50
4	*0*	*150*	61.89	54.89	56.54	5.63	5.95	6.03
5	*0*	*200*	67.98	64.30	63.69	5.19	5.51	5.57
6	*-50*	*0*	62.43	55.82	57.04	5.56	5.90	5.97
7	*-50*	*50*	61.04	53.99	55.78	5.68	6.00	6.09
8	*-50*	*100*	58.31	51.88	53.33	5.85	6.14	6.26
9	*-50*	*150*	55.42	49.62	51.26	6.04	6.31	6.45
10	*-50*	*200*	64.65	59.14	59.88	5.40	5.75	5.77
11	*50*	*0*	60.84	53.91	55.52	5.70	6.02	6.11
12	*50*	*50*	61.54	54.18	56.31	5.64	5.95	6.03
13	*50*	*100*	63.95	57.83	59.17	5.45	5.77	5.80
14	*50*	*150*	67.37	63.76	63.59	5.26	5.54	5.59
15	*50*	*200*	74.33	71.77	70.63	4.55	4.97	4.91

4.1.2 CIRCE

Within the tests of VICTORIA project conducted at the CIRCE facilities, current and voltage harmonics have been calculated according to IEC 61000-3-4. In addition, the procedure was carried out up to 150 kHz in order to include supraharmonics. Because a PWM (Pulse Width Modulation) multi-level converter was used at the grid connection, apart from low harmonics, there was no measurable impact of charging alignment on harmonics. Therefore, these tests are not presented here.

Figure 13 shows all voltage harmonics up to order $h = 40$ (2 kHz) as established by the standard IEC 61000-3-4. This test represents 5 different measurements at nominal condition (50 kW power transfer from the grid) and one reference measurement with the system switched off (Tek0000). It can be observed that there is no significant difference between the reference spectrum (grid without system) and the spectra with the system charging at nominal power. Therefore, it can be considered that the small differences between the spectra are due to changing grid conditions, rather than changing parameters of the charging equipment.

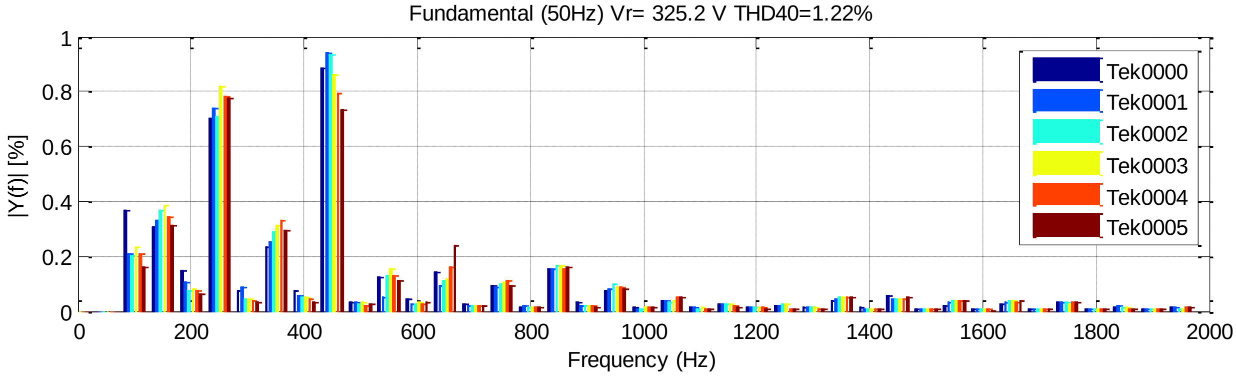

Figure 13 Comparison between voltage harmonics of V_{RN} up to 2 kHz (Tek0000 measurement with system switched off)

The following figures show the current harmonics of the 5 test conditions. It can be observed that the harmonics were very low, compared to the permitted values shown in Figure 14. Only in test one (Tek0001) harmonics I_2 and I_3 (second and third order) of phase b surpassed 1%. The reason for this outlier could not be traced back, but it might capture a transitory condition which was just captured in at a given moment, as it was not reproduced in the other tests.

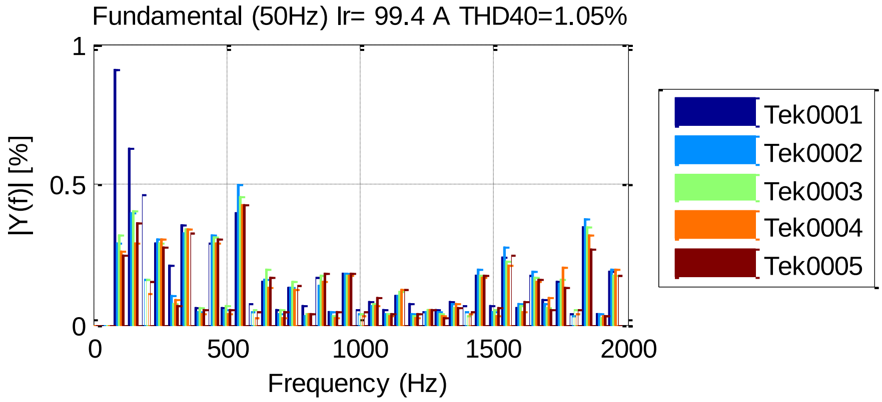

Figure 14 THD Ia and harmonics up to 2 kHz

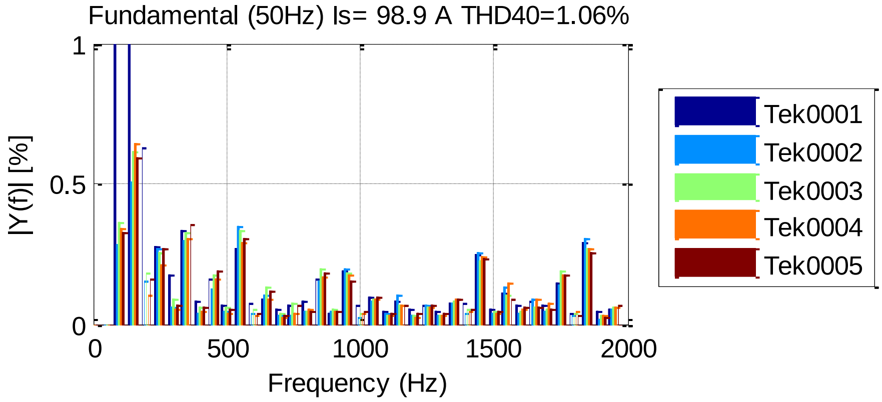

Figure 15 THD Ib and harmonics up to 2 kHz

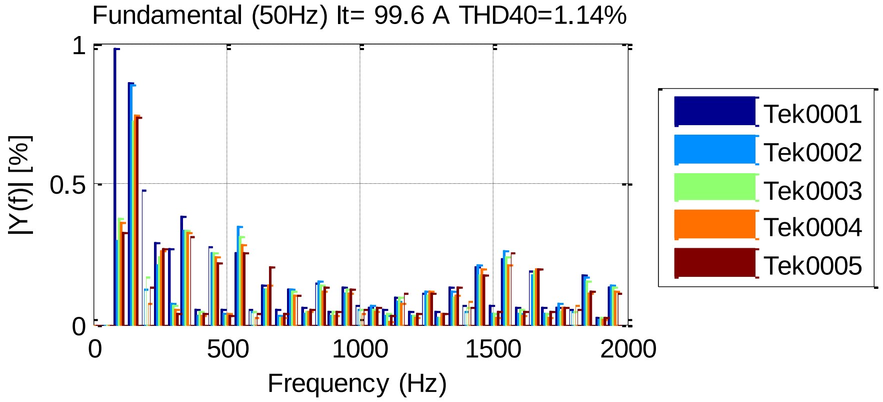

Figure 16 THD Ic and harmonics up to 2 kHz

Currently, typical switching frequencies of 10 kHz or higher are not captured by standard THD measurements according to IEC 61000-3-12. Therefore, there is a standard under development (IEC SC77A). International studies are under way to analyse the actual impact of supra harmonics. This topic will be further discussed in D 5.5.4 of the FABRIC project. Given this circumstance, in the following figures, spectra are shown up to 150 kHz (harmonic order h=3000).

Figure 17 shows the spectrum of the grid voltage up to 150 kHz. It can be observed that frequencies above 2 kHz were practically not present. In this graph, again the reference voltage (Tek0000) is included and a very slight increase of the fundamental component can be observed. This can be seen as the actual impact of the system on the grid voltage, which is very small.

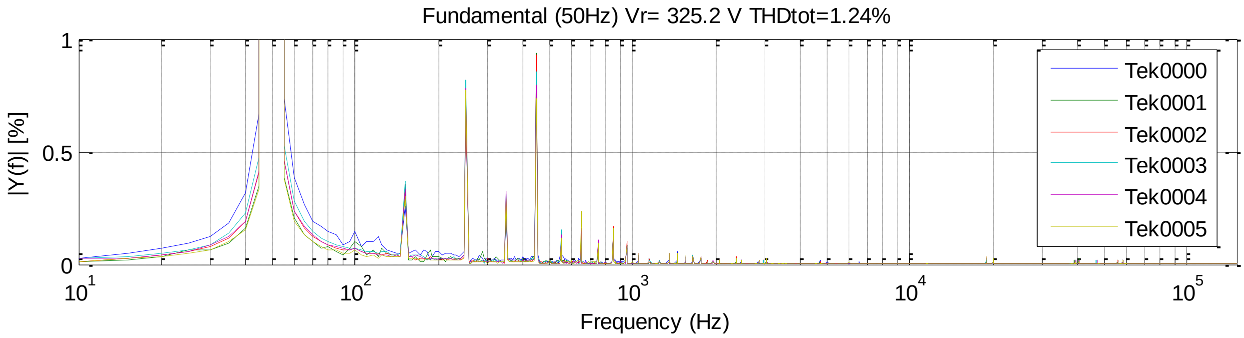

Figure 17 THD Van and harmonics up to 150 kHz

The fact that no supraharmonics could be measured in the voltage spectrum shows that the problem mentioned above is currently not an issue in the test site in Zaragoza (Spain), where the measurements were taken. Nevertheless, harmonic content of the current drawn by the system is important.

Figure 18, Figure 19 and Figure 20 shows the current spectra with the same frequency range for each phase. In this case harmonics of higher orders are visible, especially around the switching frequency of the inverter of 25 kHz. But still, harmonics are below 0.5% for all frequencies above 2 kHz. This result shows that with adequate filtering, high-frequency switching devices can be grid friendly. This is an important outcome for the analysis of large-scale implementation of this kind of equipment.

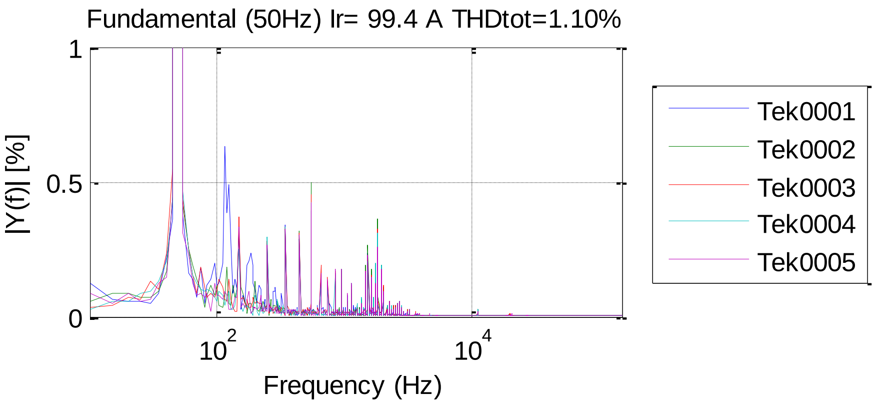

Figure 18 THD Ia and harmonics up to 150 kHz

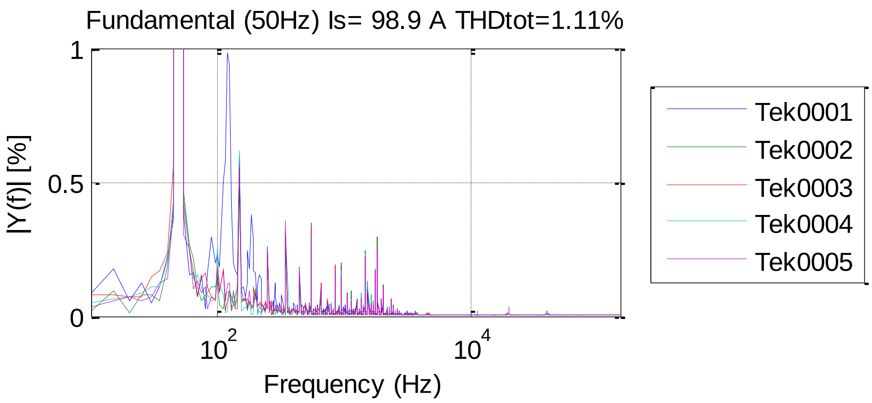

Figure 19 THD Ib and harmonics up to 150 kHz

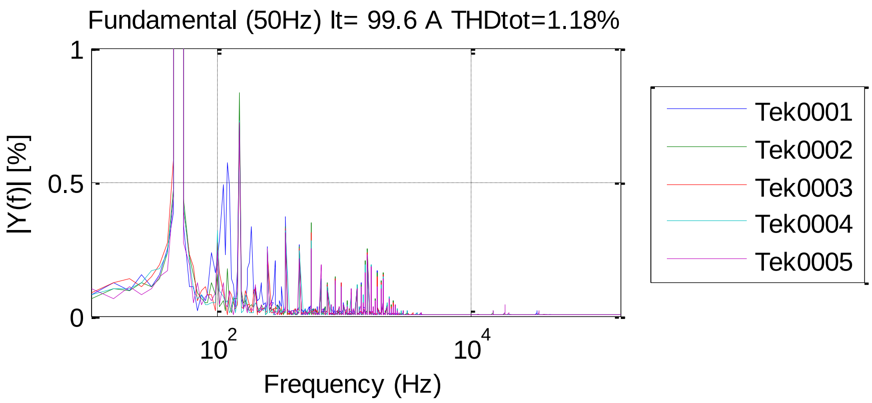

Figure 20 THD Ic and harmonics up to 150 kHz

A summary of the observed total harmonic distortions at the grid connection point is given in the table below. These values are averages of the five test runs carried out at nominal power of the system.

Table 8: Summary of THD values obtained under nominal conditions of the CIRCE system at laboratory tests

Variable	THD (%)	
	2 kHz	150 kHz
Voltage (a)	1.30	1.31
Current (a)	1.19	1.24
Current (b)	1.27	1.31
Current (c)	1.26	1.30

4.2 Power Factor

4.2.1 POLITO and SAET

Figure 21 and Figure 22 show the power factor results for the POLITO and SAET solutions at various lateral and vertical offset levels. The power factor for zero offset was 0.84 for POLITO and 0.87 for SAET; both solutions were below 0.95. The reasons for the low power factor is the type of rectifier used that intrinsically leads to a low PF of around 0.85; rectification is also responsible for the highly distorted grid current; therefore resolving current harmonics issues could significantly increase the power factor. Power factor can also be increased by improving the compensation circuit and/or using active filtering. Note that the first point (lateral=0 vertical=0) in Figure 21 and Figure 22 is the test at 60% power (6.6 kW) with no x, y and z misalignment, the remaining points are the results for testing at 100% power (11 kW).

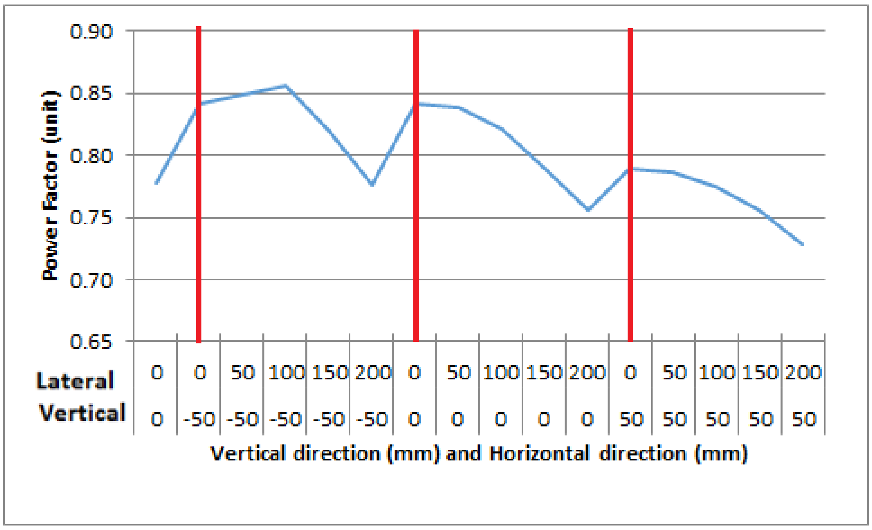

Figure 21: Power factor for POLITO

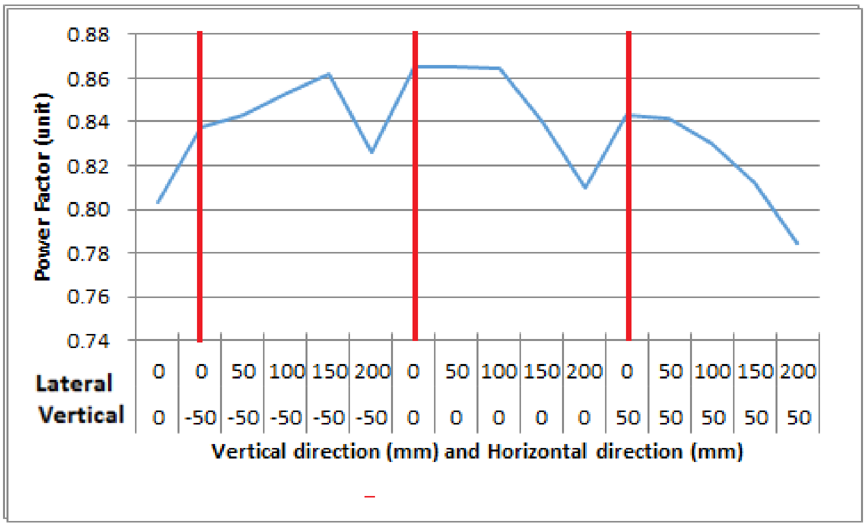

Figure 22: Power Factor for SAET

4.2.2 CIRCE

CIRCE's grid converter is a fully controlled PWM multi-level converter that allows for a total control over the power factor, which means that this converter can generate or consume reactive power if required by the grid or just operate in standard mode with unity power factor. Therefore, the power factor at the PCC and any operating conditions of the WPT system was not affected.

Figure 23 wave forms are shown for L-N voltage in phase A (V_{an}) and the three phase currents (Ia, Ib and Ic) in order to illustrate the capability of this converter to create any reactive power. The measurement was taken for a set point of 50 kVAr inductive power consumption. Of course, if the 50 kW active power is required from the charging system, no reactive power can be added, as the apparent power rating of the device is 50 kVA.

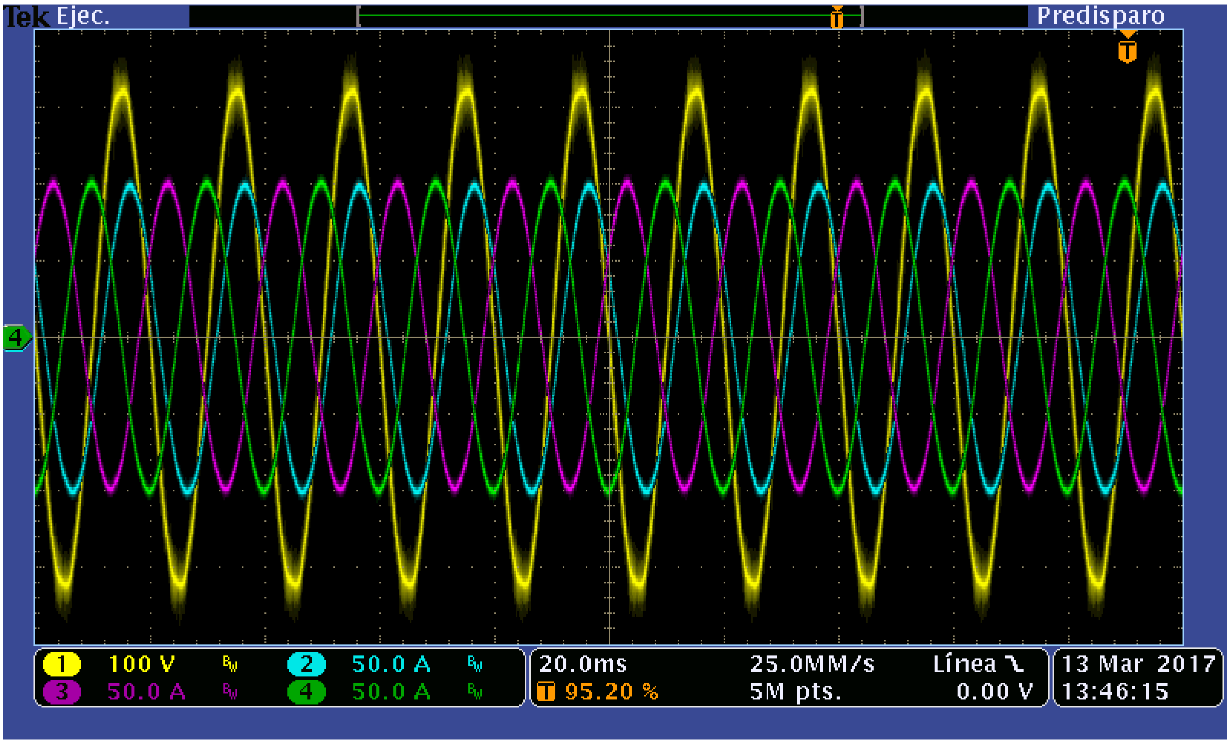

Figure 23 Van, Ia, Ib and Ic with Q=50 kVAr

4.3 Voltage fluctuations

Voltage fluctuations on the grid side are expected to be within 5% of the nominal voltage, according to EN50160. The voltage fluctuation is calculated by finding the ratio between average voltage when the solution is switched off and minimum voltage when the solution is switched on.

No voltage fluctuations have been observed during the tests for the CIRCE solution. Also, measurements are typically for a very short duration (in the range of seconds), which makes it difficult to capture any random event from the grid. On the other hand, it has been shown that the charging system did not exceed the voltage fluctuation requirements.

5. IMPACT ON ROAD AND VEHICLE ANALYSIS

Table 9 shows the mechanical parameters for the primary side for all three solutions. POLITO and SAET solutions are designed to be installed in the road by using trench-based construction methods; only a small strip of road surface needs to be excavated in order to install the primary coils. The primary side electronics are located at the road side. The geometric values show that the coils can easily be installed into a lane of a road and they will be fully covered by the body of a vehicle whilst active.

Table 9: Physical validation parameters regarding the on-road charging pads equipment.

	Solution 2 - POLITO	Solution 3 - SAET	CIRCE
Geometric features			
Length (mm)	1600	1900	800
Width (mm)	610	600	600
Height (mm)	15	15	170
Weight (kg)	11	5	40
Water resistance			
Standard compliance (e.g. IPX6)			The pit is water proof

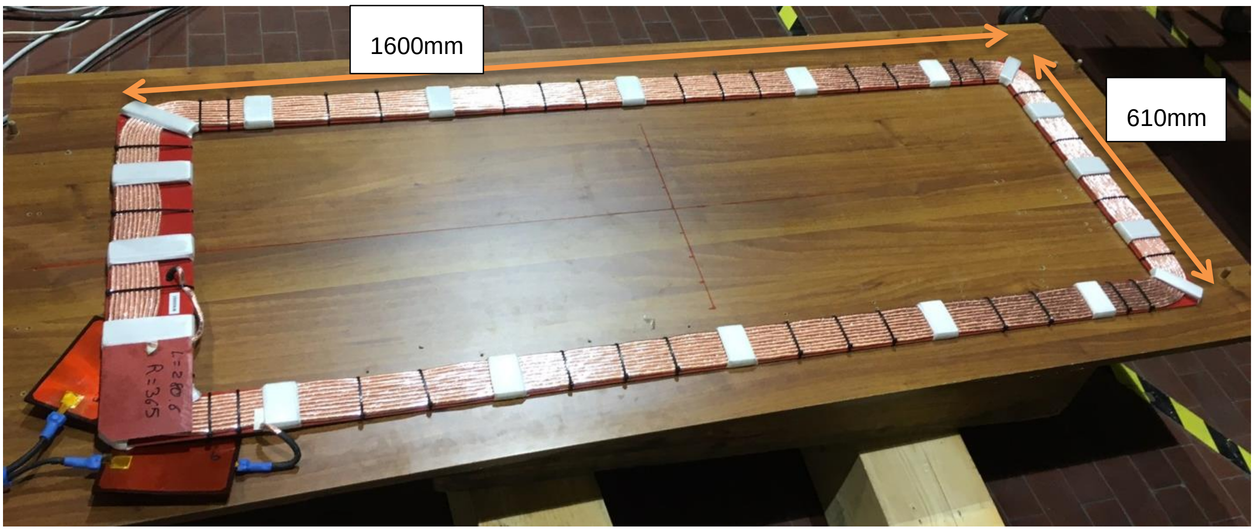

Figure 24: POLITO primary coil dimensions

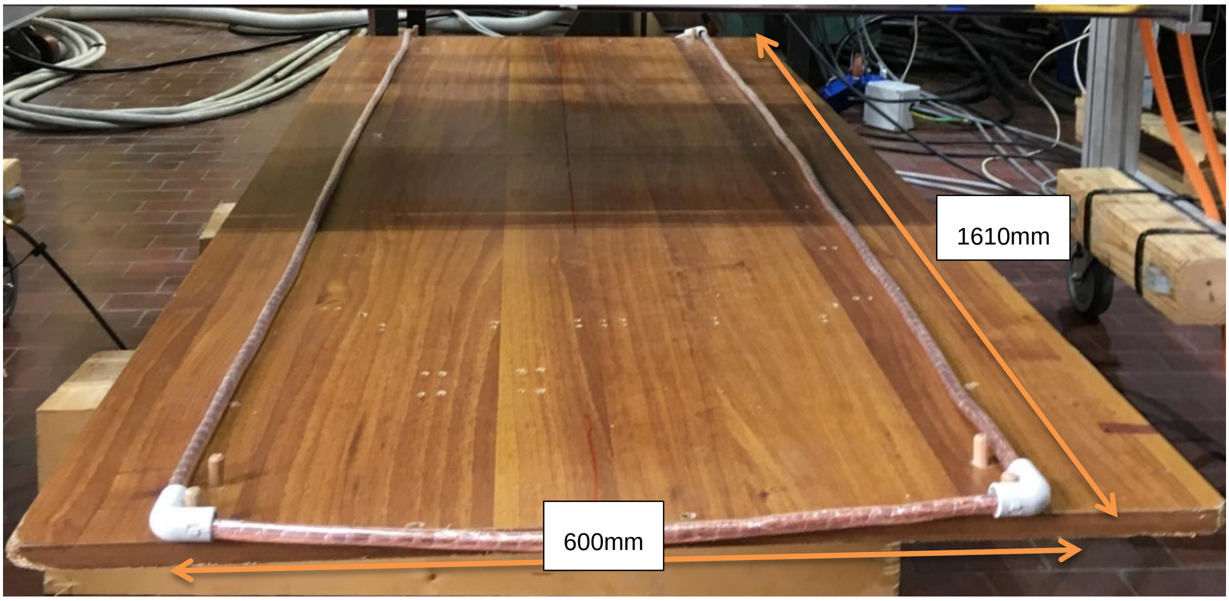

Figure 25: SAET primary coil dimensions

Table 10 shows the mechanical parameters for the secondary coil. The results show that the CRF solution, which is used as the secondary for both the POLITO and SAET primary-side solutions, adds additional 64kg on a vehicle, including the shielding. The height of the solution is 160mm; this may have an impact on the ground clearance between the vehicle and the ground, therefore the height of the solution must be reduced in order to maintain ground clearance.

Table 10: Physical validation parameters regarding the vehicle charging pads equipment

Parameter	CRF	CIRCE
Length (mm)	1430	2500
Width (mm)	530	600
Height (mm)	160	52
Weight (kg)	64	30
Water resistance		
Standard compliance (e.g. IPX6)		Yes

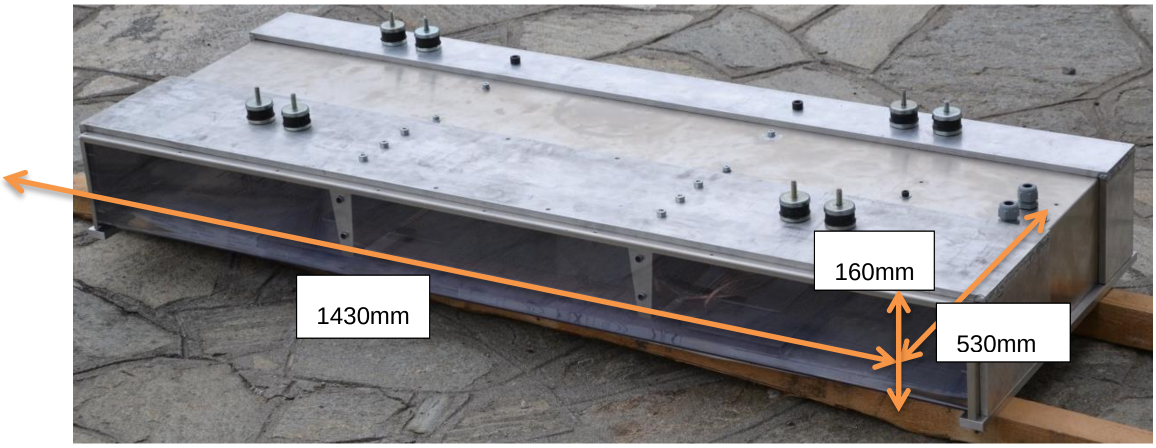

Figure 26: CRF secondary coil

Figure 27 shows the CIRCE in-road solution (primary coil), as it was also installed at Zaragoza laboratory (outside the building) for the laboratory tests. The original pit dimensions were recreated identical to the final installation in the road at the Malaga test site. In this solution, the primary coil and the parallel resonance capacitor are inside the pit, while the HF converter and serial resonance capacitor are located at the road side. The pit is covered by a non-ferric material which supports up to 30 tons of weight (a requirement of the bus used in the project).

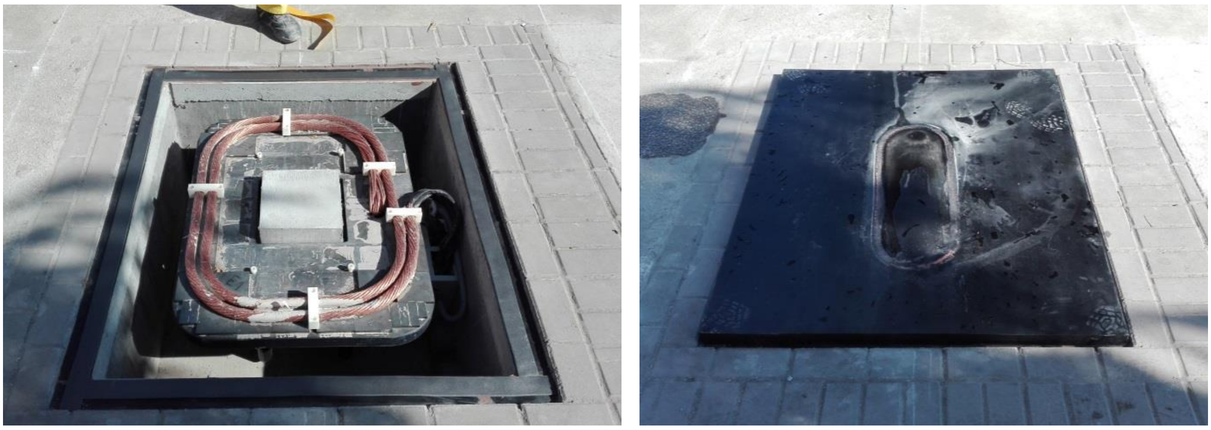

Figure 27: CIRCE solution, primary coil

Figure 28 shows the secondary coil of the CIRCE solution. The coil is embedded in a polymer canal which is filled with isolating epoxy resin, which makes the secondary coil water proof. This was a requirement, as the coil is located below the bus and is exposed to outside weather conditions.

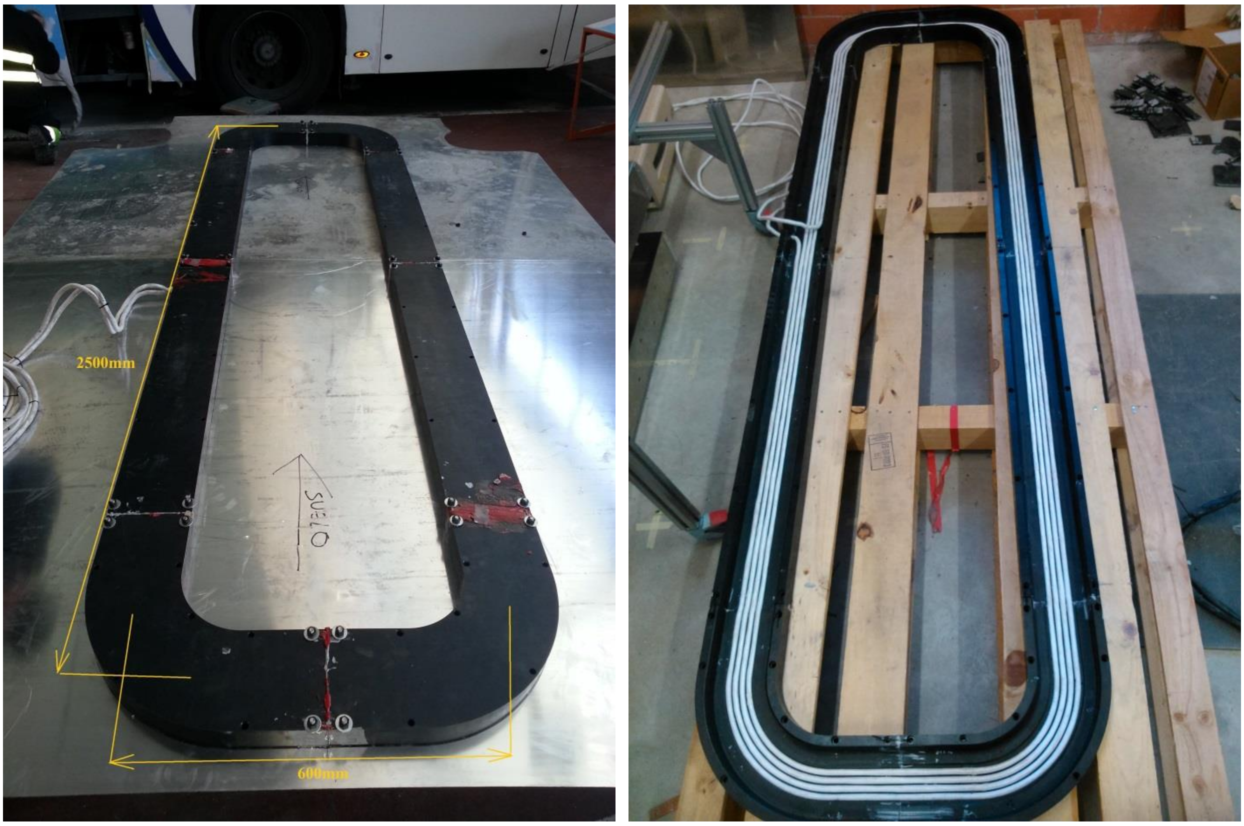

Figure 28 CIRCE solution, secondary coil

6. OPERATIONAL TEMPERATURE ANALYSIS

6.1 POLITO and SAET

The verification tests for SAET and POLITO showed that the coil temperature remained at the ambient temperature. The average coil temperature during testing for POLITO and SAET was 24 and 27 degrees Celsius respectively. The temperature was measured at primary and secondary coil. The coils were active for a very short amount of time (0.4s); therefore the temperature was not expected to rise. However, the tests were carried out one after the other and the coils temperature remained the same, even during the last series of test where the coils have been switched on and off for a number of times.

The on-board subsystem used air cooling and heatsinks to control the temperature; the temperature measurements showed that at peak current the heat sink temperature was 55°C, which meant that the cooling fan was operating at half of its nominal speed, therefore there is a tolerance to cope with higher temperatures. The primary side was cooled through natural convention of heat; the primary side was not equipped with any air or liquid cooling systems, the solution was designed to operate without any cooling for 10 seconds, for more intensive use cooling should be considered, if the tests show that the temperature exceeds the limits.

6.2 CIRCE

Figure 29 shows the temperature increment in the primary coil during a 3-minute static charging test for the CIRCE solution. The temperature rises quickly; this is due to the high resonant currents (more than 1000 A). Therefore, for static applications (minutes or hours of charging), active cooling is required. CIRCE is considering water cooling for this application.

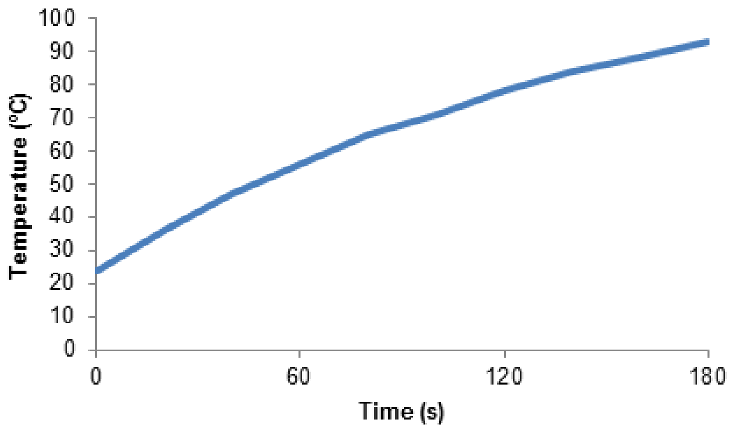

Figure 29 Primary coil temperature increment in a 3 minutes time in CIRCE solution

The tested prototype did not have a cooling system, however, requirements for a cooling system in static mode can be derived from efficiencies at nominal power (50 kW). The approximate efficiencies for each subsystem are:

- Grid-tied power electronics: approximately. 95%
- Inductive power transfer (IPT): approximately 90%
- On-board power electronics: > approximately 99%

Losses in power electronics on the primary side are mostly related to the grid-tied inverter and filters. Losses of on-board power electronics are very low, as it is a simple rectifier. The largest losses are during inductive power transfer (between primary and secondary coil); the losses during inductive power transfer are:

- Ohmic losses in primary coil: 6%
- Shielding losses: 1%
- Ohmic losses in secondary coil: 3%

6% ohmic losses in the primary coil equates to 3 kW of thermal heat flow that needs to be removed by the cooling system, the primary coil is buried under the road surface therefore it is essential to remove this excess heat in order to ensure that the system functions properly. The secondary coil excess heat flow is 1.5 kW, however, the temperature on the secondary does not rise to critical values because smaller currents result in smaller ohmic losses. In addition, larger dimension of the secondary coil favour natural cooling, which maintains coil temperature stable, even in static mode.

7. EMF AND EMC ANALYSIS

7.1 POLITO and SAET

Figure 30 and Figure 31 shows the EMF exposure in the general vicinity of the test rig (500 mm form the centre of the primary coil at nominal alignment) for the POLITO and SAET solutions. The results show that the EM level for all test setups was below 27 uT as recommended by ICNIRP 2010. However, the magnetic field level was very close to 27uT level, when the lateral offset was at 200mm.

The induction or magnetic flux density for the POLITO solution was 7.02 uT with nominal air gap and perfect alignment. The magnetic flux density or induction level for the SAET solution was 12.96 uT. The induction level for the SAET solution was higher than the POLITO solution. The higher magnetic flux density is due to the shape of the coils. The width of the SAET coil is 5 cm larger than the primary coils of the POLITO solution (this is mainly because of the necessity of optimising for the resonance frequency)/ Note that both POLITO and SAET solutions use the same secondary coil. Therefore, the shielding on the receiver was more effective for the POLITO solution when compared the SAET solution, this exposure can be mitigated by additional shields or re-designing the shape of the coils.

Assuming a linear behaviour of the magnetic structure of the secondary coil (this has been proven in simulation but also by the measurements that did not show a distortion in the current) the magnetic flux density is directly proportional to the current. Therefore, the magnetic flux density is expected to be twice as much when the current is doubled. In order to reach the full power of 20 kW it is necessary to increase the value of the current by 50% from the value used in the tests. This clearly indicates that the expected values of the magnetic flux density are still expected to be below the limit when the power transfer rate is 20kW.

When the power transfer rate increased to 15kW for the POLITO solution, the EM field was 11.34 uT at nominal air gap and zero horizontal offset. The EM field level appears to increase with increasing power; however the levels were still significantly below the ICNIRP 2010 limit.

Note that the first point (lateral=0 vertical=0) in Figure 30 and Figure 31 is the 60% power (6.6 kW) with no x, y and z misalignment, the remaining points are the results for 100% power (11 kW).

POLITO and SAET have not yet carried out EMC testing; this was not considered as a priority at this stage of the solutions development. However, both solutions were tested on a vehicle in order to observe the impacts of wireless power transfer on CAN bus. Various tests were carried out on the CAN bus with presence of active wireless power transfer and without wireless power transfer. The tests were carried out at different power and misalignment levels and the results show that there was no induced errors or malfunctioning of the existing communications within CAN bus as a results of presence of active wireless power transfer systems.

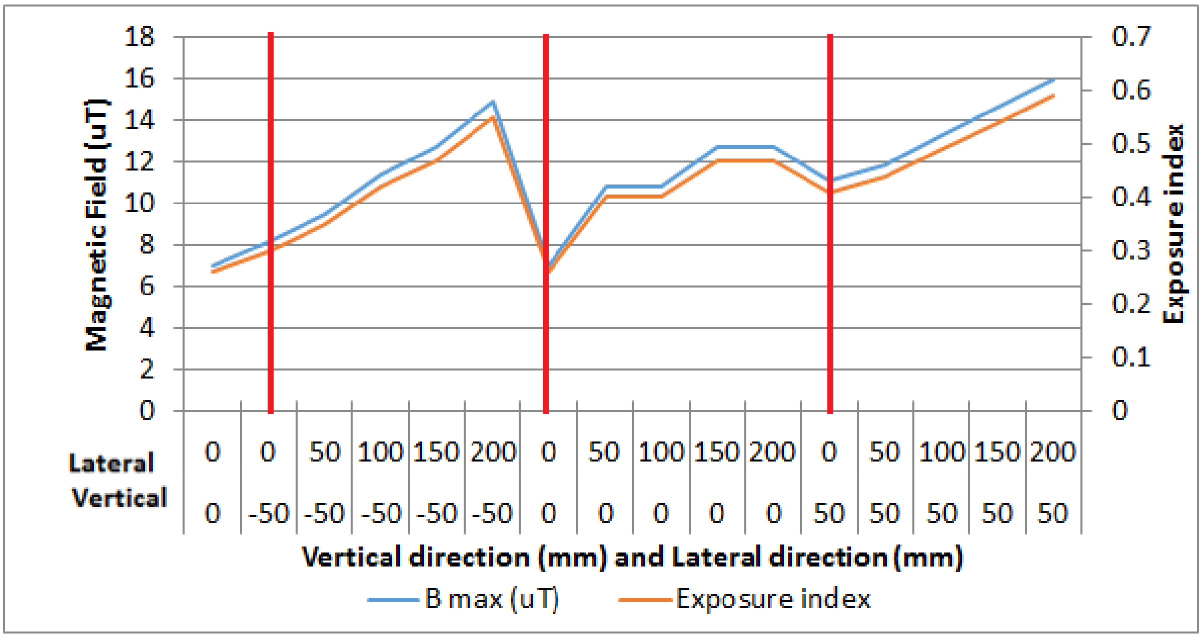

Figure 30: POLITO EMF measurements

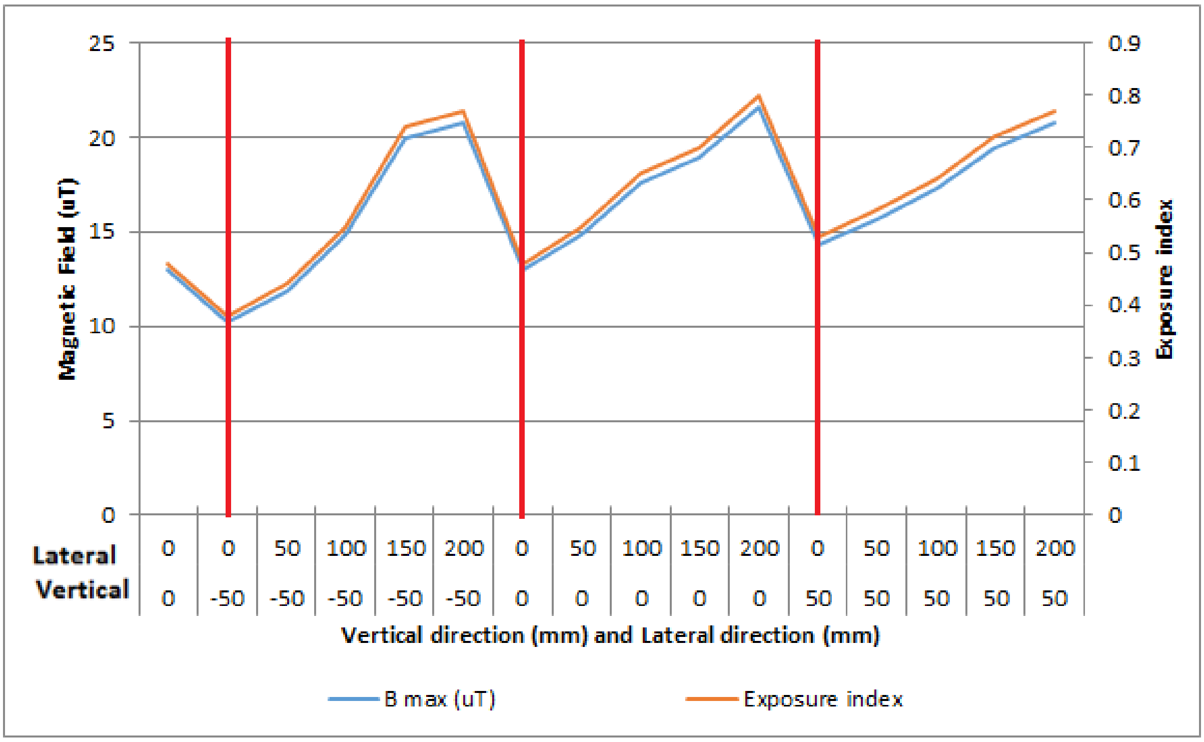

Figure 31: SAET EMF measurements

7.2 CIRCE

EMF measurements were carried out for the CIRCE solution and compliance with the norms was confirmed. As the EMF measurements were done before the CIRCE solution got involved in the FABRIC project, no comparable measurements are available. Nevertheless, during the final tests at the test sites in SP4, the test procedures described in D4.7.1 will be applied for EMF measurements for all solutions.

Regarding EMC, the original cabling of the bus (not done by CIRCE) was not compliant with Spanish EMC standards, therefore the solution did not pass the tests carried out by an official entity. The reason for this was the fact that the company that developed the bus did not respect basic rules of electrical installations for high frequency equipment. As a result, CIRCE replaced the old cables with the compliant ones. After this redesign, the bus passed successfully internal laboratory tests. The final EMC certification test is foreseen.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 POLITO and SAET

The verification test consisted of five test conditions and 15 different test setups. The detailed raw data was captured by the manufacturers (POLITO and SAET) for all test conditions. The POLITO and SAET solutions were tested at the same laboratory using the same methodology and equipment. In more detail, they were tested at 10kW at various vertical and horizontal offset conditions. The maximum power reached was 15kW from POLITO. This limitation arose from the power rating of the rectifiers used to convert the power from the grid into DC at the primary side. It is recommended that this issue can be resolved by upgrading the rectifier to provide power up to 20 kW.

The efficiency for POLITO was greater than 80% for the majority of the test cases except when the lateral offset was 200 mm. The efficiency of the SAET solution was below 80% for the majority of the cases except when vertical offset was -50 mm and lateral offset was 0 mm. The result showed that the SAET solution should be improved in order to achieve at least 80% efficiency when the solution is perfectly aligned at nominal airgap. The efficiency of the SAET solution can be increased by improving the coupling between primary and secondary. The primary coil is a loop of wire on a platform; even small changes in the shape of the loops could have a significant effect on the power transfer rate. Therefore, using a rigid frame to ensure that the primary coil is securely mounted could increase the efficiency of the system.

The Total harmonic Distortion (Current) was as high as 61.9% for 0 mm horizontal and vertical offset condition. The current harmonics were high because of the use of six pulse rectifiers which distort the current waveform at the input. The solutions were laboratory test solutions at the moment of conducting the verification tests; therefore meeting current harmonics requirements was not seen as priority. However, the solutions are expected to meet all harmonics requirements during validation tests in SP4. There is a need for further harmonics treatment such as introduction of 12-pulse rectification in this solution, which should lead to a better current waveform hence improved THD. A second improvement would be an AC/DC converter with unity power factor. These improvements should completely solve the THD problem, although they may increase the cost.

8.2 CIRCE

The laboratory tests with this solution were successful and all required functionalities of the power transfer equipment were verified. The power transfer efficiency was high, over 80% in most of the operating conditions, including various misalignment positions. Major emphasis was given to the grid impact of the system (namely harmonic distortion and power factor). It was demonstrated that the employed PWM multi-level converter, which was developed for conventional fast charging stations, is most suitable also for this application and provides excellent grid friendliness with fully controllable power factor and current THD below 2%, even considering supraharmonics up to 150 kHz. Regarding EMF, all measurements indicated compliance with current standards. Nevertheless, during final tests at the test sites in SP4, exhaustive measurements will be taken.

The laboratory tests were carried out under near real-world conditions, as charging tests were done with the integrated bus outside of the laboratory in Zaragoza. Test results were satisfactory and no major issues where detected. This positive result was mainly due to the previous experience from the UNPLUGGED project, where most of the issues of the WPT system were solved.