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On the evaluation of Electromagnetic Compatibility (EMC) of a prototype electric vehicle

Electromagnetic interference filters and EMC remedies to conducted disturbances in AC-charging

Pliakostathis K., Scholz H.

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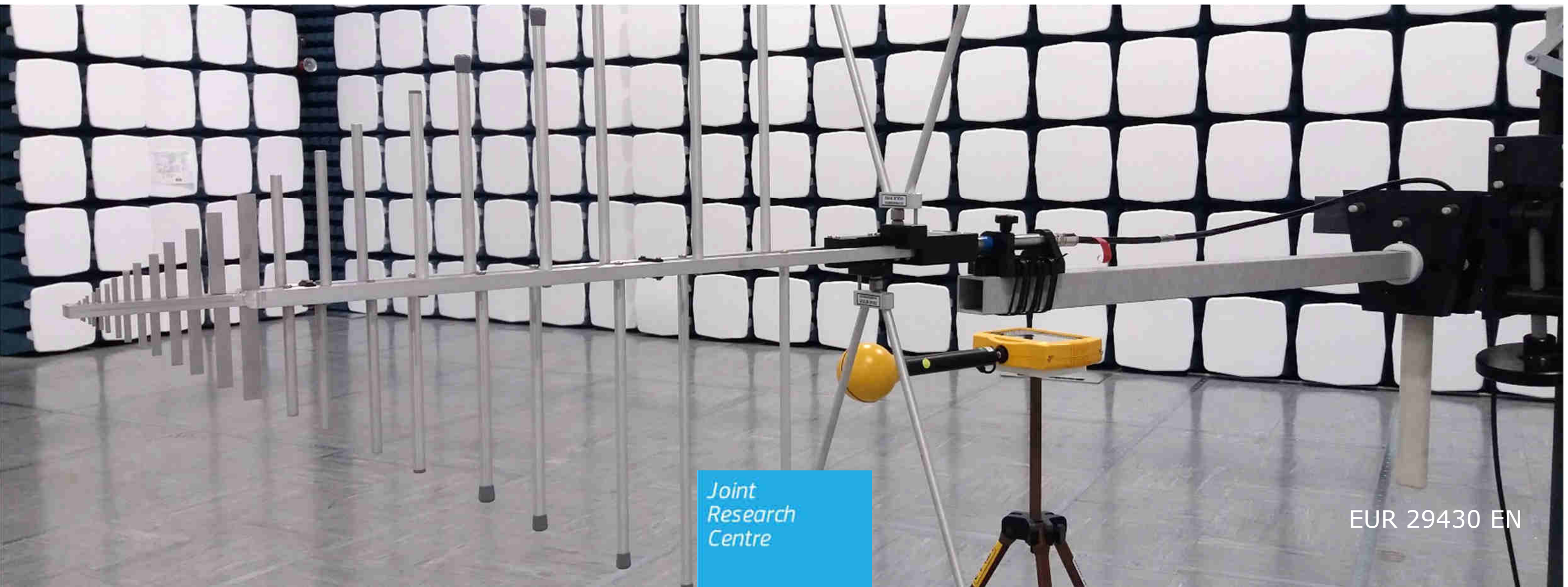

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Authors

Konstantinos Pliakostathis

Harald Scholz

Abstract

As a part of its mission, JRC performs pre-normative research in strategically important areas, often in private-public partnership, if methodological knowledge consolidation is in reach. Specifically for road-bound electro-mobility, the JRC's European Interoperability Centre for Electric Vehicles and Smart Grids can test the electromagnetic compatibility of electric vehicles in full road simulation and in recharging, by virtue of its V*e*LA 9 electromagnetically semi-anechoic chamber (SAC) with integrated, filtered recharging power supplies and a shielded 4x4 roller bench. In this context, the authors accepted requests by several external vehicle manufacturers to carry out conductive and radiated emissions measurements on prototypic and series electric vehicles (EV) under charge, in accordance with national and international electromagnetic compatibility (EMC) automotive and electro-technical standards. Such measurements require the presence of dedicated EMC instrumentation and properly validated laboratory facilities, not only including the semi-anechoic chamber itself, but also antennas, shielded cablings, electromagnetic interference (EMI) receivers and line impedance stabilisation networks (LISNs) that V*e*LA 9 is equipped with for such purposes, all complying to the requirements of EMC regulations.

1 Introduction

The rapid spread of electronic devices and modules which rely on the wired and wireless channel for their communication, is more evident than never before. As the complexity and intelligence of the corresponding systems increases, the need to control and manage their intended operation becomes critical. Components shrink in size, their packing density, together with their signal frequencies, tend to improve and this makes the possibility of electromagnetic interference to become even more dominant.

There are numerous reports e.g. [8] that have linked EMI with the ability of a device to function in accordance with its intended purpose. Navigation, automotive, aviation, defence systems, medical devices, portable equipment, satellite services and so on, can have their functions be disturbed due to the presence of EMI. This is a concern that involves not only system designers but also national and global standardization authorities, as they have to deal with the implications of the radio frequency 'pollution' caused by the EMI.

EMC regulations (e.g. [1], [9]) and directives e.g. [10], come into force as a means to tackle and control the problem of EMI. EMC ensures that an electronic system:

1) does not generate an intolerable radio frequency disturbance to its environment
2) has the capacity to function as intended in its electromagnetic environment

The EMI relies on radiated and conducted phenomena that can reach or generated by any electronic system [2]. Radiated emission is in principle electromagnetic energy that propagates in the open space, while conducted emissions travel through a conductive medium. Immunity examines the ability of a system to operate correctly under the presence of intentional and unintentional electromagnetic noise and interference. EMC test laboratories ensure that scenarios of radiated emissions, conducted emissions and immunity can be established and analysed in order to assess a product's tolerance against EMI. This, together with the test procedures prescribed within the relevant EMC standards, ensure that a product, prior to its release on the market, has been designed and developed in accordance with the correct EMC practices.

EMC standards define the exact methodology, which is required to apply in order to judge whether an electronic circuit or system complies and deals effectively with the EMI problem. In many cases, these also come into force to limit the human exposure against strong electromagnetic fields, e.g. mobile phones [11].

Therefore, it can be seen that EMC is not an option but a necessary procedure, which has to be incorporated into a product at the very start of the design process to avoid any implications during testing. Equally important is for the EMC engineer to have the knowledge and skills to configure the EMC test equipment, setup the laboratory, conduct the test in accordance with the EMC standards, analyse the results and provide solutions to EMI problems.

The aim of this Technical Report is to reveal a series of observations and propose suggestions that can be applied in practice in order to control and minimise, as much as possible, the EMI conducted on the 230VAC power line of an AC-charging adapter charging a prototype fully battery-electric delivery van in single phase. As indicated by the vehicle manufacturer, the EV under consideration can be directly charged from the grid with AC power via their adapter, which means that EMI (if any) generated internally by the vehicle can,

1) propagate conductively towards other equipment that shares the same AC power line of the grid and
2) radiate in the open space causing possible disturbances to the normal operation of other nearby equipment or wireless services.

2 Radio Frequency (RF) Conducted Disturbances on a prototype EV

An extensive and systematic approach into the measurement of RF conducted spurious emissions from 150 kHz to 30 MHz was carried out in the V*e*LA 9 SAC, to investigate the EMC performance of the prototype full electric delivery van during AC charging. For this purpose a single-phase line-impedance stabilization network (LISN model: "LISN 1600" made by LAPLACE INSTRUMENTS Ltd.) was connected to a Rohde & Schwarz EMI receiver (model ESR7), while all procedures for the proper configuration of the instruments and system losses (cables, attenuators, etc) were considered accordingly to ensure the accuracy of the measurements. Figure 1 shows the laboratory setup for the conducted emissions inside V*e*LA 9 EMC semi-anechoic chamber, the latter installed with RF filters on the mains power line to provide a clean, from RF disturbances, AC power to all apparatus.

EMC limits of disturbances propagating along AC Power Lines were applied as per Regulation No. 10 of the United Nations (E/ECE/324/Add.9/Rev.5) [1], specifically therein: Table 7 "*Maximum allowed radiofrequency conducted disturbances on AC-power lines*", which in turn had been based on IEC 61000-6-3 limits [12]. This was decided due to the fact, that at the time of the tests, the IEC 61851-21-2 was still in draft status, and the EV manufacturer had based its prototype programme on this Regulation No. 10 procedures.

The results of the measured conducted emissions inside V*e*LA 9 EMC chamber with the EV charged directly from the single phase AC main grid, together with the limit line, are shown on Fig. 2. Both the phase and the neutral lines showed EMI levels that were not obeying the maximum limit, a clear indication that the EV was generating excessive disturbances during charging. A detailed listing of the measurement conditions and instrumentation settings are shown on Table 1.

From figure 2, it is evident that the major interference occurs at around 8.15 MHz and exceeds the limit (50 dBμV for the "average" detector as defined in [1]) by almost 8 dB on the neutral line and by 15 dB on the phase line. It was also observed that the emissions show a broadband behaviour, spanning as high as 30 MHz, although the detected RF voltages on the upper end of the band are within the limits. As a next step and in order to face this problem, EMC troubleshooting procedures were applied by installing on-board EMI line filters. These were mounted between the EV battery-charging module and the entry point of the AC charge socket.

The vehicle manufacturer offered us a series of EMI line filters for the purpose of minimising the conducted interference caused by the EV during AC charging. However, none of these filters provided an adequate solution to the conducted emissions problem. In this frame, the authors carried out, in addition to the aforementioned LISN measurements, a series of measurements on the RF filters themselves in order to examine their transmission characteristics and validate their performance. Two AC power-line filters were measured, firstly a FUSS-EMV model 4F480-032.260 and then a custom-made 3-line RF filter based on ring ferrite topology. These filters were mounted on the vehicle according to the company's own methodology.

Figure 1: Laboratory pre-setup of the conducted emissions inside the VeLA 9 semi-anechoic chamber (not shown here is the charge cable z-folding and the 100 mm spacing above ground which were applied later)

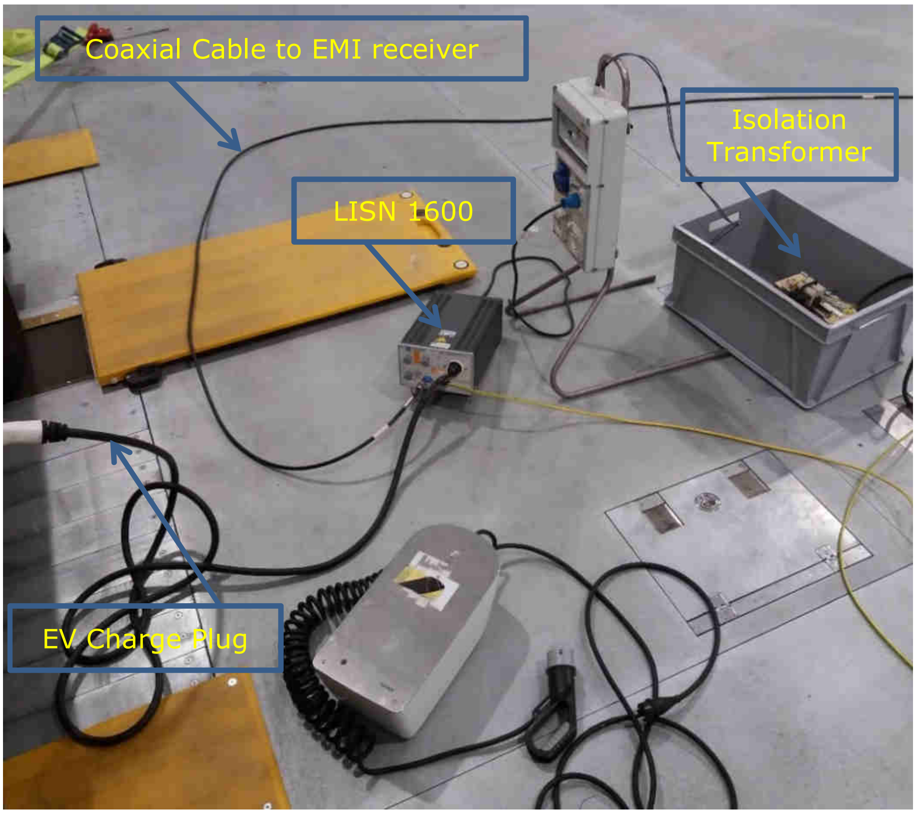


Figure 2: Conducted emissions measurement, 150 kHz to 30 MHz with Average detector (RBW = 9 kHz), of prototype EV during AC-charging, neutral (blue trace) and phase (brown trace) line. The limit (Avg.) is shown with the red line.

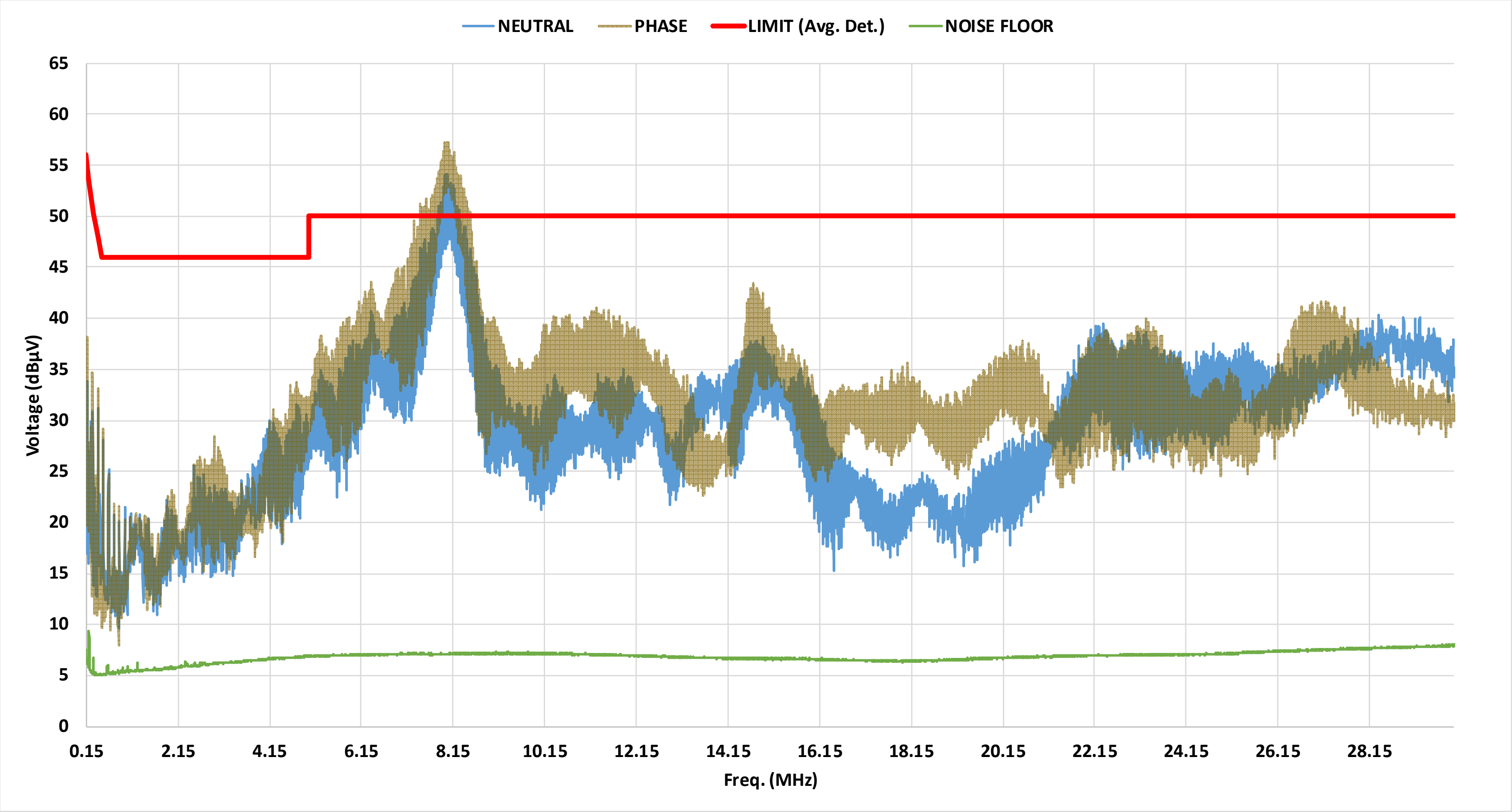


Table 1: Conducted Emissions Test Summary

SUMMARY OF CONDUCTED EMISSIONS MEASUREMENT	
Test Location	VeLA 9, Interoperability Centre, JRC, Ispra, IT
Chamber type	Semi-anechoic with RF filtered AC power grid
EUT	EV (full battery-electric delivery van)
EUT condition	Prototype, with different internal filters
Test Standard limit applied	Regulation No. 10 (E/ECE/324/Add.9/Rev.5), Table 7 : "*Maximum allowed radiofrequency conducted disturbances on AC-power lines*"
Test Type	Conducted Disturbances on AC Power Line
Rated Voltage	230VAC
Rated Frequency	50 Hz
Number of Phases	Single Phase
State of EUT during test	*Off* and *in charge* mode
Charge Cable Type	3 wires (P+N+PE), unshielded as in real world application
Test Frequency Range	150 kHz – 30 MHz
LISN	LISN-1600 (Laplace Instruments)
EMI receiver	ESR7 (Rohde and Schwarz)
Measurement Detector Type	Average
Resolution Bandwidth (RBW)	9 kHz
LISN Attenuation	20 dB
LISN RF Filtering	150 kHz High Pass Filter
EMI Receiver Attenuation	10 dB
Supplementary Instrumentation	MS4630B Vector Network Analyzer (Anritsu) for measuring various internal filters proposed by the manufacturer for application in the EV under test
Test Result	Deviation (phase and neutral)

3 Common-mode filtering concepts

Conducted emissions are greatly influenced by the common mode currents, which flow in the same direction along single or multiple cables, as opposed to differential mode currents [2]. These currents do not only contain unwanted high frequency components that can penetrate conductively the circuitry of nearby sensitive low-voltage circuits (e.g. digital, etc.) forcing them into an error state, but can also be radiated from the cables in the open space causing radiated EMI. In extreme cases, these high frequency components can pass over to close-by conductors through cross coupling. Hence, it is very important that conducted emissions are restricted as early as possible at the noise source. This can be achieved - amongst other approaches - by properly installing and carefully wiring AC power-line RF filters that are targeted to attenuate the above-the-limit critical frequencies.

Testing the effectiveness of these filters requires the application of accurate and structured laboratory practices. One of the authors (KP) carried out filter tests in accordance with standardised engineering methods to ensure validity of the results. Firstly, the EMI-filter (made by FUSS-EMV) was considered and the results were correlated to those that the manufacturer FUSS-EMV claims on its product datasheet.

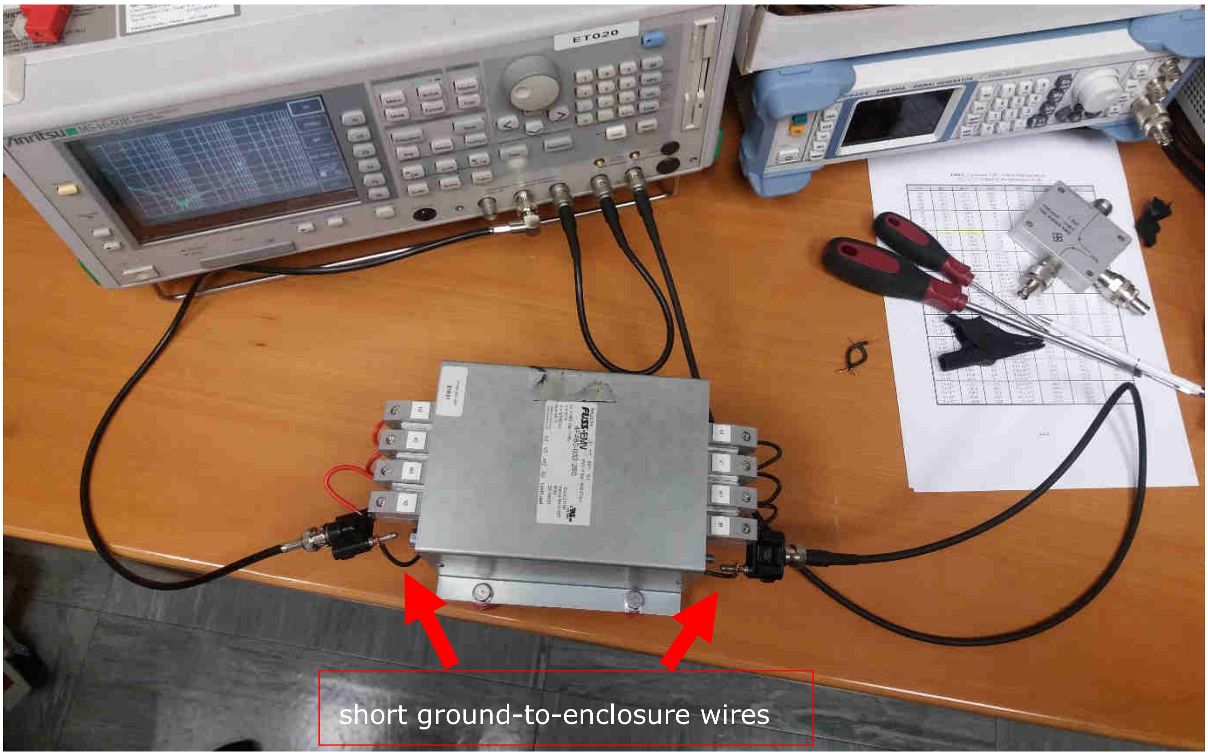
4 FUSS-EMV EMI-filter validation

The test setup for this filter is shown in Figure 3. The input and output of the AC power line filter, which provided the 3 phases, a neutral and a ground port, were wired accordingly to measure the common mode effectiveness, which is the main concern in conducted emissions [2]. As widely known for this type of filters, effective common mode signal rejection is achieved when there is a high transmission loss (S_{21}) between the input and the output of the filter. The filter was measured on V*e*LA 9 on its rejection (in dB) characteristics against high frequency spurious signals through the filter ports, i.e. the 3 phases and the neutral lines, using a calibrated vector network analyser (VNA) by Anritsu (model MS4630B).

The results of the measurement setup as per Fig. 3 are shown on Fig. 4, for the spectrum between 100 kHz and 100 MHz. This response presents an excellent agreement with the manufacturer's data about response [3], see Figure 5 (black trace for Common Mode = "CM"), validating our setup. Any minor deviations are due to cable and adapter losses, and instrument accuracy, which are unavoidable. It can be observed that the FUSS-EMV filter provides maximum attenuation of around 80 dB at 450 kHz, while good rejection around this frequency spans from about 300 kHz up to 7 MHz, sharply rolling down outside this frequency band. The 'spikes' observed at around 450 kHz are due to the instrument's noise floor characteristics and resolution bandwidth (RBW).

Table 2, summarises the common mode attenuation (in dB) introduced by this filter at representative frequencies, for the measured response shown on Figure 4.

Figure 3: Laboratory setup for the common mode rejection performance of FUSS EMV 4F 480-032.260 line filter



It has to be underlined that the filter's rejection capacity requires proper wiring of the line filter in consideration. Specifically, during the installation and wiring process one has to ensure that the conductive enclosure of the filter is connected to the grounds on both the input and the output sections of the power lines and by using the shortest possible wire length, as shown on Figure 3. This means that the ground cable on the input side (left section) of the filter on Fig. 3 starting from the cable, is connected to the closest point of the filter's enclosure. A screw is provided on the filter for this purpose. This was similarly applied to the output section of the filter: The ground of the wire leaving the filter was connected to the enclosure (which serves the purpose of ground) at the nearest ground point, where a separate screw is provided for this. Not doing so, the performance of the filter deteriorates dramatically making common mode filtering, if not obsolete, at least problematic, hence allowing unwanted conducted emission frequency components to travel down the AC line from the EV.

In order to emphasise the importance of proper grounding methodology, the FUSS-EMV filter was again measured for its common mode response without grounding (i.e. 'floating' enclosure) or only partially grounding either side of the filter's enclosure. The response of this scenario is shown in Figure 6. From this figure, it is clear that the rejection properties of the line filter degrade by at least 50 dB or more, making it inappropriate to block efficiently any conducted spurious high frequency components. At best, the filter can provide a 30 dB attenuation, down from 90 dB, at around 250 kHz and less than 5 dB at around 8 MHz, where the conducted emissions are above the limits. So in order to achieve optimum filter performance, someone has to consider not only good wiring practices (i.e. short cabling) but also proper ground practices as applied to EMC product design.

Figure 4: Measured common mode transmission response of the FUSS-EMV 4F480-032.260 EMI line filter (attenuation of the filter is plotted from the reference value 0 dB at top towards the bottom of the ordinate axis)

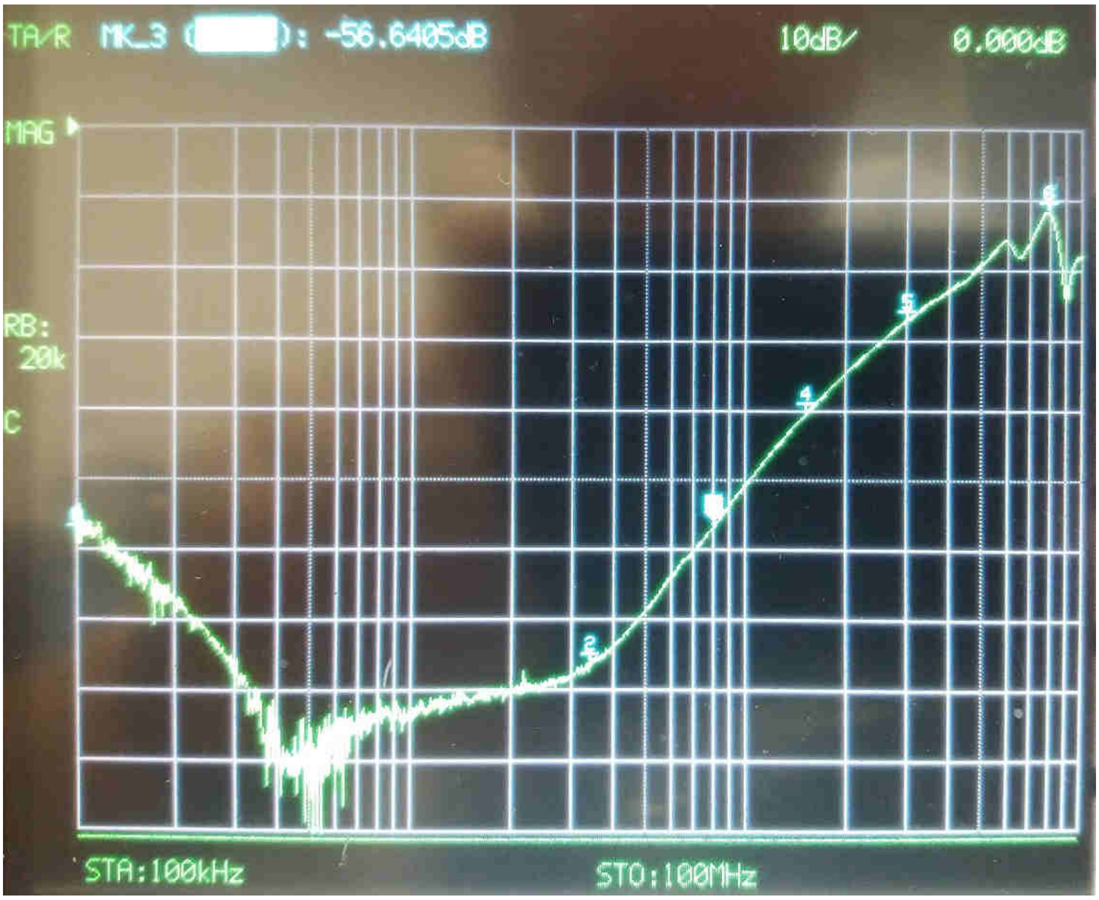


Figure 5: Manufacturer's (FUSS-EMV) data sheet regarding the response of their EMI line filter (Common Mode = CM with black trace; Differential Mode = DM with green trace) [3]. (Here, the attenuation of the filter is plotted from the reference value 0 dB at bottom towards the top of the ordinate axis)

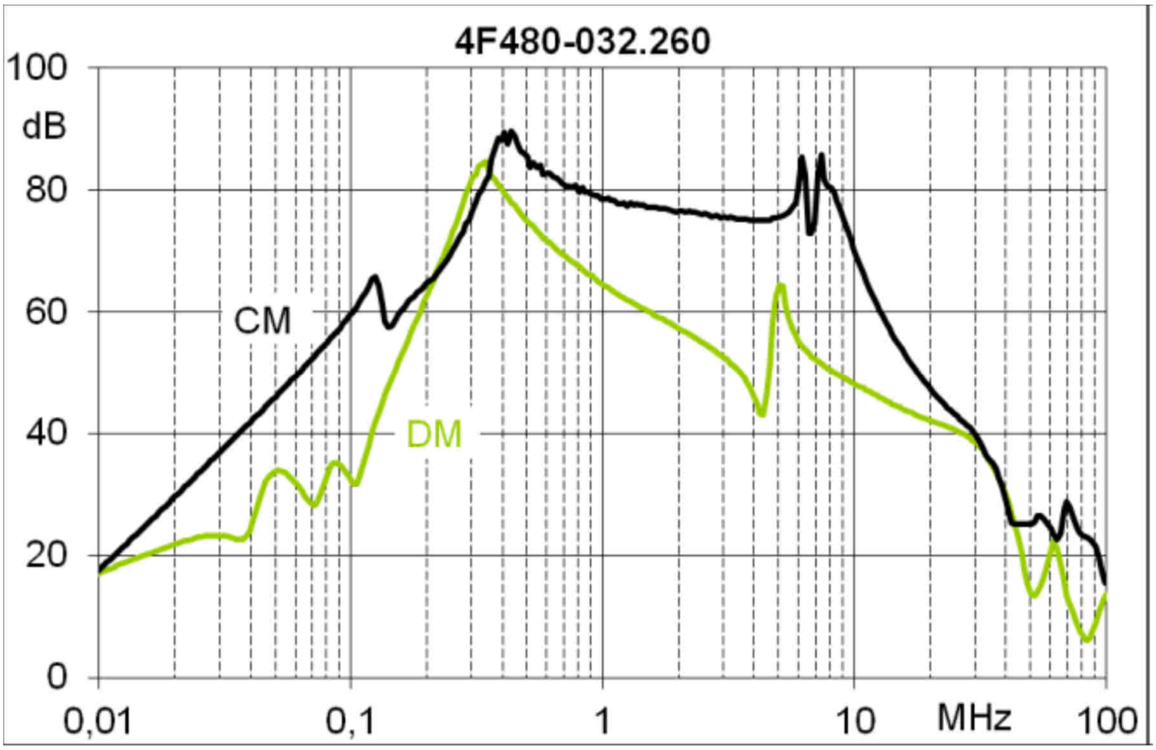
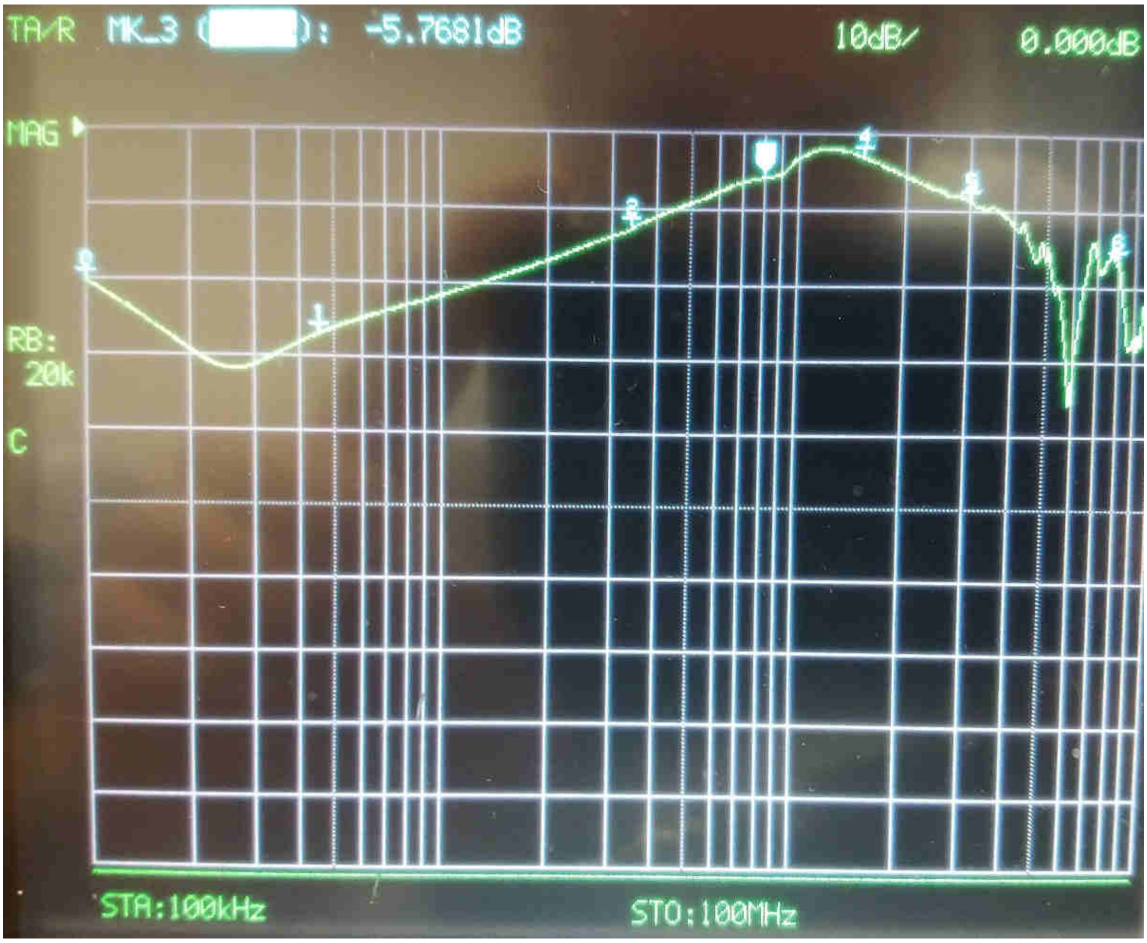


Table 2: Measured common mode attenuation of FUSS-EMV power line filter at various frequencies

FREQUENCY	COMMON MODE ATTENUATION
100 kHz	55.80 dB
450 kHz	76.07 dB
3.39 MHz	61.45 dB
8 MHz	57.30 dB
15.07 MHz	49.46 dB
30 MHz	32.40 dB
80 MHz	12.84 dB

Figure 6: Measured common mode (rejection) response of FUSS-EMV filter with ground enclosure ‘floating’



5 Laboratory assessment of custom made 3-line EMI-filter

The next filter that was evaluated for its common mode performance on VeLA 9, was a custom made 3-line filter based purely on toroid ferrite implementation. The design concept of this type of filter differs in some respect to the FUSS-EMV filter, notably due to the absence of ground enclosure and the shunt capacitive topology, see figure in Annex 1 for internal circuitry of FUSS-EMV. Nonetheless, it is used in practice due to its simple construction procedure and low cost, although its performance cannot reach that of the more advanced circuit topologies of other EMI filters.

The measurement setup for this filter is demonstrated in Figure 7. Likewise in the FUSS-EMV filter, in order to assess the effectiveness of the common mode behaviour, the input ports (1, 2, 3) of the filter were connected (shorted) together in order to apply a common signal across them. The same applies for the output of the filter; the output lines were connected together and the output signal of the filter was sent to the VNA. The measured response of the transmission characteristics of this arrangement is presented in Fig. 8. In this case, the ground point of the test cables were left disconnected, since the filter did not provide a ground for this purpose. By adding a connection between the input and output ground sides, a current loop would be established which will make the results inaccurate, as the VNA provides already a common path for these two ground points.

It can be seen (Fig. 8) that the highest rejection, or about 28 dB, is achieved at around 3 MHz. Table 3 shows the measured attenuation of the filter at representative frequency points. The filter possesses an amount of attenuation to common mode signal, which is, if not worse, at least comparable, to the poor response of the FUSS-EMV filter when it is left ungrounded. At 8 MHz, where most conducted noise is generated by the EV in charging mode, the attenuation is limited to 20 dB.

As outlined beforehand, uncontrolled mounting of the RF filter on an actual system is expected to deteriorate the filtering performance, unless proper EMC installation procedures are followed. The EV prototype provided an on-board mounting box for a quick swap of the filters, which is useful in practice, but that has to ensure as well that the location and wiring of the filter itself prioritises the EMC noise problem caused during the EV charging.

In addition, someone has to ensure that the correct ferrite type [4] material for the frequency of interest is used [5], properly sized to be able to handle the high current values along the AC lines to avoid saturating the ferrite material. Excessive currents can saturate the ferrite core (of permeability (μ_r)), which in turn reduces the effectiveness of the filter against high frequency residual currents [4]. For better EMC performance, it is also equally important to provide a conductive enclosure in order to protect the ferrite core against unwanted pick up noise from the surroundings or radiation of its RF currents in the open space.

A final note has to be made, which concerns the actual wiring layout of this filter. It is essential that the output and input lines of the filter shall not placed in proximity. Doing so, will result in unwanted cross-coupling between the input and the output ports, which in effect would bypass or degrade the isolation action of the filter. For example, a closer look into the inside of the physical construction of the filter, Fig. 9, reveals that there is a strong overlap between the input and the output cables. Such an arrangement is generally not recommended for EMC purposes, as it enhances the unwanted coupling between the cables, which in turn can allow noise to propagate down the lines in an uncontrolled manner. It is suggested to separate input and output lines and distance them from each other as much as possible, if space allows it.

Figure 7: Laboratory setup for measuring the common mode (rejection) performance of the custom made 3-line RF filter

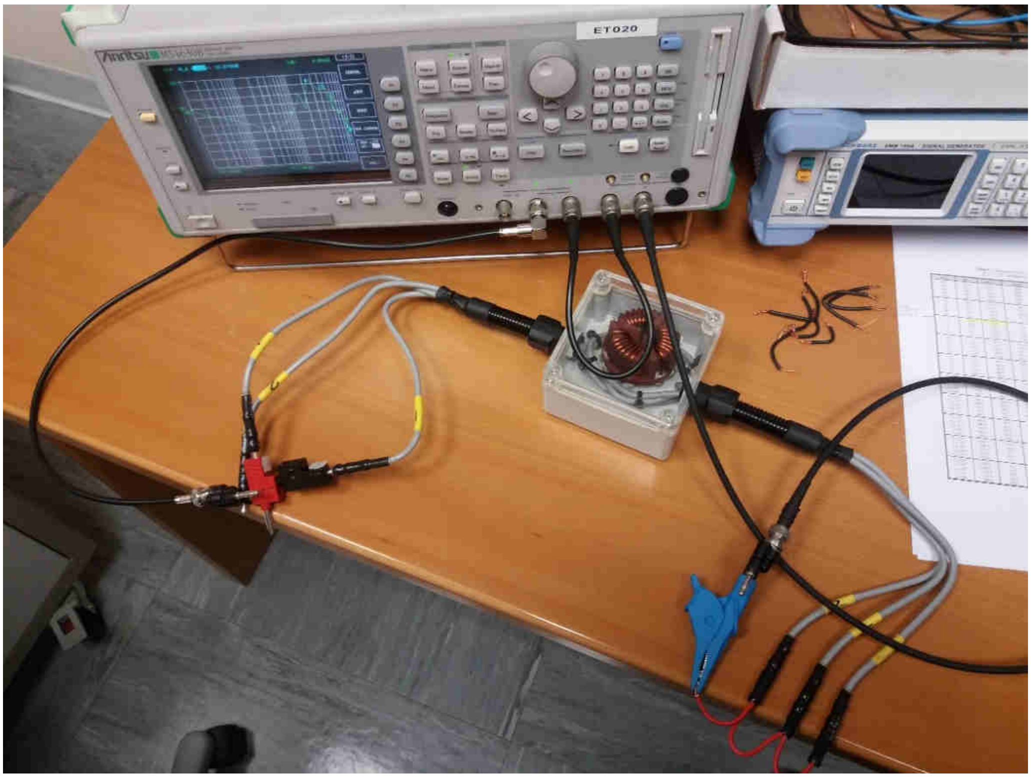


Figure 8: Common mode (rejection) response of the 3-line filter, measured at JRC

Table 3: Measured common mode attenuation of the custom-made power line filter at various frequencies

FREQUENCY	COMMON MODE ATTENUATION
100 kHz	16.14 dB
500 kHz	22.27 dB
3 MHz	28.88 dB
8 MHz	21.52 dB
23.6 MHz	4.08 dB
46.12 MHz	8.60 dB
100 MHz	34.70 dB

Figure 9: Unwanted cross coupling can be caused between the input and output cables seen inside the red circle

6 Outline of conducted EMI troubleshooting techniques

In any case, the ideal response of a line filter, as shown for example on Fig. 4, assumes best case EMC performance scenarios like those established within controlled laboratory conditions. In practice, this means that a filter mounted on a product, such as the EV vehicle in this case, may show a reduced performance depending on the EMC particularities of the EV system as a whole. The filter itself, for example, should be installed as close as possible to the noise generating source, e.g. the inverter in the charging unit of the EV that converts the supplied AC electricity into DC for its driving-battery charging process. Further, in order to attenuate as early as possible any spurious signals, the wiring should be done in a way such that the (clean) output of the filter is not in proximity to any noise generating sources, see for instance Fig. 10 [6]. Such a noise source could be caused by the poor filtering performance of the above mentioned on-board AC to DC inverter used during the charging of the DC EV battery system. Quite often, such inverters are known to rely on switched mode signals that generate EMI, if not filtered properly at PCB level. So here, the manufacturer can analyse the situation from a design point of view.

In addition, as discussed before, proper grounding techniques need to be applied, see Fig. 11 [6], to ensure that the return ground of the noise source is wired to the filter ground (enclosure) in order to stop spurious signals from propagating down the AC line or getting cross-coupled to the chassis of the system. Another quick fix would be to add ferrite-rings of clamp-type on all the entry and exit points of the noise-generated box [7]. No single wire should be left disconnected, float or not properly be terminated; unused cables are susceptible to noise pick up or generation since they can act as unintentional antennas.

There are numerous studies and reports in the literature (e.g.[4]) that outline these and other remedies in order to ensure the correct EMC compliance of a product against conducted noise. As the number of electronic devices, which are integrated within the driving system of the EV is rapidly growing, it is more than mandatory to consider good EMC procedures.

Figure 10: (a) Incorrect and (b) correct mount practice for EMI line filters; reproduced from [6]

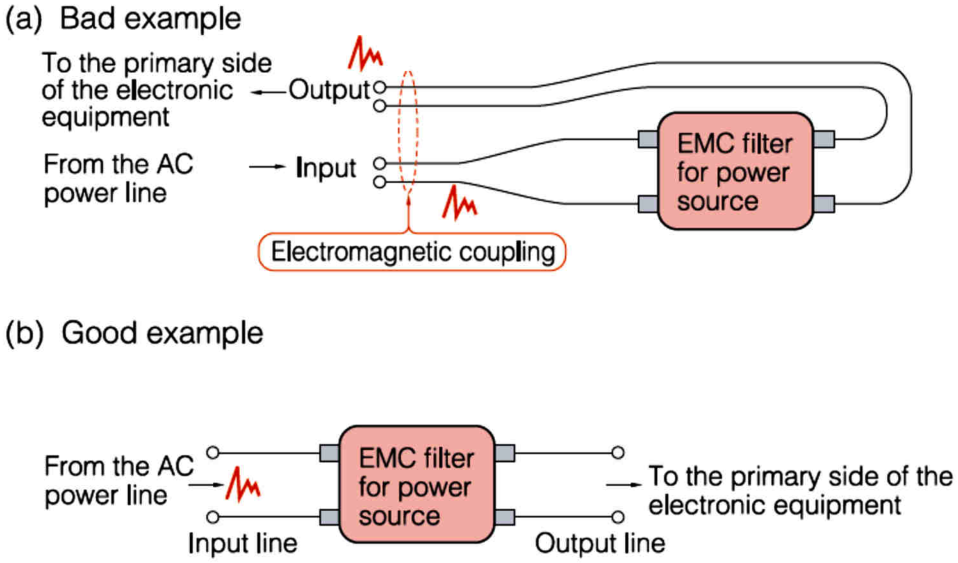
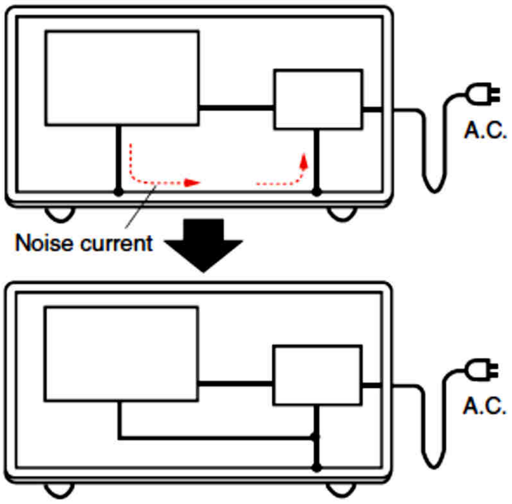


Figure 11: The importance of proper grounding methodology, reproduced from [6]



7 Conclusions

The V*e*LA 9 EMC laboratory at the Joint Research Centre of the European Commission carried out a number of methodological studies regarding measurements in accordance with Regulation No. 10 EMC automotive standard of the United Nations [1] in order to assess the EMI conducted emissions on a prototype EV. The installation of various AC power line EMI filters, as considered by the EV manufacturer, did not rectify the above the limit conducted emissions issue.

Additional measurements on the EMI filters, which were carried out with the help of specialised instrumentation of V*e*LA 9, verified that one of the filters required proper grounding while the other suffered from weak RF signal rejection due to general construction characteristics. The authors showed, that it is possible to improve the conducted EMC performance of the EV by carefully considering the frequency response of the filter itself and establish its dependence to the system (EV) ground and the location of the other subsystems (e.g. charging circuitry, layout of cabling, etc).

The facilities and the scientific expertise of the JRC's V*e*LA 9 scientists' team can provide a platform for benchmark analysis to those manufacturers who wish to carry out an independent pre-compliance EMC measurement of their prototype products in line with the accepted global standards, next to the provision of scientific feedback on technical issues. Applying EMC practices on the initial design stage of an EV prototype can ensure that any expensive and time-consuming modifications to the final product can be avoided or at least minimised prior to its market release. Pre-normative research also on the measurement techniques make sense, as more and more electronics control systems are advancing within the EVs and any errors or failures due to EM noise can affect the vehicle's electromagnetic compatibility in today's urban environments, if not even driving performance and safety of the driver/passengers. As the JRC's Interoperability Centre has already tested > 40 different electric and plug-in hybrid electric vehicles for interoperability with > 80 AC and DC- charging devices (so-called EVSEs, Electric Vehicle Supply Equipment), the setup of conducted disturbance testing during charging processes has been shown to be a relevant element in the typical interoperability/compatibility test programme for EVSE and EVs. Methodologically, DC charging, and generally fast charging is of course requiring much more powerful LISNs, which in fact have been purchased, and these will allow to realize conducted emission measurements for high power (up to 175 kW) EVSEs.

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List of abbreviations and definitions

AC	Alternative Current
CM	Common Mode
DC	Direct Current
DM	Differential Mode
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EUT	Equipment Under Test
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
JRC	European Commission's Directorate General Joint Research Centre
LISN	Line Impedance Stabilisation Network
PCB	Printed Circuit Board
RBW	Resolution Bandwidth
RF	Radio Frequency
SAC	Semi Anechoic Chamber
VNA	Vector Network Analyzer
VeLA	Vehicle Emissions Laboratory
μ_r	Permeability

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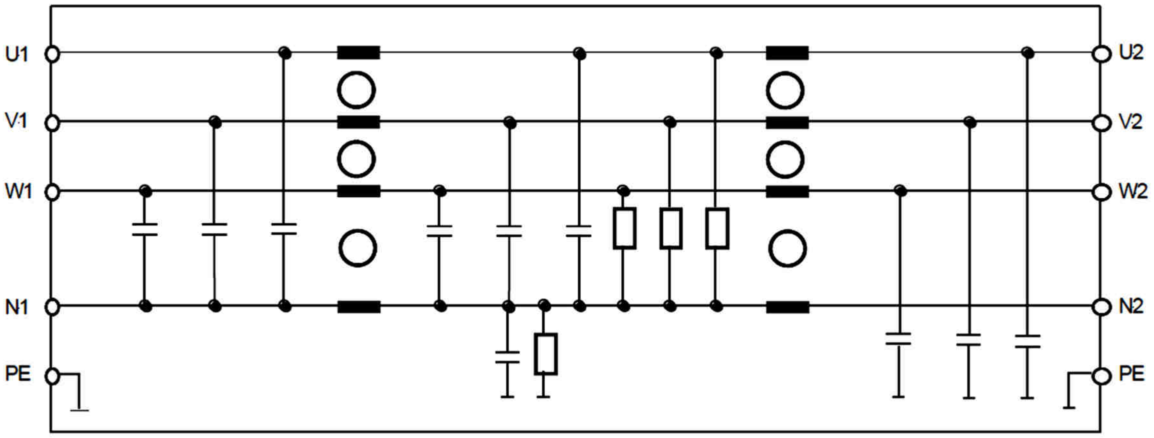
Figure 12: Internal circuit topology of FUSS-EMV 4F480-032.260 EMI line filter provided in the datasheet of reference [3]



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