Study of Random Field Coupling onto a Scooter following the Risk-based EMC Approach

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***Abstract*—The new continuously emerging technologies, over the last years, increase the complexity of electromagnetic environments as more electronic devices are implemented in modern applications such as e.g., vehicles, aircrafts, etc. The already applied electromagnetic compatibility standards, however, struggle to keep up with these new age technologies and do not always account for characteristics met in real dynamic environments as required by the EMC directive. Therefore, potential harmful electromagnetic interference sources cannot always be identified and overcome. For detection of such threats, deeper investigation towards actual environments and existing cases is necessary. Risk-based EMC analysis can help distinguish critical cases in a common real electromagnetic environment as it deviates from the fixed standardized conditions. In this paper, a real case of a scooter, acting as a victim is represented via a simple model and macro-scaled parameters to identify and determine significant induced values caused by a coupling of an unknown source. Experiments as well as simulations validate the macro-parameter concept of the applied case and allow to perform a simplified study of its behavior when exposed to a complex electromagnetic environment without the necessity to run expensive and lengthy measurements. Even though the expected precision of such a test is expected to be relatively low, it is sufficient to be incorporated in the macro-parameter-based model focused on rough-but-usable EMI estimations within a complex environment rather than exact-but-wrong solutions obtained in a perfectly clean laboratory setup.**

Keywords—Risk-based EMC, macro-parameters, scooter, EMI, coupling

I. INTRODUCTION

For proper functioning of electronic devices or complete platforms such as e.g., vehicles, airplanes, etc., a series of electromagnetic compatibility (EMC) tests need to be performed following specific EMC standards. According to the EMC directive [1] proper operation of any system under test (SUT) in its intended environment should be established. However, EMC testing is conducted in fully controlled laboratory environments [2] with defined equipment and fixed settings without incorporating other possible influential parameters as shown in [3]. The increasing modern technologies and numerous new embedded devices [4] create a very complicated electromagnetic environment (EME) introducing, thus, new challenges in EMEs as e.g., in the automotive [5] (Fig. 1). Additionally, as shown in [6] and [7], radiated emission and immunity EMC standard test methods show deficiency. Therefore, investigations towards real dynamic EMEs are necessary to include, estimate and identify potential electromagnetic interference (EMI) sources [8].

Fig. 1. The increasing modern technologies create a very complicated electromagnetic environmen introducing new challenges in EMEs such as e.g., in the automotive.

Specifically, for large systems, the risk-based EMC approach can be implemented as shown in [9]. Risk-based EMC analysis deviates from the strict standardized techniques [10] as it incorporates other factors as e.g. electromagnetic risks regarding safety aspects [11]. It accounts for unpredicted parameters as well as it deals with real conditions. This approach has been successfully applied in maritime [12], hospital [13] as well as automotive [14] environments.

Previous studies have used in-detail modeling procedures to describe specific cases as e.g., aircrafts [15]. These procedures intend to find precise solutions using analytical [16] as well as numerical [17] models. However, such models describe and examine fixed specific cases that cannot be widely implemented [18]. In real conditions, however, many parameters are random, unpredictable and continuously altered. For example, the case of a car on a street contains numerous continuously changing parameters as e.g., the number of other cars nearby. So, deterministic and full-detailed models are very difficult to estimate such conditions as they limit the alterability of these variables. Oppositely, other tools, such as statistical analysis and macro-scaled models [19] can come closer to estimating any changes causing deviations of the intended operation of an SUT [20].

In [14], a 3-point model incorporating known and unknown sources is introduced. Via a simple case, the concept of such a macro-scaled model in a harsh EME, characterized by multipath coupling, variable distances to multiple sources of unknown radiation properties, is presented. In this paper, an

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investigation of an unknown source (or EME overall) coupling onto a scooter (acting as the victim) is made based on the 3-point model and macro-parameters introduced in [14]. Scooters are systems which have already proven to be susceptible to EMI as shown in [21]. The unknown source, here, is modeled as a field coupled onto the scooter, whose amplitude can cause an unexpected behavior such as e.g., motor acceleration. Traditionally, such a case can be examined as a pre-compliance test in specific test sites as e.g., anechoic chambers (ACs) [22] and/or reverberation chambers (RCs) [23]. However, these field measurement campaigns take a lot of time and are also quite expensive to perform. Alternatively, a conducted susceptibility test procedure such as the bulk current injection (BCI) method [24] or direct power injection (DPI) method [25] can be implemented directly to an SUT and can test its susceptibility in a relatively time- and cost-efficient manner. Therefore, a correlation of radiated E-field intensity with the signal induced via the DPI method can help to detect faster and more efficiently EMC issues and possible EMI occurrence. This is especially useful when resources such as access to the chambers or amplifiers needed to perform a high E-field measurements, are limited. Furthermore, injecting the electromagnetic (EM) disturbance directly to the critical component of the system allows to bypass the effects introduced by the rest of the SUT, e.g., scooter chassis and allows to test the component exposed to various disturbances more efficiently. DPI can also be helpful in terms of testing different operational modes of the SUT as e.g., different speeds with ease. To achieve that, though, the crucial induced voltages as well as currents at the components of the SUT due to the coupled-onto-the-victim field shall be determined. A way to estimate these values is to calculate them according to specific macro-parameters of the SUT following the risk-based EMC approach as proposed in [14]. Another approach to pre-compliance immunity assessment is based on performing numerical simulations. They can however be just as time- and cost-expensive as actual measurements. Not only modelling of the exact system is often insufficient, it is often plain wrong and delivers results that are very precise, but incorrect. Although the today's numerical solvers are very powerful, simulating a complex disturbance, e.g., a multipath illumination, is also not trivial. Since a structure such as a scooter contains numerous parameters and it is very difficult to define its exact structure, this paper simplifies the case to a simple model following transmission line theory and benefits from the symbiosis created by the hybrid usage of both numerical simulations and measurements, while maintaining the advantage of simplicity and good-enough accuracy. All in all, "done is better than perfect". Via experiments on a real scooter and simulations of a simple model, macro-parameters are selected to investigate a possible method for estimating crucial voltage values induced on the SUT by illumination of an unknown source.

In Section II, the injection methods and complex EME relation using macro-models is discussed. Section III applies the proposed macro-models of Section II supported by experimental as well as simulation results. Finally, Section IV concludes the paper.

II. INJECTION METHODS AND COMPLEX EME RELATION USING MACRO-MODELS

To test a complete SUT or a certain component of an SUT for its susceptibility against fields present in its designated EME, pre-compliance tests can be performed in specific test sites such as ACs and RCs. However, these procedures can be expensive, time consuming and cannot create the complexity of an actual EME, especially in traditional free space (semi-AC conditions). RCs allow to create a more realistic multipath environment and put lower strain on the input power requirements due to the resonant fields, yet still require a large Faraday cage. A vibrating intrinsic reverberation chamber (VIRC) further alleviates these requirements and is also a cost-efficient solution, but can only be used in mode stirring mode, which is not optimal due to difficulties in controlling the dwell time. Such laboratory-created conditions limit the ability to understand what the critical components are actually experiencing. Oppositely, creating a complex EME spectrum based on real measurements of a scooter and further implementing it directly to the critical components of the SUT, can result in easy and quick EMI threat estimations. So, a complex EME can be represented and directly induced to the victim component so that potential malfunction of the SUT can be easily detected. Such a technique is the DPI method, where power levels can be directly injected to the components of an SUT. Therefore, a link between the complex fields coupled onto a scooter with the DPI method, needs to be made. Then, the complex EME can be linked to the experienced-by-the-victim directly-coupled power levels and therefore to the crucial induced voltage and/or current values. Similar concept on this connection is given via total efficiency in [26]. This ratio already hints the direct link between the two values. To achieve that link and output a ratio between voltage and E-field values in the complex case of a scooter, a simplified study is proposed and applied in this paper, based on the risk-based EMC approach and application of macro-models.

According to traditional EMC standards, components of an SUT such as e.g., a controller in case of a scooter, shall pass the corresponding compliance tests before production and application [27]. The same applies also for the whole SUT [2]. However, in real conditions the environment is changing, involving random and transient effects which can couple onto the SUT and create a certain malfunction [14]. A coupled field can create critical induced voltages or currents into the components of the SUT, influencing thus its intended operation. Such an example is the field coupling onto one of the components of a scooter as e.g., a cable. Therefore, a risk-based EMC approach can help identify and detect potential threats. As described in [14], the 3-point model, can give a good estimation of the causes of malfunction of the SUT by using variability of parameters via statistics and the link-budget analysis. Following the concept of link-budget analysis and incorporation of macro-models modularly, three macro-models can be created representing the applied complex case of the scooter illuminated by known and unknown sources in a complex EME. To incorporate the behavior of the victim, macro-models can be created regarding its response to the illumination of the E-field for both it's radiated as well as conducted characteristics. Therefore, more information can be given resulting to the final estimation of the critical induced values. These macro-models are shown in a block-diagram in Fig. 2 and are discussed in the next subsections:

- Macro-model of the complex EME
- Macro-model of the victim – Radiated side
- Macro-model of the victim – Conducted side

A. *Macro-model of the complex EME*

The macro-model of the EME, here, can be described as the complex environment containing an undefined number of known and unknown sources. The nature of them, however, cannot be entirely known as real environments present unpredictability as well as randomness. According to [14], a case of unpredictable coupling can be described as the 3rd point in the introduced 3-point model. More specifically, here, the scooter (acting as the victim) represents the 1st point, while it can be coupled by both known (2nd point) and/or unknown (3rd point) sources. Following the concept of the 3-point model, we can easily simplify the complex case of a scooter to a plain model, since the 3rd point already incorporates the unpredictability factor. Attempts regarding automotive EME characterization have proven the complexity and difficulty of these environments to be estimated as shown in [28]. So, an EME, here, can be characterized through measurements without, though, including properties of the victim.

B. *Macro-model of the victim – Radiated side*

A certain victim can be characterized via its radiated as well as its conducted characteristics. From the radiated side, each SUT has a specific radiation pattern that indicates its susceptibility profile. However, complex structures as e.g., the scooter in this case, have a difficult-to-define radiation pattern due to geometry, shape, etc. An example of a hypothetical radiation pattern of a complex case such as a scooter can be seen in Fig. 3 (continuous black line). In such cases, there is need for a certain characterization of their radiated effects that can be easily calculated and used. According to [29], devices (or here whole systems) can act as unintentional radiators since the angle of an incident field coupled onto them can not be correlated to the maximum caused interference directly. That is also one of the main reasons why the radiation pattern of an SUT shall be determined. [30] predicts the maximum radiated electric field strength of such a case while [31] applies the theory to an actual EUT. These cases present the worst-case scenarios, considering the extremes. Such an assumption can also be made in the complex case of the scooter. Assuming the worst-case scenario occurring, the susceptibility aspects of the SUT can then be accurately determined.

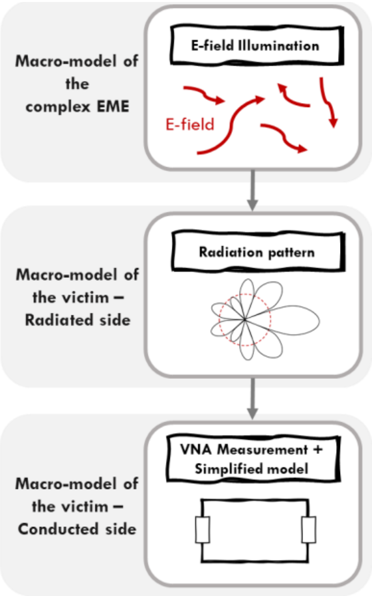

Fig. 2. Block-diagram of the three created macro-models representing the applied complex case of a scooter (acting as a victim) being illuminated by a complex EME.

C. *Macro-model on the victim – Conducted side*

For concluding towards a good estimation between the induced voltages and fields ratio, the behavioral model of the victim needs to be also characterized from the conducted side. Since a scooter is a complex system containing numerous parameters and any malfunction cannot be directly detected, it can be considered as a black box [32]. In such a case, the internal structure of the system is considered unknown, giving only an output behavior in a certain input variance. However, the coupling to the critical component is of interest here, and the rest of the circuit acts as a mere interface between the radiated field and that component. Therefore, the case can be converted to a gray-box testing case. The measurement of the input impedance can be performed with the use of a Vector Network Analyzer (VNA) and act as a reference to the created simplified single-lined case. In conjunction with the experiments, the simplified model, can then create the behavioral gray-box model, which can be simulated. From the simulations, the induced voltage caused by the illumination of the E-field, and the interactions between these components can be found. Afterwards, they can be linked to the according power levels of the DPI method.

Scooters can be characterized as complex systems due to their structure, geometry, and interactions between their components. Even though different scooters show variations in their structure, the critical interface creating a coupling path between the EME, and the sensitive component is created by the long cable connected to it. Therefore, the model investigated here can be narrowed down to three important functional units: a potentiometer, a transmission line, and a controller. A potentiometer is an adjustable voltage divider which acts as a variable resistor. It is directly connected to the steering wheel of the scooter, and it alters the resistance values changing the voltage seen at the controller side. The link between the potentiometer and the controller is usually a cable with the return path through the chassis or another cable, acting together as a transmission line for the coupled high-frequency disturbances. Although, by design, the speed is controlled by DC voltage, and normally there should be a low-pass filter at the input of the controller, it is not always the case due to costs. If there is no filter present, the induced high-frequency signals received by the cable propagate towards the controller and can affect its performance.

According to [14], such a complex system as the scooter can be simplified to a macro-model incorporating multiple parameters. Following the potentiometer-transmission line-controller link, the complex structure of a scooter can be represented via two loads and a transmission line as seen in Fig. 4. The potentiometer is represented as the impedance of the source Z_S (although in this particular case it is a passive element), while the controller is set as the impedance of the load Z_L. For the potentiometer, a resistive value can be used, while the controller is modeled as a complex impedance. The transmission line is represented by two cables, signal and return path, in proximity with a ground plane representing the scooter chassis, which might have a significant effect on the transmission line impedance due to its sheer size and proximity. The other elements of the scooter are considered here to be sufficiently negligible to not cause significant changes in the coupling and are incorporated in the impedances of the three elements.

To examine the case of the straight-line simplified model being illuminated by a certain field as an unknown source, the model first needs to match and represent the real case, with respect to the circuit element impedances. This can be achieved by optimizing the simulation model based on the VNA impedance measurement performed on the actual scooter. The structure shown in Fig. 4 incorporates parameters such as e.g., loads, lengths and radius of the cables, distance between the cables as well as distance between the cables and the ground plane. Oppositely, the two loads representing the potentiometer and the controller are varied between a range of values according to the real case so that an estimation close to the experimental results can be made. This way, specific load values can be selected to be used for calculation of the induced voltages and currents.

This simplified model is created based on an actual scooter and validated to match the VNA measured values of the input impedance. The case aims to prove the concept of macro-parameters by hybrid usage of numerical simulations as well as experiments. However, such a simplified case cannot represent the complex structure of an actual scooter completely since it misses multiple other influential parameters. Even so, it can come closer to an estimation using simple and easy tools. Following such a procedure, though, might sacrifice the precision of such an investigation, due to the lack of real representations and incorporation of precise parameters. Use of more parameters, however, can result to more precise results. Overall, as it will be shown, the accuracy of such a procedure can remain high, concluding to the fact that presumably good results and conclusions can be made maintaining simplicity.

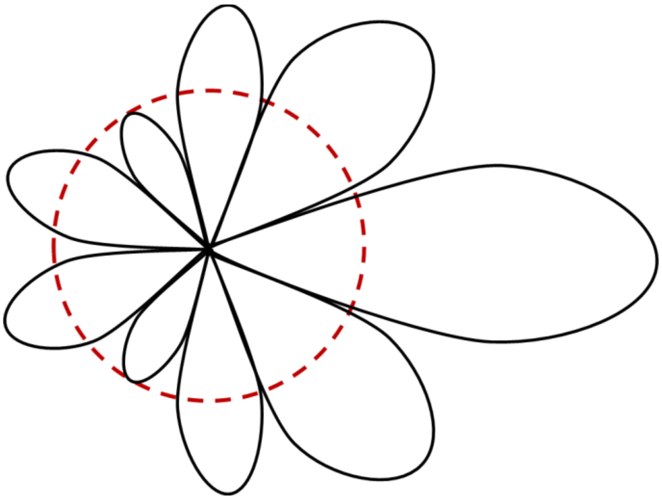

Fig. 3. Schematic of the simplified model with its hypothetical radiation pattern (black line) and a hypothethical isotropic radiation pattern that it should be corrected for (red dashed line).

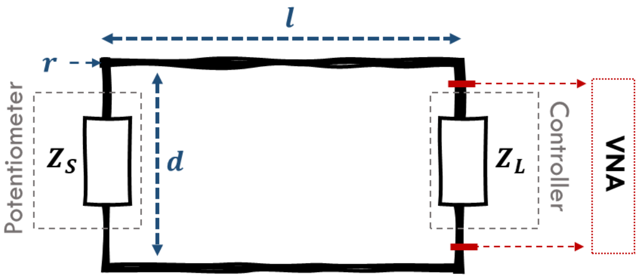

Fig. 4. Schematic of the simplified model representing a scooter based on transmission line theory.

III. APPLICATION OF THE MACRO-MODELS

To apply the previously proposed macro-model concept, a series of steps need to be made. These steps are shown in Fig. 5 and are discussed in this section supported with some experimental as well as simulation results. Firstly, to combine the simplified case to the real scooter from the conducted side, VNA measurements (Fig. 6) need to be performed to create a gray box, representing the victim. After constructing the simplified model according to section II (Fig. 4), simulations need to be run to match the VNA impedance measurement of the actual scooter via the simulation optimization step. During this step, selection and alteration of multiple parameters need to be made to calculate the values of the two loads incorporated in the model so that the simulated graph can match the experimental results. Fig. 7 shows the simulated plot that was the closest to match the measured impedance of the actual scooter at 0 RPMs. As observed, the two graphs present considerable dissimilarities. All and all, the two graphs present two different cases: the real case and the simplified model. However, even though they are not really matching, they practically follow the same pattern, already hinting a link between the real case and the simplified model. So, it can already be presumed, that inclusion of more influential parameters could come closer to an accurate solution and representation of the complex system. This could be achieved by adding more macro-parameters, following the proposed modelling procedure of [14].

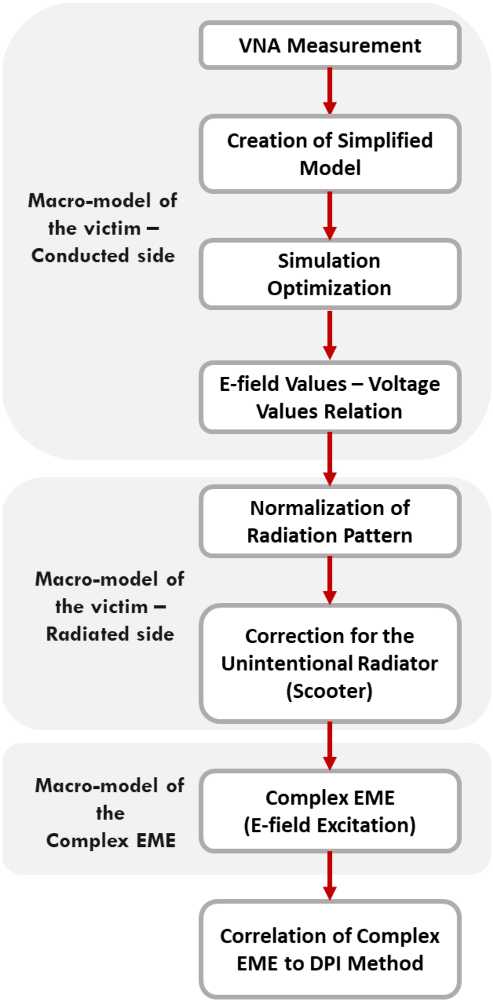

Fig. 5. Block-diagram of the steps to be followed for correlating the complex EME to the DPI method.

Following the conventional way for calculating induced voltages and currents according to EMC theory, we conclude to a depiction of the induced values as shown in Fig. 8. E-field illuminations from three different polarizations (endfire, sidefire, broadside), according to transmission line theory, can give a good estimation of the induced values. However, real environments include unpredictability as well as randomness and can cause unexpected deviations in such "expected" measurements. These calculations are sensitive to certain parameters such as e.g., angle of incidence. Therefore, to include this influence and correct for it, the radiated characteristics of the victim shall be considered. A complex case such as a scooter has an unknown radiation pattern (Fig. 3), as also discussed in section II. For comparing it to the simulated model, both should be converted to match an equivalent radiation pattern. To achieve that, the illuminated-by-the-field simulated case can be corrected via its gain values to match an isotropic radiation pattern. This way, the significance regarding the angle of illumination can be excluded. The link between the simulated case and the actual case, can then be achieved via this normalized isotropic radiation pattern as shown e.g., by the red dashed line in Fig. 3. However, considering the complexity of the scooter, the real case can further be corrected to match the radiation pattern of an unintentional radiator corresponding to the worst-case scenario by using the according gain values. Then, excitation of a complex EME incorporating known and unknown sources can be made, so that the actual critical induced voltages and currents can be accurately calculated. Following such a procedure, the E-field values generated by the complex EME can be linked to the induced values that can be used via the DPI method. Therefore, the critical values can be directly injected to the crucial components indicating possible EMI issues with ease.

Interestingly, from Fig. 6, we can extract some more information regarding the macro-model application and the advantage of using a device such as a VNA. Fig. 6 shows the input impedance measured with a VNA (Fig. 4) at three individual speed settings (0 RPMs, 60 RPMs and 110 RPMs) of the scooter. As it is observed from the figure, the three curves deviate slightly from each other following, though, mainly the same pattern. Additionally, it is easily noticed that for the two speeds (60 RPMs and 110 RPMs), the two graphs present smaller deviations compared to the stationary case of the scooter. The differences between these graphs can be explained due to the changed parameters caused by change of the set speed. As similarly shown in [14], a slight change in our system (change of speed) caused a noticeable deviation to the results proving, thus, the concept of macro-parameters. As the only parameter that was changed in these measurements was the resistance of the potentiometer, it can be assumed that this variable was also the reason for the deviation. Such a conclusion, though, cannot be made, since other parameters of the system are unknown as e.g., the impedance of the controller, geometry of the cable, etc. Therefore, further investigation needs to be made regarding influential macro-parameters as also discussed in [14]. Selection of significant macro-parameters and further investigation on their behavior, can help come closer to describe such a case. Additionally, as shown, via a simple and quick sweep, using the VNA, multiple information can be extracted regarding the SUT, resulting to the fact, that the application of such a macro-models can be done easily and relatively fast without the necessity of performing long and costly measurements.

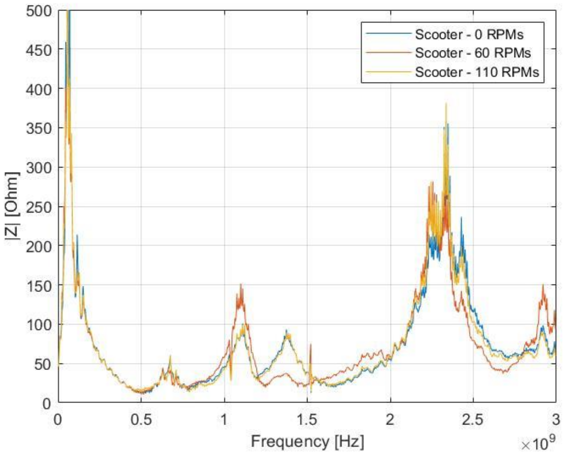

Fig. 6. Impedance measurements at the controller of the scooter at three different speeds.

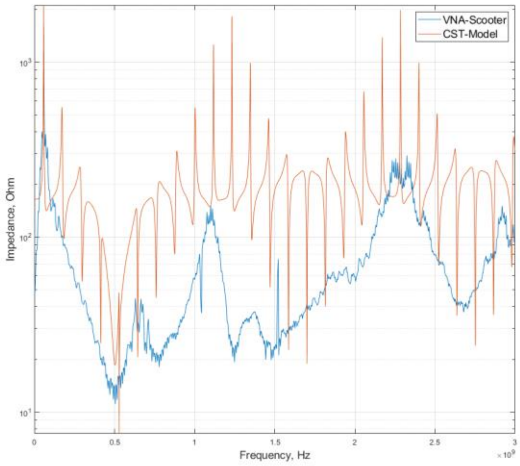

Fig. 7. Impedance measurements at the controller of the scooter at zero speed along with the respective calculated via simulations impedance.

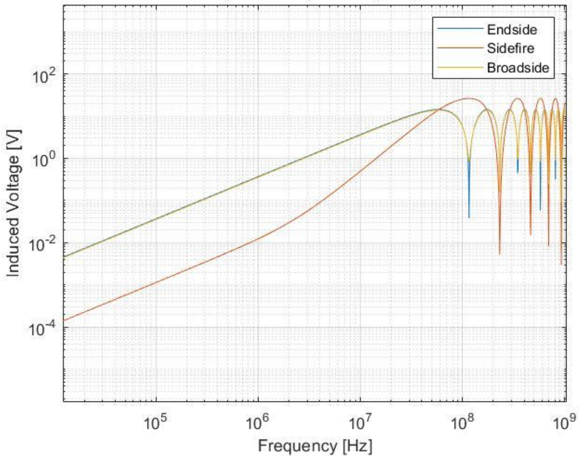

Fig. 8. Induced voltages of the three illuminations of the field (endfire, sidefire, broadside) with altered parameters calculated in Matlab.

IV. CONCLUSION

The paper proposes and applies a study regarding random field coupling onto a scooter following the risk-based EMC approach. In the paper, a link between the DPI method and the complex EME is suggested for better detection of EMC issues. Following the 3-point model introduced in literature, and the concept of macro-models, a complex case is proven to be described sufficiently by a simplified model. The importance of incorporation of characteristics from both the source and the victim sides of the coupling seems to be of significance. Furthermore, use of statistical tools via simulations have been applied via parameter alteration at the simplified case, proving their importance. Simplifying the complex structure and geometry of the scooter to a simplified model can result to accurate solutions linking complexity to simplicity. Good estimations of the induced values can be further made, and then applied via the DPI method to create a link to real complex EMEs.

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