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► **To cite this version:**

Mouna Kharrat, Nourhene Abdeljabbar, Olivia Penas, Régis Plateaux, Jamel Louati, et al.. EMC risk assessment process through a topological analysis. 12th France-Japan and 10th Europe-Asia Congress on Mechatronics, Sep 2018, Tsu, Japan. pp.21-26, <10.1109/MECATRONICS.2018.8495844>. <hal-02019829>

HAL Id: hal-02019829

<https://hal.science/hal-02019829v1>

Submitted on 13 Jun 2023

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Abstract— This paper deals with the evaluation of the electromagnetic compatibility (EMC) risk of a 3D mechatronic system architecture during the conceptual design. We propose to couple the MBSE SAMOS approach with a topological analysis to qualitatively and quantitatively assessed EMC risk. Topological analysis allows to automatically detect the potential electromagnetic (EM) disturbances based on the electrical schema of electrical/electronic (E/E) components. Then, based on the components EMC requirements (including their EM emission/immunity levels) and their 3D position, the EMC risk of identified EM couplings can be quantitatively evaluated through some 0D/1D (Modelica/Dymola) models. This approach has been illustrated with a power train of an electrical vehicle.

Keywords—EMC, mechatronic design, topological modeling, EMC risk assessment, conceptual design.

I. INTRODUCTION

A. EMC issues in mechatronic systems

The increasing integration of new IT-based technologies in common systems make them become mechatronic systems, and notably in the transports electrification context. Then, these mechatronic systems integrate a large number of electronic equipment in their architecture and notably in the automotive and aeronautic sectors (autonomous vehicles, advanced driver-assistance systems, comfort, ubiquitous connectivity, etc.). For

instance, software and electronics make up today more than 30 percent of the cost of a typical modern car [1]. Indeed, in recent decades a general trend in industry is to replace mechanical and hydraulic systems with “by-wire” configurations including sensors, actuators and microprocessors. This ongoing demand for even more electronic systems is also causing an ever growing number of Electro-Magnetic Compatibility (EMC) concerns [2][3]. In this perspective, Zhao et al. provide an overview of some current research on EMC issues and alternative solutions, notably for the problems encountered in some vehicle E/E systems [4]. Indeed, the variation of voltage or frequency in such mechatronic systems can generate electromagnetic interference (EMI) and then increase the disturbance risks in electronic circuits. Typical EMC problems in E/E subsystems are based on three main factors leading to EMI that degrades the functioning of electrical equipment or causes its failure: the interference source, the coupling path and the sensitive equipment. Thus, during the design process of such product, the consideration of EMC constraints is essential. Unfortunately, numerous EMC standards are difficult to implement in upstream design phases, where knowledge of components may still be imprecise, and EM features are often specified later (once the product has been manufactured) depending on customer specifications [5]. However, these phenomena must be assessed as soon as possible, in order to limit the risk of EMIs while facing technological industrial challenges and existing legislative

requirements and standards [3]. Thus, the design of mechatronic systems ensuring that the integration of their Electrical/Electronic (E/E) components meet EMC requirements without increasing costs and safety risks is considered as a major challenge for industry [6].

In parallel, manufacturers may encounter some EMI emerging behaviors when integrating successful experimental tested components in the entire system [1]. In that respect, this problem for vehicle integrators is highlighted by Karen Burnham who strongly suggests taking electromagnetic compatibility issues into account both at the beginning of the design and at the vehicle level [7].

Finally, mechatronic designers are lacking means that take into account the positioning of components to be integrated into the overall system, to assess EMC problems from the early design phases.

B. SAMOS and 3D multi-physical sketcher

System engineering is an approach that allows to manage complex system design, such as mechatronic ones, where multi-physical phenomena occur. During the conceptual design phase, the choice of a concept is critical, as it has to ensure that a corresponding 3D physical architecture fulfilling these multi-physical constraints. Therefore, the evaluation of such a physical architecture of concept under multi-physical constraints is required as of the early design stage, in order to reduce the design time and cost. Our research focuses on extending the Barbedienne et al. developed SAMOS approach [8] for the thermal constraints [9] to the EMC issues [10]. This Model-Based System Engineering (MBSE) approach has been implemented in a 3D Multi-physical Sketcher framework. It first aims at facilitating the collaboration between the different design actors during the conceptual design, which is a significant advantage for such multidisciplinary mechatronic systems. Moreover, it ensures the consistency and traceability of data and models, in accordance with the System Engineering principles.

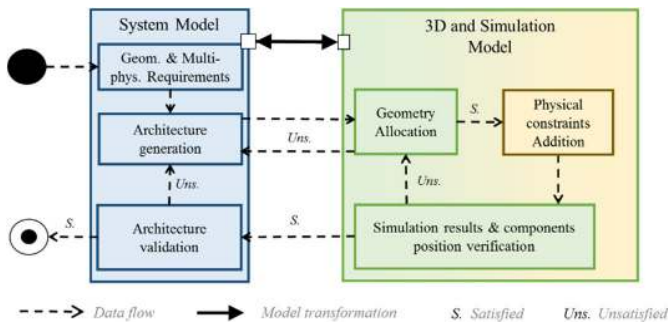


Fig. 1: SAMOS approach [8].

This paper deals with the identification of the EMC risk, based on a topological analysis.

C. Topological modeling

A topological collection is a collection in which structure is captured by a neighboring relationship between the data, that is to say, by providing one of the elements in the collection, we can provide all the other data which are directly related. The

organization of a topological collection is founded on a cellular complex where values are associated with each cell. A cellular complex is composed of elements of various dimensions called topological cells which are organized by following the incidence relationship.

A topological structure is defined as a set of vertices linked by edges. Topological graph makes it possible to describe any type of structure. It can be seen as a petri networks, a mechanical structure or an electrical networks [11].

Our previous research on topological modeling deals with the design of a methodology applied to dynamic multi-physical models with dynamic topology for the optimization of complex systems [12]. In recent work, Abdeljabbar et al. introduce a topological modification within a structure, exemplified in the case of the removal of some bars in a 2D piezoelectric truss structure [13]. Then this breakthrough has also been applied to a multi-physics pogo-stick, by applying a topological approach based on a new methodology [14].

The main objective of these works consists in having an optimal unique model of any complex mechatronic system through the models connectivity study within a multi-level and a multi-scale modeling. In order to reach this goal, extensive work must be done and notably regarding the consideration of two-dimensional cell in the topological structure.

Regarding research on the EMC modeling using topological model already [15], existing approaches decompose the system into smaller parts and propose a topological approach to support the definition of EM interfaces before the numerical implementation [16][17][18]. For example, Parmentier uses an EM tool which integrate the topological model to simulate the entire system at system level. However, this method is limited at low frequencies particularly for common mode problems [19][20].

In this paper, where the topological modeling is used to evaluate EMC from an electrical network, the topological entities will consist in taking into account the definition of source and victim components and their interactions corresponding to EM flows, and will be modeled through a relevant topological structure. The difference between using this topological method in this work from another uses works is in the objective of the research; that is mean the use of the topological structure to identify different modes and victims/sources is a new objective to reach.

D. Research issue

The intent of this paper lies in combining EMC modeling and topological approach to support an EMC evaluation process during the conceptual design of mechatronic systems, in order to reduce the risk of late costly architecture changes.

The paper is structured as follows: Section 2 first details our proposal, in the context of the SAMOS MBSE approach, to evaluate EMC during the conceptual design, and describes the scenario we addressed: EMI between two electrical circuits (High Voltage and Low Voltage) located in the traction chain of an electrical vehicle. Based on the electrical modeling of such

a scenario, the EM couplings modeling is then outlined, followed by the EMC risk assessment. This section ends with the analysis of the scenario results and some discussions. The last section summarizes our contribution and conclusions and propose future work.

II. OUR PROPOSAL

As the distance between interacting components severely impacts EMC performances [21], 3D architecture have to be evaluated as of the conceptual design phase to check that the emission/immunity levels of the chosen placed E/E components fulfill the predefined EMC requirements, without having to performing time-consuming numerical simulations.

To tackle this challenge, an EMC risk assessment process is proposed, by coupling a topological approach with 0D/1D (Modelica/Dymola) modeling simulation. This approach will detect the EMC disturbances taking into account the position between interacting components and the useful parameters required to evaluate by short simulation their resulting EMC behavior, before verifying whether their level constitute a risk with regard to the EMC requirements.

A. Process overview

The EMC risk assessment process we propose for the conceptual design is based on both qualitative and quantitative evaluations.

First at all, as this process is supported by a MBSE approach, the EMC requirements needs to be collected. This step is ensured by the EMILE SysML extension for EM modeling, and will be detailed in a future paper. These requirements includes EM properties of components, limits values of Standards, physical solicitations, quantified limits, and also geometrical information (components geometry and relative positioning constraints).

Then we first begin with a qualitative evaluation, from the physical modeling of the system. For the EMC, as we address E/E components whose EMI highly depend on their electrical features, the physical structure will be here represented by the electrical diagram including the components studied.

Then we perform the topological modeling of the physical structure (electrical schematics), in order to identify the interactions between components. The analysis of the corresponding topological graph allows to identify all potential EMI and to choose the main disturbances to consider for the quantitative assessment. These identified interactions can then be converted in a component / component interaction matrix enabling a visualization of potential critical interactions when moving the components of the whole system in the 3D architecture framework. Each component may act as source or victim on another component.

For the quantitative assessment, we use the risk of disturbance formula (1) proposed by O. Maurice [15].

$$R = \frac{W.S}{P_c} \quad (1)$$

W : related to the energy of sources (aggressors); S : Transfer function that transmits the aggressors' energy to the victims; P_c : immunity threshold power of the victim components.

W is determined by the electrical characteristics (voltage, current, emitting spectrum density) contained in the electrical diagram. S depends on the interaction law of the EMI identified including component geometrical information, numerous behavioral equations are available in the literature, some of them have been synthesized in the Table 1. The chosen interactive components have been simplified into 3 main categories (cable, equipment/device, antenna (all components with an "emitting/receiving antenna" behavior). P_c is given by previous EMC quantified requirements.

TABLE 1: LIST OF EM COUPLINGS AND RELATED LITERATURE REFERENCES

N°	Interactive components	Coupling paths	References
1	Cable to cable	Inductive crosstalk	[22][23]
2		Capacitive crosstalk	[24][26]
3	Cable to cable	Differential mode	[22][24]
4		Common mode	[26]
5	Equipment/antenna	Radiation (E, H fields)	[25][26]
6	Antenna/equipment		
7	Antenna to antenna	Radiation (E, H fields)	[25][26]

These interaction laws will be then modeled in Modelica language in the Dymola environment, in order to evaluate the risk values through simulation results and to be compared with the critical risk value. The critical risk RC is calculated from both the requirements limits values and the geometrical information of components (shape, dimensions and position) coming from the 3D environment. It corresponds to the value beyond which the risk is not acceptable and means that the 3D architecture considered has been modified.

B. Scenario description

To illustrate our approach, we have chosen a traction chain scenario. Indeed, the EMC of electric traction systems is a major task in the development process of electric driven cars. In most electric vehicle (EV) concepts, the required position of the traction battery power electronics and electric machine impose long cable harnesses, which can be sources of EMI [27] and then cause components malfunctions [28].

Fig. 3 shows a block diagram of an Electric Vehicle (EV) traction chain composed by a High Voltage (HV) battery that supplies a power inverter (which converts DC voltage into three-phase AC voltage for the electrical motor) and a DC/DC converter (to buffer the Low Voltage (LV) system (such as sensors, on-board net). This scenario presents numerous potential EMI, be it conducted or radiated, as represented in Fig. 2 and Table 1.

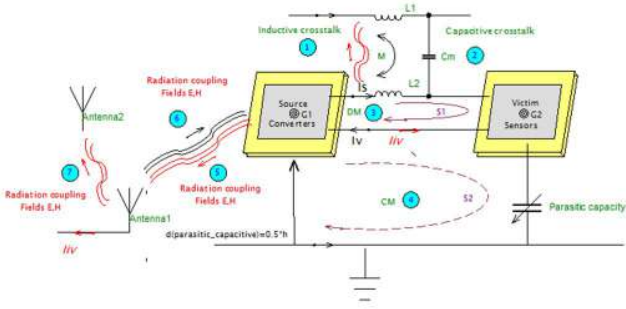


Fig. 2: Potential EMI in the traction chain scenario.

Among these EMI, we choose to focus on the transmission lines EMI, i.e on the EM coupling case between two cables (Table 1) and notably on the inductive crosstalk, in order to illustrate them.

C. EMC Requirements

This scenario has some requirements (which can be linked to some standards), defined during the conceptual design phase, about the electrical solicitations (frequency, voltage, current), the components geometrical parameters (shape, dimensions...), and their physical properties (material properties, emission or reception properties for EMC: minimal and maximal emission/immunity level of components). These requirements can be defined through the EMILE SysML extension.

The position of components, and if necessary updated geometry dimensions or shape will be provided by the 3D architecture in the 3D environment (this step will be automated in future work), and can be changed very easy.

These requirements about the components and electrical features are synthesized in Table 2 from [26], some unknown parameters have been estimated.

TABLE 2: COMPONENTS REQUIREMENTS

Parameter		Value
Nominal HV voltage (V_s)		$V_s = [46V, 58V]$
Immunity power of victim components		$P_c = 18 \text{ dBm} = 63 \text{ mW}$
Maximal HV intensity		$I_{smax} = 360 \text{ A}$
Frequency range		$f = [300\text{kHz}, 200\text{MHz}]$
Geometrical parameters	\emptyset	$\emptyset_{i,HV \text{ cable}} \approx 8 \text{ mm}$ $\emptyset_{i,LV \text{ cable}} \approx 4 \text{ mm}$
	L	$L_{HV \text{ cable}} = L_{LV \text{ cable}} \approx 2\text{m}$
		HV/ LV cable diameter
		HV/ LV cable length

D. Electrical and ElectroMagnetic Coupling identification

The electrical model is then represented by a simplified *Electrical model* (Fig. 3) including the equivalent impedance of both circuits (source and victim).

From the physical structure (i.e electrical links between the considered components), we identify all the possible EM couplings (from the Table 1) that may occur in the considered electrical circuit. For each identified EMI, we represent the

corresponding electrically active components topology in a Physical (electrical) model.

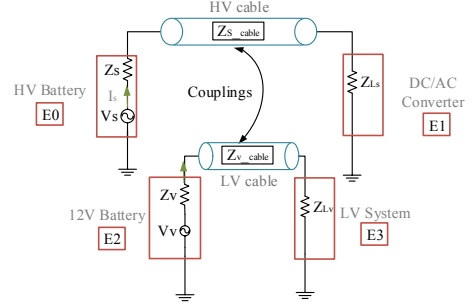


Fig. 3: Electrical Model of the traction chain scenario.

E. Topological modeling

As a first step, different equipment/components, cables and antenna are modeled as described in Fig. 4. Then, considering parallel cable sets, the physical elements are schematized to associate a physical (electrical) topological modeling (graph and matrix) to the physical electrical model, as shown in Fig. 4, with the signs of the matrix M_E (Electrical Matrix between Equipment and Cable) defined by the respective current flows direction.

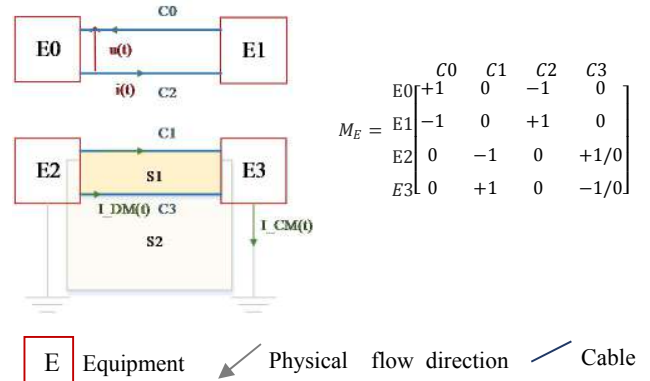


Fig. 4: Topological modeling of the electrical schema corresponding to the traction chain scenario.

In our case study, we focus on the inductive and capacitive crosstalks based on cable to cable interactions.

With regard to the inductive crosstalk, a variable current flows in a conductor (like $C2$) generates a magnetic field which is coupled in the current loop formed by the neighboring conductors (like the $E2E3$ circuit), and generates a counter-electromotor force, which can appear as a differential (between the 2 wires of a current loop, like the $C1/C3$) parasitic voltage or as a common mode (parasitic voltage between a neighboring conductor (e.g. $C1$) and the nearest ground plane). This coupling is modeled through the mutual inductance parameter, which both depends on the distance between the aggressor ($C2$) and the victim ($C1$) and on the surface of the loop of the disturbed circuit ($S1$ in differential mode or $S2$ in common mode).

Concerning the capacitive crosstalk, a conductor (e.g. $C2$) exposed to a variable voltage creates a variable electric field $E(t)$ which can be intercepted by a the nearby conductor (e.g. $C1$), and thus causes a parasitic current to appear in this conductor

(C1). This current appears as a differential or as a common mode in the victim circuit, depending on whether it flows in the current loop of the second circuit or in the loop connecting it to ground. The parasitic current is then proportional to the mutual capacity (noted Cm) which depends on the distance between the aggressor cable (C2) and the victim cable (C1).

F. Risk assessment

The risk assessment considering crosstalk couplings is described here by two main steps. First, we have defined a qualitative method to evaluate the EMC risk by directly identifying the potential victims and aggressors in such scenario, based only on the topological modeling of the electrical circuit. The next step consists in performing the EMC risk quantitative assessment using the law (1), in order to identify the EMC risks between E/E components of a given 3D architecture.

- Qualitative risk assessment

The proposed quantitative risk assessment process in the case of the crosstalk coupling is detailed as follows:

- first, we identify the existence of current loops in the electrical circuit in order to identify the potential victims;
- then, we identify the corresponding potential aggressors;
- finally, we propose some mathematical formula, based on topological structure, to identify the inductive and the capacitive crosstalk on one hand, and both differential and common modes on the other hand.

The first step is the identification of the existence of current loops from the matrix M_E filled with signed values, in accordance with the current flows direction of the electrical circuits. If the number of current loops is greater than or equal to 1, a risk of crosstalk coupling exists.

The mathematical formula which allows to easily identify the set of current loops \mathfrak{B}_m in the M_E matrix is given in (2):

$$\mathfrak{B}_m = \left\{ (E_k, E_l, C_i, C_j) \setminus \begin{cases} \text{sign}(C_i, E_k) = \text{sign}(C_j, E_l) \\ = -\text{sign}(C_i, E_l) \\ = -\text{sign}(C_j, E_k) \\ \neq 0 \end{cases} \right\} \quad (2)$$

With $i, j = \{0 \dots n\}$; $k, l = \{0 \dots m\}$; ($k \neq l$) and ($i \neq j$)

The Fig. 5 a) shows the current loops identified in the case study, respectively for the HV and the LV circuits, which can be considered as crosstalk victims. As, we have not represent the ground in the topological modeling, when considering that the parasitic current flows through the ground (Fig. 5 b), the C1 current flow is just identified.

$$M_E = \begin{matrix} & \begin{matrix} C0 & C1 & C2 & C3 \end{matrix} \\ \begin{matrix} E0 \\ E1 \\ E2 \\ E3 \end{matrix} & \begin{bmatrix} +1 & 0 & -1 & 0 \\ -1 & 0 & +1 & 0 \\ 0 & -1 & 0 & +1 \\ 0 & +1 & 0 & -1 \end{bmatrix} \end{matrix} \quad \text{a)}$$

$$M_E = \begin{matrix} & \begin{matrix} C0 & C1 & C2 & C3 \end{matrix} \\ \begin{matrix} E0 \\ E1 \\ E2 \\ E3 \end{matrix} & \begin{bmatrix} +1 & 0 & -1 & 0 \\ -1 & 0 & +1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & +1 & 0 & 0 \end{bmatrix} \end{matrix} \quad \text{b)}$$

Fig. 5: Identification of current loops in the M_E a) in differential mode b) in common mode cases

Then, to determine the potential aggressors corresponding to the crosstalk nature (inductive or capacitive), we need some complementary physical information on electrical parameters. Indeed, whereas the inductive coupling is defined by the presence of an ‘‘aggressive’’ cable between two equipment associated to a disruptive variable current (4), the capacitive coupling occurs when there is a variable electric field which is created by an aggressive cable exposed to a variable voltage (3), thus we obtain these following mathematical formulas:

$$\exists u_k(t) \neq 0 \setminus \{ \{E_k, (C_i, C_j)\} \neq \{\emptyset\} | (E_k, C_i) = -(E_k, C_j) \neq 0 \} \quad (3)$$

$$\exists i_i(t) \neq 0 \setminus \{ \{C_i, (E_k, E_l)\} \neq \{\emptyset\} | (E_k, C_i) = -(E_l, C_i) \neq 0 \} \quad (4)$$

To identify the inductive crosstalk, we have to verify these conditions: the number of cables $N_c \geq 3$, the number of current loops $N_{cl} \geq 1$ and the number of equipment ($N_E \geq 2$). For the capacitive crosstalk, the number of active cables $N_{ac} \geq 2$ with a number of ground planes $N_{gp} \geq 4 - N_{ac}$. Finally, for each crosstalk phenomena, the different coupling modes have to be identified, depending on the victim nature.

For the differential mode, a new rule is required to be added to the rule (3) or (4) depending if the crosstalk considered is inductive or capacitive: i.e. the existence of a current loop L_c that does not include the aggressor (5):

$$\exists L_c \in \mathfrak{B}_m = (E_r, E_n, C_p, C_q) \neq \emptyset \setminus (E_r, E_n, C_p, C_q) \neq \{E_k, E_l, C_i, C_j\} \quad \text{(involved in the aggressor)} \quad (5)$$

For the differential mode, another rule is required to be added to the rule (3) or (4) depending if the crosstalk considered is inductive or capacitive: i.e. the existence of a current flowing in a cable C_r that does not belong to the aggressor (6).

$$\exists C_r \notin \{C_i, C_j\} \neq \emptyset \quad \text{(involved in the aggressor)} \quad (6)$$

- Quantitative assessment

The quantitative assessment is performed through the risk law expressed in (1), when considering the identified EMI coupling and the 3D components position.

To illustrate this step, we have chosen the inductive crosstalk in the common mode. With that respect, we take the victim parasitic voltage as an indicator of the S transfer function, depending on the mutual inductance M_{12} (7).

$$M_{12} = 0.1 * \ln(1 + \left(\frac{2*h}{s}\right)^2) \quad (7)$$

The simulation results give V_{victime} values and allow us to calculate the risk of perturbation R which will be compared to the defined critical risk R_c . Due to the limited place, we will present this part in a future paper.

CONCLUSIONS AND FUTURE WORK

This paper deals first with the evaluation of EMC risks of a conceptual architecture based on the MBSE SAMOS approach, combined with a topological analysis and taking into account EMC constraints required in such mechatronic system. To identify the potential EMI occurring between the E/E components of the power train scenario of an electric vehicle, we have performed a topological modeling and analysis based on the physical and electrical structure, and formalized some mathematical rules to automatically detect inductive / capacitive crosstalk in differential and common modes. Then, this approach has to be validated in our future works by the quantitative assessment of the risk calculated from 0D/1D Dymola/Modelica models simulation, taking into account the components 3D position. Another future work will address the implementation of this approach in the 3D multi-physical sketcher environment.

ACKNOWLEDGMENT

We thank in special R. Barbedienne for his valuable contribution to this research in helping us to extend his former work.

We are very grateful to O. Maurice from Airbus Safran Launcher and F. Lafon, from Valeo, for the time they spent to collaborate by sharing their EMC expertise and viewpoints that have greatly contributed to this work.

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