Improved convergence speed using hybrid AI for TD EM modeling in power electronics

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ABSTRACT

This paper presents a time-domain (TD) approach based on hybrid artificial intelligence (AI) to speed up convergence of radiating sources characterization in power electronics. To obtain a representative equivalent model of device under test, a dedicated optimization framework has been developed in TD using a particle swarm optimization (PSO) toolbox. In addition, for elementary feature extraction, a pseudo-Zernike moment invariant (PZMI) descriptor has been defined. Finally, with the aim of identifying remaining dipole parameters and classification problems, artificial neural networks (ANN) have been implemented. A coupling of TD electromagnetic (EM) inverse method based on a PSO algorithm along with PZMI and ANN application has been investigated and applied to a real test case. Experimental measurements have been conducted using the near-field scanning technique above an alternating current (AC)/direct current (DC) converter. Obtained results are discussed based on a comparison between measured and estimated EM field distributions using both the hybrid AI method and a conventional TD inverse method based on genetic algorithms (GA) only. This study confirms that, compared with those given by non-hybrid method, the proposed algorithm further improves the convergence speed while maintaining high accuracy. Hence, the present work offers an impressive perspective for radiated emissions characterization using hybrid AI algorithms.

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1. INTRODUCTION

Technological changes speed up exponentially over time. This can be noticed through the highly progressive miniaturization and embedding of electronic equipment, along with an impressive increase in the operating frequency, integration rate, and required power. However, this development provokes risks of frequent and undesired electromagnetic (EM) interferences in and around systems, which can cause its malfunctioning. Thus, electromagnetic compatibility (EMC) studies have to be investigated before designing and manufacturing of any electronic device. It has become necessary to develop a representative radiation model to estimate EM emissions of each embedded system. In this context, the generation of an equivalent model using an inverse method has been widely proposed [1]-[3]. To circumvent the limits of forward measurement methods, the EM inverse problem resolution based on the near-field (NF) scanning has been extensively developed [1]-[4]. In the literature, to estimate radiated disturbances of power electronic circuits, the most popular method used is the EM inverse method based on elementary dipoles (electrical and/or magnetic) [5], [6]. In particular, for energy control and power systems, due to an important switching activity, high levels of EM interference can be generated. Consequently, a wide frequency band and an important transient response are issued. Indeed, it is difficult to handle EM inverse methods in the frequency domain [3]. Therefore, researchers have investigated the use of time-domain (TD) analysis to obtain an equivalent model representing the radiation behavior of the device under test (DUT) for all the frequency band [2]-[4], [7]. These studies have shown adequate results in particular when the number of variables is not very important. However, in the case of a complex structure, some weaknesses can be noticed such as a computational complexity and the lack of convergence warranties. As a solution, advanced artificial intelligence (AI) has been introduced to provide more efficiency in characterizing radiating structures [8]-[11]. These algorithms are adequate for the identification and optimization problems [12]. For instance, Labiedh and Slama [13] have investigated the use of the particle swarm optimization (PSO) technique for EMC application. However, these results suggest multiple possible improvements. Thus, further extension studied can be made for intuitively obtaining the optimal patterns from the AI models in the least computation time.

In this work, a hybrid AI algorithm is proposed to further improve the convergence speed of the TD EM inverse method. The workflow is based on the automation of the pre-analysis processing of radiation maps using TD analysis. This will help in deducing more significant information on the obtained elementary dipole characteristics, such as the type (magnetic or electrical) as well as position coordinates parameters (xd, yd, zd). By analogy with the FD–based method [14], the pre-analytical phase has been carried out using the coupling of the pseudo-Zernike moment invariant (PZMI) and the artificial neural network (ANN). The latter has been introduced as an image-processing technique for EMC applications. Indeed, PZMI has been successfully used in the field of pattern recognition for feature extraction and it can provide information about system redundancy [15], [16]. In addition, ANN is used for clustering and in supervised classification [17]. For EMC studies of power electronics, these methods appear very interesting for radiating dipoles identification. However, it is still crucial to involve a good performance criterion allowing finding an optimum or a satisfactory solution for the inverse problem resolution. Preview study [18], it has been demonstrated that for this purpose PSO technique is more efficient than genetic algorithms (GA) in terms of complexity, iteration and accuracy. Besides, PSO has also ease of implementation. For this purpose, to guarantee convergence and reduce the processing time, we suggest applying the PSO method using TD analysis in a hybrid approach. The proposed method is a coupling of the EM TD inverse method based on a PSO algorithm along with a PZMI descriptor and an ANN, which is an original use of AI algorithms in EMC applications. For validation purposes, experimental measurements have been carried out using a magnetic field probe. An automated NF test bench has been developed for TD measurement. The device under test (DUT) is a flyback alternating current (AC)/direct current (DC) converter typically found in low and medium-power applications as in automotive and battery charging. In these kind of circuits, multiple transient disturbances with a short duration occur and affect the functioning of the system.

The organization of the paper is as follows: It starts by presenting the TD EM inverse problem with respect to NF scanning. Then, in section 3, the proposed hybrid AI algorithm is described for equivalent radiation model investigations. Section 4 includes implementation and a real application of the procedure, followed by a detailed discussion. For comparison purposes, measured and obtained results have been exposed to those found by temporal inverse method based on GA only. Finally, section 5 presents the main conclusions.

2. TIME-DOMAIN ELECTROMAGNETIC INVERSE METHOD

To fulfill the demanding needs of recent technological advancements, such as in power systems where undesired EM radiation has to be investigated at early design stages, in addition, to forward characterization problem, inverse methods have been widely developed. It consists in retrieving various unknown information of the model inputs starting from a given response (outputs). In the literature, this process has been applied for different purposes, mainly to provide a framework for the characterization of black-box systems behavior [19].

In EMC studies, inverse problem has been employed to identify potential emissive sources through an equivalent radiation model of the DUT and hence point out harmful components. Authors in [9] and [20] have proposed to use the EM inverse method along with TD analysis. In fact, either it is possible to provide temporal signals of EM fields by taking measurements with high precision timing instruments in the NF region of DUT or by simulations using numerical solutions or using temporal analytical equations that describe EM radiation of elementary dipoles [3], [9]. The aim is to obtain a set of equivalent electric, magnetic or both dipoles type representing an accurate radiation model along time. Indeed, in NF, there are strong capacitive and inductive effects from currents and charges flowing in the circuit and generating considerable EM disturbances. The acquired equivalent model provides an approximate estimation that represents at best the real DUT radiation behavior. Figure 1 shows a flowchart picturing the principle of the studied method.

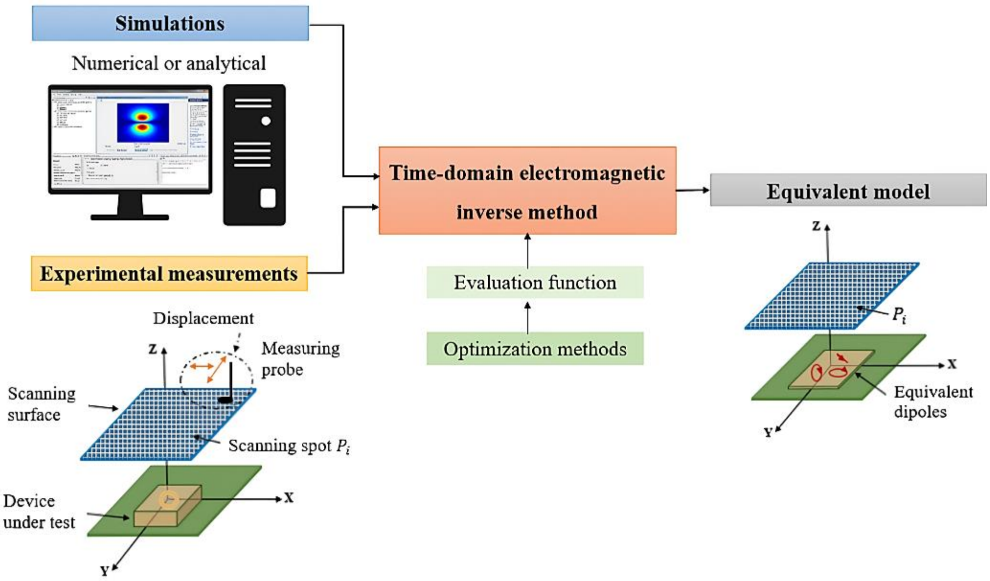

Figure 1. Principle of TD EM inverse method

3. PROPOSED HYBRID AI METHOD

Several research papers have investigated the application of artificial intelligence in power systems. For instance, an interesting work has been presented in [21]. Other approaches using AI algorithms in the study of EM interferences have been introduced in [11]-[13] and [22]. Preview study [14], great work has been done in the frequency domain in order to introduce machine learning-based methods for EMC studies. In time-domain, Zitouna and Slama [3] have proposed the use of an EM inverse method based on genetic algorithms only. This method consists in identifying a single radiating dipole per local map (scan window) until finding all equivalent sources while going through the total field map. Indeed, an optimization process is carried out to search a magnetic dipole in a first iteration, and then if a convergence has not been achieved, the search feature becomes an electric dipole and so on. Consequently, this procedure is time and memory consuming. It is necessary to switch to a more suitable method that requires a minimum of information on the type of dipole and its involved parameters. In this study, a hybrid artificial intelligence algorithm is developed based on the coupling of three techniques; PSO as an optimization method, PZMI descriptor, and artificial neural network (ANN) for the evaluation of the main dipole characteristics. On the one hand, PSO is a population-based search algorithm where the system is initialized with a population of random solutions, and the investigation for an optimal solution is carried out by updating generations. Hence, the potential solutions (particles) move in the problem space by following the current optimum particles. In the literature, PSO has been applied for several optimization studies such as explained in [13], [18], and [23]-[25]. Unlike GA, PSO has more ease of implementation and no evolution operators, such as mutation and crossover. Therefore, it is computationally more efficient in terms of memory and speed requirements. On the other hand, the PZMI descriptors are employed for pattern recognition. It has been widely established that PZMI allows capturing information from the map with a satisfactory robustness to noise [14], [16], [26], [27]. In addition, ANN technique has been extremely successful in clustering and classification processes in particular in the areas of computer vision [14], [20], [21]. In this work, coupling of PZMI and ANN is employed as an image-processing tool with an aim to classify radiating sources using TD analysis. To implement this algorithm, MATLAB toolboxes such as particle swarm optimization research toolbox and neural network toolbox are employed.

The proposed TD search algorithm treats first the highest radiation level (potential source) and continues until reaching a weak magnitude. To reconstruct the shape of each dipole excitation signal with a good accuracy, the initially measured (or simulated) radiation map is introduced to a subprogram that seeks the signal with the maximum amplitude at each iteration. Based on the measurement position that corresponds to the most intense radiation area, we extract a scan window and propose an elementary dipole for this zone. The extracted window scans the entire map. It is worth noting that the size of the scan window relies on the measurement height (distance between the measuring probe and DUT) and the step of displacement of the probe between two successive measuring points. In extreme cases where several radiating sources are very close to each other and are located in the same extraction window, the algorithm will gradually decrease the size of the window until the convergence is achieved. If the method fails to converge, the initial sizes of the extraction window are taken over and the search frame is extended to more than one equivalent dipole.

In the context of inverse problems, a critical step in the problem setup is the configuration of the model, which means to characterize the solution by a set of parameters (working variables and desired outputs). This choice is not evident because the solution may not be stable, exist or be unique and the model may need to define some assumptions. Thus, to facilitate the convergence of the search algorithm and avoid possible couplings, a reduced set of parameters is chosen. In this study, as in [3], parameters are the radiating source center coordinates (Xd, Yd, d), the orientation angles (θ, φ), and the moment waveform (Md). The main steps of the proposed hybrid AI method are summarized in Figure 2 and explained below, this procedure is repeated until the defined noise level is reached and all sources of radiation on the maps are identified:

- In the extracted scan window, an image-processing algorithm utilizing PZMI descriptors and an artificial neural network (ANN) is implemented to determine the position and type of the equivalent dipole. More theoretical details are provided in [14].
- To accelerate the convergence of the proposed method, for optimization routines, a PSO algorithm is carried out to search remaining parameters (Md, θ, φ), as in [13].
- Consequently, the identified parameters of the first dipole are used to calculate the magnetic field emitted by identified dipole using analytical equations of the magnetic field. Then, the generated distribution is subtracted from initial cartography.

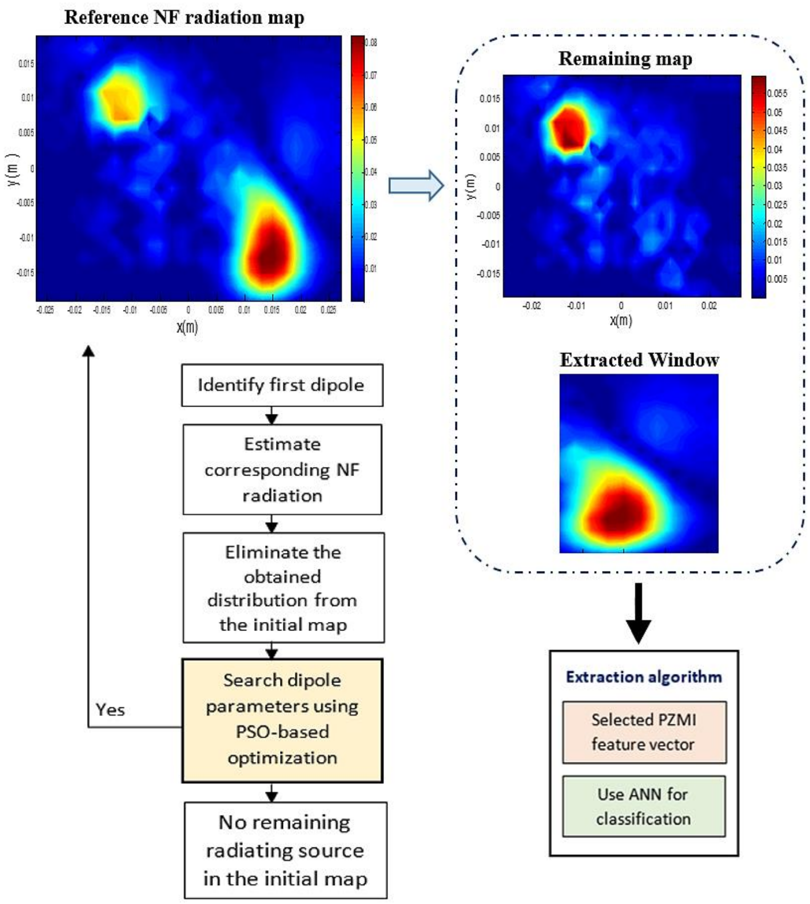

Figure 2. Summary of the proposed hybrid AI approach

4. RESULTS AND DISCUSSION

4.1. Application to an AC/DC

The most practical way to evaluate the proposed method is to apply it to a real test case. Hence, for experimentation purpose, an AC/DC converter of a flyback topology has been studied, as show in Figure 3. More details of the DUT and the test environment can be found in [9]. In order to perform TD measurements, a NF test bench has been developed using a high precision oscilloscope with a wide bandwidth. Magnetic field signals are measured using a magnetic probe of 1.6 mm radius that moves above the circuit board to scan the whole surface. Since it is mandatory to take measurements under the same conditions, the motion of the shielded probe is automated and can be carried out in the three axes (*x*, *y*, and *z*). Acquisition has to be synchronized with a reference signal, which is chosen to be the control signal of the optocoupler of the converter because of its receptivity, periodicity and electrical isolation. In order to obtain a distribution map per time step, TD signals showing the system behavior are measured for a defined duration. An example of EM field signals of 20 us duration is depicted in Figure 4. As we can see, radiated signals are of different shapes along time. It is not evident to be treated using FD domain method (extraction radiation maps at all spectrum frequencies). Furthermore, in this test case, we have focused on the following working variable configurations:

- The height of measurement: in order to avoid troublesome components while using the probe, we have preferred to carry out measurements on the bottom side of the board. Thus, for this particular practical case, it is possible to define a good distance of scan. We have measured at 12 mm of height.
- The scanning area has to include the surface of interest of (38 mm × 54 mm). The probe moved into 560 different scanning points with a step of 2 mm.

Source identification is a supervised learning issue. ANN has been employed to classify radiating dipoles using PZMI vectors. We have used a simple structure of multi-layer perceptron network (MLP) that contains the PZMI vector as an input, along with hidden and output layers giving identified sources information. A back-propagation learning phase has been carried out to make a training with a database of 1158 PZMI vectors (from different maps). Indeed, 30% of the database has been employed for testing and the rest has been generated to create the NN. Table 1 presents the learning data set. To evaluate the efficiency and accuracy of the proposed hybrid AI method, its results are compared with those obtained using a non-hybrid approach. By applying a genetic algorithm (GA)-based method to the same measured time-domain (TD) signals, we generate alternative maps to represent the radiation behavior of the studied converter. Information's about the chosen parameters for each optimization method are given in Table 2.

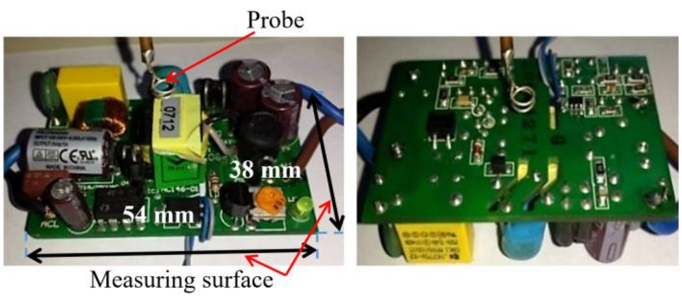

Figure 3. The studied structure

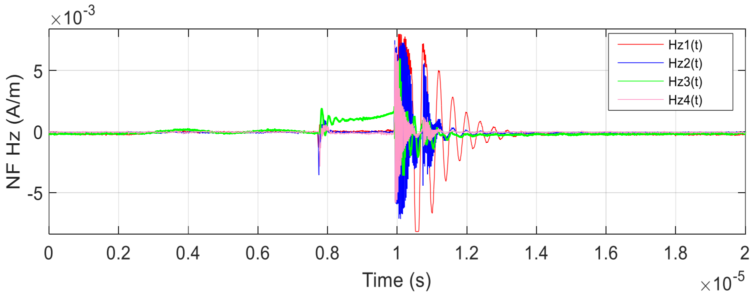

Figure 4. Measured radiation signal

4.2. Conventional method/hybrid AI method comparison

Tables 3 and 4 present the obtained results using a conventional method base on GA algorithm and those obtained by using the proposed method. Based on obtained results in Tables 3 and 4, we can conclude that methods based on the proposed hybrid method as well as the one based on the GA only give efficient and accurate results that represents well the DUT radiation sources. Figure 5 illustrates an estimation of the obtained positions using the proposed hybrid method. It is worth noting that this representation highlights that during the operation of the converter, the transformer has been the most radiating component. Then we can list the transistor, the inductor, and lastly the diodes. Estimated EM radiation maps at t = 9.95 µs and t = 9.78 µs based on identified dipoles parameters using both methods are presented in Figure 6. The second line represents the magnetic field distribution derived from the time-domain (TD) electromagnetic inverse method using a genetic algorithm (GA). The third line displays the results obtained using the proposed hybrid AI method, which integrates particle swarm optimization (PSO), PZMI descriptors, and artificial neural network (ANN) algorithms.

It is crucial to highlight that employing both methods. In particular, the hybrid AI method using the coupling of PZMI/ANN/PSO-based has given about 8% relative error, as shown in Table 5. Indeed, the major advantage of implementing a hybrid method is the significant reduction in computing time by about 35 times less than the GA-based method, which is an interesting achievement. Therefore, using the proposed hybrid AI method can be an original solution when dealing with real complex structures such as those employed in power systems. It is worth noting that it is possible to perform measurements and apply the proposed method also for Hx and Hy components.

Table 1. ANN database

The learning database	Output
Test base	348 PZMI vectors
Magnetic dipole	370 with output 0
Electric dipole	370 with output 1
Indifined cases	70 with output 0.5

Table 2. Control parameters

PSO parameter	Value	GA	Value
Error limit	10%	Error limit	10%
Swarm size	48	Population size	120
Nombre of generations	Inf	Nombre of generations	Inf
Number of parameters	6	Number of parameters	6

Table 3. Obtained results using a conventional GA-based method

Non-hybrid method					
N	Dipole	M_d (A/m²) × e-7	X_d Y_d Z_d (mm)	θi(rad)	φi(rad)
1	M	3.12	14.6, -13.3, -6.45	0.01	0.13
2	M	4.42	14.2, -3.2, -7.9	1.02	-2.32
3	M	11.1	1, -2.1, -12.1	0.16	0.17
4	M	2.96	-9.6, 2, -6.1	-0.2	-0.31
5	M	3.86	-13.4, 11.9, -6.5	-0.76	2.25
6	M	1.48	-3.5, -10.8, -3.7	1.27	3.13
7	M	0.18	-13.6, -7.4, -6.2	1.45	0.15

Table 4. Obtained results using the proposed method

Hybrid method					
N	Dipole	M_d (A/m²) × e-7	X_d Y_d Z_d (mm)	θi(rad)	φi(rad)
1	M	3.11	14.71, -13.25, -6.44	0.02	0.17
2	M	4.41	14.1, -3.3, -7.86	0.97	-2.39
3	M	11.07	1.1, -1.99, -12.05	0	3.13
4	M	2.99	-9.61, 2.08, -6.17	-0.18	0.1
5	M	3.83	-13.09, 12.1, -6.52	-0.77	2.24
6	M	1.51	-3.49, -11.1, -3.7	1.26	3.11
7	M	0.19	-14.2, -7.41, -6.03	1.43	0

Table 5. Performance of each method

PZMI/ANN/PSO-based method	Value	GA-based method	Value
Relative error (%)	7.97	Relative error (%)	9.51
computing time (min)	38.26	computing time (min)	1355.45

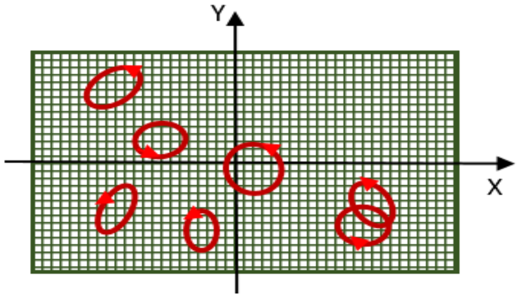

Figure 5. Approximate representation of equivalent sources positions using the hybrid method results

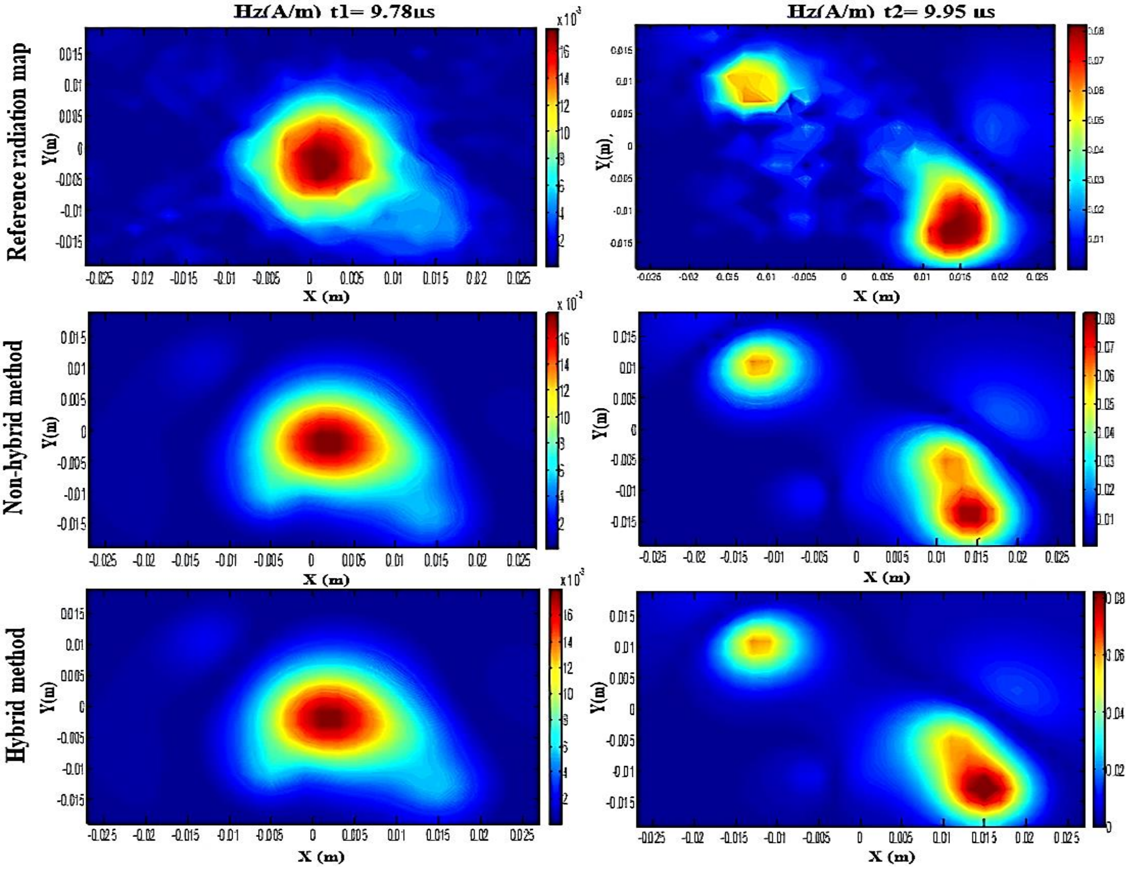

Figure 6. Measured and estimated maps using both non-hybrid and hybrid methods at two-time steps

5. CONCLUSION

This paper has outlined a detailed investigation of a hybrid AI algorithm for EMC applications. The proposed method based on coupling of PZMI descriptor, ANN, and PSO technique has been implemented. To assess and validate the proposed approach, we applied it to a measured NF radiation signals emitted by a flyback AC/DC converter. This structure is complex enough to validate the performance of the proposed method, especially when using experimental measurements. A dedicated TD measurement test bench has been developped for the characterization of radiating sources. A comparison between TD inverse method based on GA only and the proposed hybrid method has proven the robustness of the latter and shown a very intresting improvement in the speed of convergence. The equivalent model parameters obtained are comparable to those from the non-hybrid method. The proposed approach has demonstrated satisfactory performance in both efficiency and accuracy. It is worth noting that obtained results are an example of the high potential of using hybrid AI-based methods in EMC applications. It opens the way to more interesting studies, particularly in the area of power electronic systems.

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