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Electromagnetic Time Reversal for Radiating Source Identification in Time Domain

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***Abstract*— This paper presents a study on the characterization of electromagnetic near field radiation in the time domain. The proposed methodology affords a radiation model based on the electromagnetic inverse method using analytical expressions of the equivalent dipoles. The identification procedure is conducted by the Time Reversal technique (TR). The advantage of this process is focusing a field in both time and space. The main goal of this paper is to investigate the use of the Electromagnetic Time Reversal (EMTR) method in the time domain. First, the EMTR principle is presented. The characterization of the time domain magnetic field distribution is then developed. The radiating source localization and the excitation signal's shape were successfully defined. In addition, the calculated distribution cartography of the magnetic field is compared to the reconstructed cartography. The obtained results show the effectiveness of the proposed approach.**

***Keywords*— Electromagnetic Compatibility, Inverse method, Near field, Time Domain analysis, Time Reversal.**

I. INTRODUCTION

With the increasing progress of the electronic systems and technology, it appears a serious complexity in circuits design. Nowadays, the EMC study becomes a crucial issue especially in the near field region, in order to improve modelling and systems design. Hence, works achieved in this field are widely ongoing. There were many methods for circuits modelling in the literature. For instance, in [1], Aouine et al used the direct method to predict radiations in the surroundings, but such an approach is not simple to apply on real complex structures. To avoid these limitations and characterize properly the electromagnetic fields distribution, research works moved to a more favourable method based on the resolution of the inverse problem. This method has fully proved its efficiency for different purposes. In the proposed work, the inverse problem is used in order to characterize the EM near field radiations.

This methodology was amply developed in the frequency domain. For instance, authors in [2-3] have used different powerful numerical techniques in order to recognize the radiating sources existing in a DC-DC converter. A parametric study was also presented in [4] to evaluate the influence of the different configurations parameters such as height measurement and resolution. Nevertheless, the frequency method still not efficient and limited in terms of time and resources especially when applied to the power electronic circuits that manifest important perturbations in a wide frequency band [2]. As a solution, the time domain analysis is recently adopted to bypass these limitations. Indeed, in the time domain several studies were developed using numerical methods, such as the Finite Element method [3], the Finite Difference Time Domain (FDTD) [4], and Finite Integration Technique (FIT) [5], but they are heavy in terms of calculation time and space.

For this purpose, the present study is based on the analytical expressions, which describe entirely the electromagnetic radiations of an elementary dipole in the time domain. These equations, presented in [8], permit the extraction of the near field cartography that shows the radiation distribution at each time of the experiment. Among the studies recently published on this topic, the researches in [9] and [10] present the generic flowchart of the time domain electromagnetic inverse problem. In order to achieve the identification procedure, the genetic algorithms were developed in a specific frequency band. In this study, the identification procedure of the radiated sources is carried out one by one, starting from the highest magnetic field until the weakest radiation by extracting at each iteration a local cartography. Such methodology is conclusive, but also too heavy in term of time.

The final aim of the present paper, being the use of the electromagnetic inverse problem based on the Time Reversal technique, is to cope with the previous limitations. Indeed, the TR technique was successfully extended to the electromagnetic domain [11-14]. In fact, the main idea is reversing signals in time by making the electromagnetic waves back-propagate to their initial source [15]. Actually, this technique is widely developed in the frequency domain using the Decomposition of the TR Operator (DORT) [16]. Due to the frequency method limitations, the use of the time domain is more and more adopted. Among the first studies using the time domain analysis, there are those by Kosmas and Rappaport [17], and those by Yavuz and Teixeira [18]. These works use numerical approachs such as the FDTD method.

Later, Benhamouche et al [7] worked with the FIT method. In this work, the electromagnetic time reversal technique, based on the analytical equations in time domain, is used in the near field region, in order to identify and localize the source of disturbances in an electronic circuit. Indeed, the measured radiated magnetic field contains a lot of information that could be advantageously extracted using TR process. The proposed methodology permits the determination of the equivalent dipole parameters, such as excitement and geometry. The great interest behind this work is to apply the Time Reversal technique in an EMC application, using the time domain analysis. This area is not very investigated, especially when dealing with analytical investigations. The proposed approach allows visualising the complete process of dipoles radiation at each instant of time, which avoid the repetitive calculations presented in works [2] and [9].

This paper is organized as follow. The general concept of Electromagnetic Time Reversal technique is presented in Section II. The proposed approach is demonstrated in Section III. Electromagnetic inverse problem in time domain and modelling based on elementary dipoles are described. Time reversal's efficiency in predicting EM radiation sources is then discussed. Simulation results are exhibited in Section IV.

II. Electromagnetic Time Reversal Concept

A. Time Reversal basis

The TR technique was originally developed by Mathias Fink's team in the early nineties in the LOA (Laboratoire Onde et Image, France). In the beginning, the TR was presented in an acoustics context that deals with the study of mechanical waves such as sound, vibration, ultrasound, etc. The basic idea of the TR technique is allowing waves to propagate backwords to its original sources. Indeed, the TR technology is executed in two phases. In a first phase, a source emits a pulse from its location at (R_0). This surge will directly spread out in the medium. So, for a fixed period Δt, and as a reception phase, the propagated wave will be recorded through a known array of probes (R_i) forming the Time Reversal Mirror (TRM), $1 \leq i \leq M$ with M is the number of TRM probes, [15]. During the next phase, the received signal will be retransmitted through each probe in a totally reversed time order, which is known as the retro propagation phase. This allows focusing field in time and space at rightly the original source location (R_0).

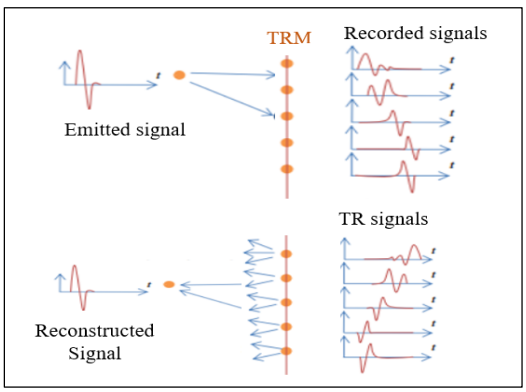

Fig.1. General TR concept.

In the literature, this process has not long ago achieved a huge success especially in telecommunication [19] and mainly in acoustics for selective focusing and detection applications [15]. This success is due to TR characteristics that permit maximising energy in both space and time.

More recently, TR technique has been also applied in electromagnetism, showing important results even in diffracting and strongly reverberant environment [14] [7]. The EMTR principles were discussed in [12] and [13]. The presented simulation model shows the convergence of the TR fields. In fact, the peak is obtained with waveforms summing in a constructive way at the source location.

B. Electromagnetic Time Reversal for EMC applications

As mentioned in the introduction, the Time Reversal has been recently applied for different EMC applications. Indeed, the EMTR has several advantages, namely its efficiency in reverberant environment, its applicability for systems bounded in space and for characterizing complex structures. For this, in [14], the TR process is used for successfully performing the susceptibility test in the reverberant chamber. In [20], authors presented the TR method as an electromagnetic source reconstruction solution.

We position this study in the context of localizing a near field radiating source, fully in the time domain. This approach is based on the use of the analytical equations in the time domain. Such an approach is a rarely explored area in the literature compared to the frequency domain, especially for EMC applications. Indeed, it requires a modelling that considers the circuit as a black box in order to apply it to any component.

III. Proposed Approach

A. Electromagnetic inverse problem in Time Domain

The basic idea of this study is to identify the radiating source characteristics of the system under test, such as source coordinates, excitation form, etc. The electromagnetic inverse problem is generally used to describe the measured radiation, in the near field region, in order to identify the different equivalent source parameters that give the same radiation. To this aim, we are going first to model the circuit's components using elementary dipoles. Since we positioned the work in the time domain, analytical expressions of the structure electromagnetic radiation are also developed in time domain. These equations allow creating the same emissions as the under-test circuit.

In this paper, a study on a magnetic source is presented. Furthermore, we have used the three components of the magnetic field H_x, H_y et H_z. An elementary magnetic dipole is characterized by its center coordinates (X_{di}, Y_{di}, Z_{di}), the magnitude of the moment M_{di}, and the angles of orientations (θ_{di}, φ_{di}) of the moment.

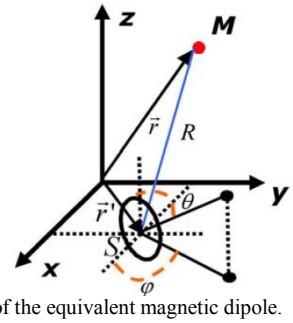

Fig. 2. Definition of the equivalent magnetic dipole.

In the time domain, the expressions of the different components of the magnetic field are calculated, in the cartesian coordinates system, using the following expressions:

- $$H_x = \frac{r^2}{4R}.I_0.\left[\left(\left(\left(\frac{1}{c^2}.\frac{\partial^2 I(t')}{\partial t^2}\right)+\left(\frac{1}{cR}.\frac{\partial I(t')}{\partial t}\right)+\left(\frac{1}{R^2}.I(t')\right)\right).\sin(\theta).\cos(\varphi)\right)-\left(\left(\left(\frac{1}{c^2}.\frac{\partial^2 I(t')}{\partial t^2}\right)+\left(\frac{3}{cR}.\frac{\partial I(t')}{\partial t}\right)+\left(\frac{3}{R^2}.I(t')\right)\right)\times\frac{1}{R^2}\times(X_d-X_0)\times\begin{pmatrix}\cos(\theta)\,(Z_d-Z_0)+\\ \sin(\theta)\sin(\varphi)\,(Y_d-Y_0)+\\ \sin(\theta)\cos(\varphi)\,(X_d-X_0)\end{pmatrix}\right)\right] \quad (1)$$

- $$H_y = \frac{r^2}{4R}.I_0.\left[\left(\left(\left(\frac{1}{c^2}.\frac{\partial^2 I(t')}{\partial t^2}\right)+\left(\frac{1}{cR}.\frac{\partial I(t')}{\partial t}\right)+\left(\frac{1}{R^2}.I(t')\right)\right).\sin(\theta).\sin(\varphi)\right)-\left(\left(\left(\frac{1}{c^2}.\frac{\partial^2 I(t')}{\partial t^2}\right)+\left(\frac{3}{cR}.\frac{\partial I(t')}{\partial t}\right)+\left(\frac{3}{R^2}.I(t')\right)\right)\times\frac{1}{R^2}\times(Y_d-Y_0)\times\begin{pmatrix}\cos(\theta)\,(Z_d-Z_0)+\\ \sin(\theta)\sin(\varphi)\,(Y_d-Y_0)+\\ \sin(\theta)\cos(\varphi)\,(X_d-X_0)\end{pmatrix}\right)\right] \quad (2)$$

- $$H_z = \frac{r^2}{4R}.I_0.\left[\left(\left(\left(\frac{1}{c^2}.\frac{\partial^2 I(t')}{\partial t^2}\right)+\left(\frac{1}{cR}.\frac{\partial I(t')}{\partial t}\right)+\left(\frac{1}{R^2}.I(t')\right)\right).\cos\theta\right)-\left(\left(\left(\frac{1}{c^2}.\frac{\partial^2 I(t')}{\partial t^2}\right)+\left(\frac{3}{cR}.\frac{\partial I(t')}{\partial t}\right)+\left(\frac{3}{R^2}.I(t')\right)\right)\times\frac{1}{R^2}\times(Z_d-Z_0)\times\begin{pmatrix}\cos(\theta)\,(Z_d-Z_0)+\\ \sin(\theta)\sin(\varphi)\,(Y_d-Y_0)+\\ \sin(\theta)\cos(\varphi)\,(X_d-X_0)\end{pmatrix}\right)\right] \quad (3)$$

Where $R=\sqrt{(X_{di}-X_0)^2+(Y_{di}-Y_0)^2+(Z_{di}-Z_0)^2}$ is the distance between the measurement point and the center of the elementary dipole, $t'=t-\frac{R}{c}$ is the delay time, (X_0, Y_0, Z_0) are the coordinates of the measurement point M, r is the radius of the magnetic loop and $I(t)$ is the excitement signal.

B. Time domain EM inverse method based on TR

Using the time domain electromagnetic inverse method expressions, in a very near region above the measuring surface of the studied structure, the magnetic field incoming to the TRM, at the position p_0 and at the time t, is defined by $H(p_0,t)$ and its reverse version is $H(p_0,T-t)$, $t\in[0,T]$.

Indeed, the radiated signals, are following, in the near field region, the excitation's form $I(t)$. Hence, at the TRM probes, a received signal component can be written as:

$$H(t)=k(t,R_0\rightarrow R_i)\otimes I\,(t) \quad (4)$$

Where $\otimes$ is the convolution product, $1\le i\le M$ with M is the number of TRM probes, and $k(t,R_0\rightarrow R_i)$ is the given impulse response of the propagation medium at each point R_i for a specified pulse emitted from R_0. Indeed, this propagation matrix is also constructed analytically, using a fixed virtual array of horizontal potential sources placed on the studied structure and excited by a delta-function excitation. The sampling step is rigorously defined. The reinjection of the reversed received fields from each TRM probe allows focusing signals at the initial source R_0 location. The focused signal can be written in the following way:

$$E_{TR}(R_0\,,t)=\sum_{i=1}^{M}k(R_i\ \rightarrow R_0\,,t)\otimes H_i(-t) \quad (5)$$

As a matter of fact, discussing the focusing quality is quite interesting. Actually, at the focusing time, source location is illuminated and gives the maximum magnitude of the recorded field. In the literature, there are many criteria to evaluate time and space focusing. In this paper, we are using the simplest criterion, which is the maximum magnitude of the focusing wave. Then, we implement its absolute value, as follows:

$$Max(R_0)=max_{t\in T}(|E_{TR}(R_0\,,t)|) \quad (6)$$

From this information, the point at which the field reaches its maximum peak is referring to the original source position in the space. The temporal focused signal E_{TR} at the point source guides to the returned excitation pulse $I(-t)$ [14].

For this, we consider a fixed number of TRM probes, positioned above the circuit under test. Then, after time reversal of each signal, fields are reinjected in the propagation medium from each probe to back propagate and focus at the original source location. The magnetic field cartography, at the focusing time, shows the maximum radiation distribution. Evaluating the focusing quality, source position and excitation pulse are found.

IV. SIMULATION RESULTS

The overall approach starts with the calculation of the near magnetic field distribution, in the time domain, above the studied structure. To visualize the field distribution cartographies, a first set simulation has been performed, on a surface of $(200\ mm \times 200\ mm)$, in the (XY) plan, above a current loop of a radius $25\ mm$, in the central position $(0,0,0)$, and at a height of measurement of $42\ mm$. To construct the transfer matrix k and get the reaction of the system in time, an array of 441 potential equivalent sources, with a resolution of $10\ mm$, is placed on the structure. Hence, we measure the inter-element impulse responses.

In addition, the TRM is constituted by 1681 calculation points arranged into a square array, and with a step of $5\ mm$ (Fig.3). The used excitation current is of a sinusoidal type and has a duration of $10\ \mu s$ at a frequency equal to $10\ MHz$ (Fig.4a). The calculated magnetic temporal signals at different points are displayed in (Fig.4b). The cartographies of the radiated field are obtained, at each instant of the experiment period, by magnetic field calculation equations, using Eq.1, Eq.2 and Eq.3 (Fig.5). We remark that the H_z component of the magnetic field has the highest amplitude compared to the other components H_x and H_y, at the instant that shows the maximum magnitude.

The transducers are now used as emitters to radiate the time-reversed signals. By applying the maximum magnitude criterion, Eq.6, at each potential source position, original and reconstructed excitation signals seem close one to another. Actually, the focusing signals magnitudes depend on several parameters, essentially the TRM probes number. We display the different maximum amplitudes at each position (Fig. 6), in order to choose the source point that has the maximum magnitude. Hence, we found on this structure only one magnetic source and its estimated coordinates are $(0,0,0)$. We observe in Fig.7a a good correlation between the calculated magnetic field H_z and that obtained using the proposed methodology. In addition, Fig. 7b shows the agreement between the original excitation shape and the normalised temporal focusing signal. Indeed, signals are normalized by dividing each element by its maximum value, which allows the comparison of corresponding normalized values for different positions.

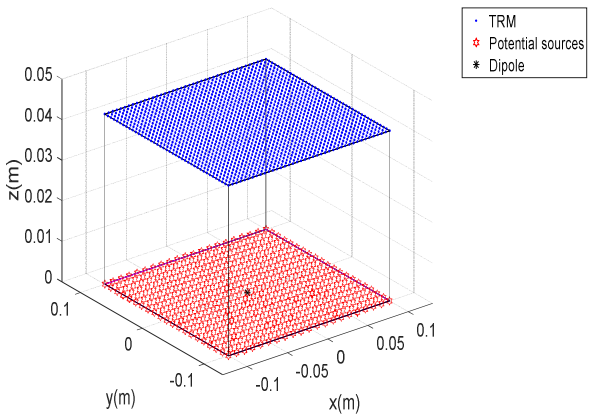

Fig. 3. Simulation domain

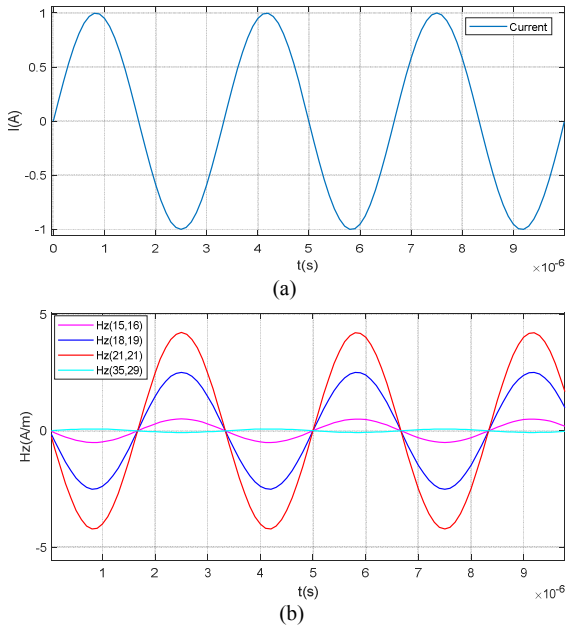

Fig. 4. (a) Excitation current, (b) Calculated H_z component at different positions.

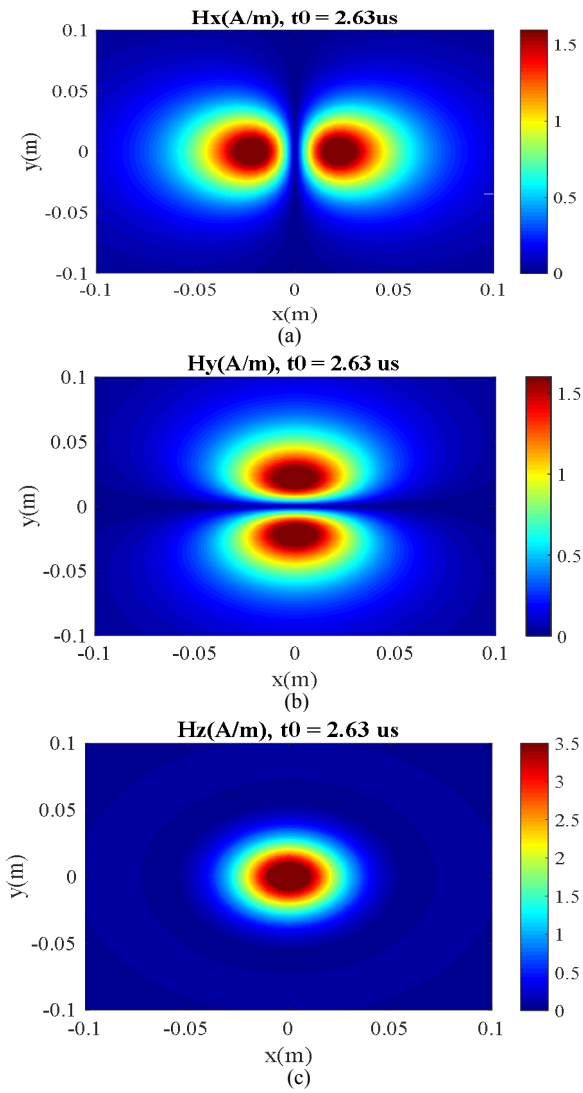

Fig. 5. Calculated near field cartography : (a) H_x, (b) H_y, (c) H_z

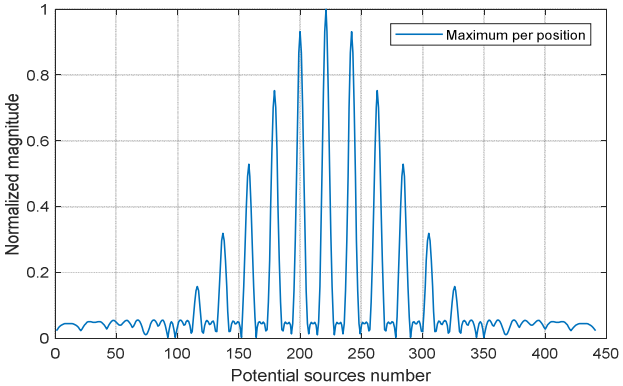

Fig. 6. Maximum magnitude of focusing.

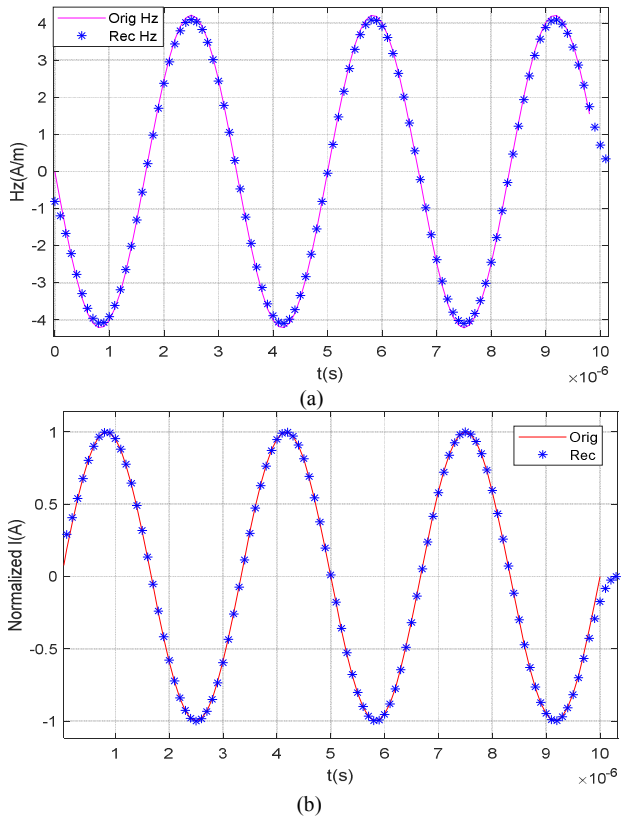

Fig. 7. (a) Comparaison between the obtained results and those calculated, at position (21,21), (b) Excitation reconstruction

Using the reconstructed excitement signal and the obtained source parameters, we can calculate the magnetic field signals at each position. The reconstructed cartography of components H_x, H_y and H_z is given in (Fig.8). We notice a good agreement between the calculated near field cartography (Fig.5) and the reconstructed distributions (Fig.8).

This work focuses on a basic structure in order to validate the developed method. Indeed, simulation is playing an important role in evaluating circuit performance when subjected to EMC studies. The present reconstruction method allows identifying source location and its excitement signal, using only the measured fields above the system (black box), which help characterizing unintentional generations present in its environment. Radiation cartographies at each time of the experiment period are calculated. The proposed methodology offers improvements in simulation efficiency and reduction in calculation time using the time domain analysis.

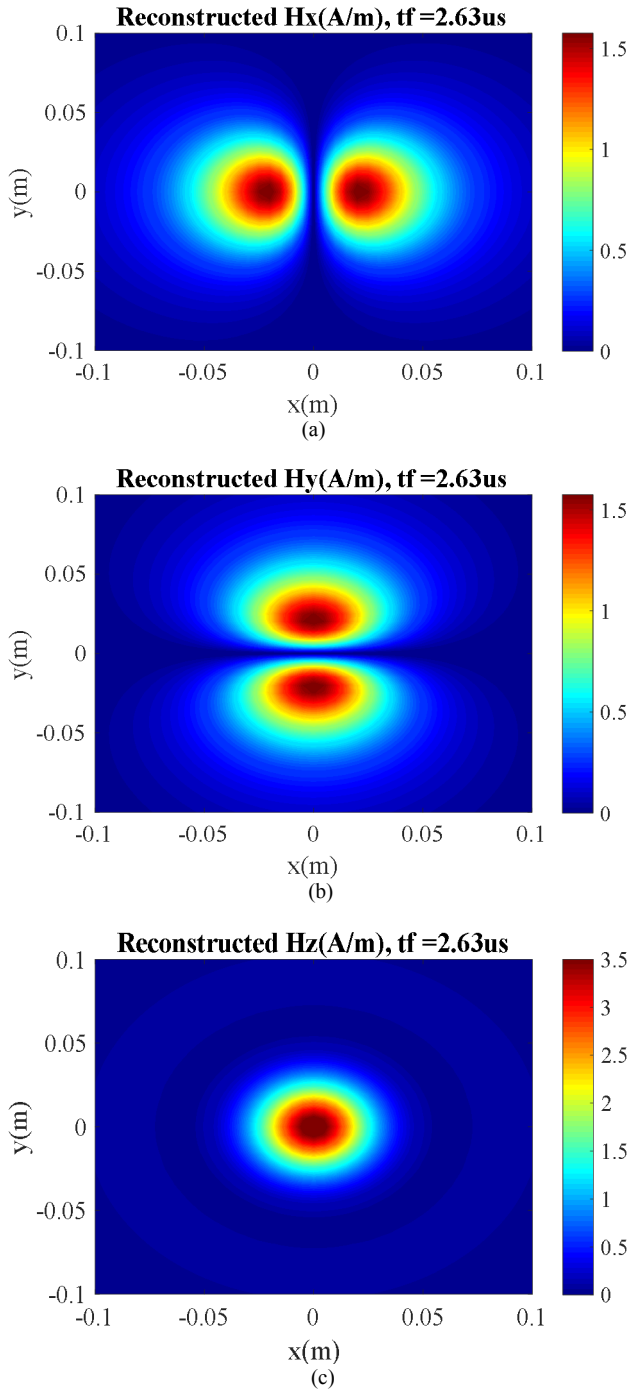

Fig. 8. Reconstructed near field cartography : (a) H_x, (b) H_y, (c) H_z

V. CONCLUSION

This paper presents the electromagnetic inverse method based on the TR technique. The specification of this study is to deal with the time domain analysis, in the near field region. The developed approach is established with the use of the analytical equations that describe the equivalent source radiations. In the first part of this work, the principle of the

TR process and its extension to the EMC field were presented. Secondly, the proposed procedure was explained. Then, the methodology was applied to a basic structure that contains a magnetic dipole. According to the obtained results, we conclude that the developed methodology is an efficient method and able to identify the parameters of the radiating dipole and characterize its excitation, in the time domain.

Actually, the flexibility offered by this method shows multiple advantageous and horizons to explore in a practical way. This is a first step and a feasibility test. Work is in progress to extend the proposed method to complex structures with a high number of radiating sources and apply it in both numerical simulation and experimental tests.

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