Hamid MEHADDENE[1], Hassane MOHELLEBI[1], Azouaou BERKACHE[1], Gérard BERTHIAU[2]

Department of Electrotechnics, Mouloud Mammeri University of Tizi Ouzou, Algeria (1)
Institut de Recherche en Energie Electrique de Nantes Atlantique (EA4642), Saint-Nazaire, France (2)

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Experimental and Numerical Multi-defects Analysis in Ferromagnetic Medium

***Abstract**. In this work, we describe an experimental and analytical study on the inspection and evaluation with eddy current testing (ECT) signals of two different thin cracks, realized with an electro-erosion process on two ferromagnetic sheets. We solved the direct problem by means of a Finite Elements approach, solving the 2D magnetodynamic electromagnetic equation. and then the inverse problem using artificial neural networks. The numerical calculated values are compared with measurements.*

Streszczenie.** Opisano analizę analityczną I eksperymentalną metody defektoskopii z wykorzystaniem prądów wirowych do badania materiału ferromagnetycznego ze szczeliną. Wykorzystano metodę elementów skończonych do konstrukcji modelu dwuwymiarowego. Metoda wspomagana jest wykorzystaniem sztucznych sieci neuronowych. **Eksperymentalna i numeryczna analiza defektoskopii wiroprądowej do badania próbek z wieloma defektami

Keywords: Multi-defects, Ferromagnetic materials, Eddy current non-destructive evaluation, Finite elements, Crack recognition.
Słowa kluczowe: defektoskopia wiroprądowa, metoda elementów skończonych, próbka z wieloma defektami

Introduction

Eddy current testing (ECT) is a non-destructive evaluation (NDE) technique that is gaining increasing interest as a key technology in the detection of small cracks in ferromagnetic specimens. Its main applications regard the analysis and testing of metallic components employed in transportation, nuclear, and other industrial plants. The method is based on the detection of the magnetic field due to the eddy currents induced on the specimen [1, 2].

One of the activities in the research field about the electromagnetic non-destructive evaluation is the discussion dealing with the efficiency of different numerical methods in solving both forward and inverse problems. From the computational point of view, a direct and an inverse problem have to be solved. The direct problem consists of the evaluation of the field perturbation at the measurement probe locations, for a given exciting field and geometry of the flaw (or flaws). In the inverse problem, one has to find the dimensions and the shape of the flaw(s), assuming the measurements and the forcing field as known quantities [3, 4]. As the inverse problem is the key objective in NDE, the success of any inversion procedure requires fast and accurate solutions for reconstruction of the geometric and physical characteristics of the thin cracks.

To overcome these difficulties and reconstruct these cracks, we used an algorithm based on an artificial reasoning system built on the basis of the human brain. A calculation tool developed under MATLAB environment was used.

Numerical model

In this study two specimen plate having the electromagnetic parameters of ferromagnetic materials is inspected.

It is a ferromagnetic stainless AISI 430 steel and a ferromagnetic S235JR steel (matter number are 1.4016 and 1.0037 respectively). The 3D configuration of the plate with the crack and the coil is shown in Fig. 1.

The specimens have a width 140 mm, a length 140 mm and a thickness 1,5 mm. The physical proprieties for each nuance are listed in Table 1.

The magnetic relative permeability and the electrical conductivity of the samples were measured respectively with the Epstein frame and a micro-ohmeter.

Table 1. Physical parameters of specimens

Material	Electrical conductivity MS / m	Relative magnetic permeability
AISI 430	σ_1 = 1,69	μ_{r1} = 110
S235 JR	σ_2 = 7,48	μ_{r2} = 178

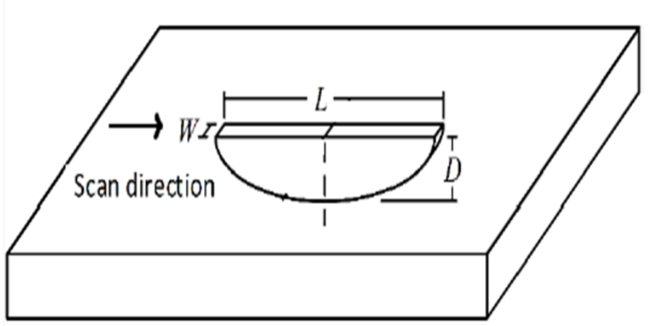


Fig.1. A coil and a test piece with a crack.

Surface breaking cracks of 0,22 mm width appears in the middle of each plate (JSAEM Benchmark Problem 6) [2]. They are modelled as regions having different electromagnetic properties from the base material. The both shapes of cracks are illustrated in Fig. 2.

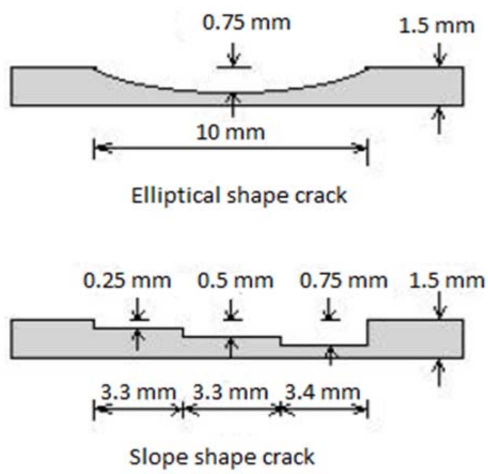


Fig.2. Forms of cracks studied.

The pancake coil is employed for the inspection of the specimen with crack. It is positioned normally regarding the surface of plate (parallel to the x-axis), and moves placed along the crack length direction. Its axis is parallel to the z-axis of the coordinate system shown in Fig. 1.

The probe is made of 140 turns, his Inner diameter is 1,2 mm, the outer one has a value of 3,2 mm and a height of the winding is 0,8 mm. It is supplied with a current of 8 mA. The frequency of the feeding driving signal is adjusted to f = 10 kHz.

The field equations describing low frequency electromagnetic phenomena are derived from Maxwell's equations. The numerical calculations are performed using a finite-element code in resolution of the 2D magneto dynamic electromagnetic equation in terms of the magnetic potential vector. In the two-dimensional case, the current density $\vec{J}$ and the magnetic potential vector $\vec{A}$ act in the positive z direction [5, 6].

$$-\frac{\partial}{\partial x}\left(\frac{1}{\mu}\frac{\partial A_z}{\partial x}\right)-\frac{\partial}{\partial y}\left(\frac{1}{\mu}\frac{\partial A_z}{\partial y}\right)+j\sigma\omega A_z=J_{sz} \quad (1)$$

The solution of the forward problem requires the determination of the impedance change of the probe. The impedance of a circular filament of radius r can be calculated directly from the distribution of the magnetic potential vector [6, 7].

$$\mathrm{Re}(Z)=-\frac{N^2}{JS^2}\omega\iint_s 2\pi r\,\mathrm{Im}(A)\,ds \quad (2)$$

$$\mathrm{Im}(Z)=-\frac{N^2}{JS^2}\omega\iint_s 2\pi r\,\mathrm{Re}(A)\,ds \quad (3)$$

This parameter is evaluated by calculation of the difference between the values obtained for the plate without crack and the values obtained for the plate with crack.

Architecture of the artificial neural network (ANN) for cracks recognition

This section describes the ANN architecture designed for the sizing of different form of crack. An artificial neural network (ANN) can be used to make an approximation function by learning from collected data, and it can objectively classify unknown data based on this approximation function. The ANN consists of a number of processing elements that are connected to form layers of neurons, although the networks may be complex. The missing links between sets of inputs and outputs were found by determining the optimal synaptic weights, based on the available training data of the inputs and outputs. In this research, various impedances of the probe were extracted and used as training data to train the ANN classifier for the purposes of estimating depth and width of the cracks [4, 8, 9].

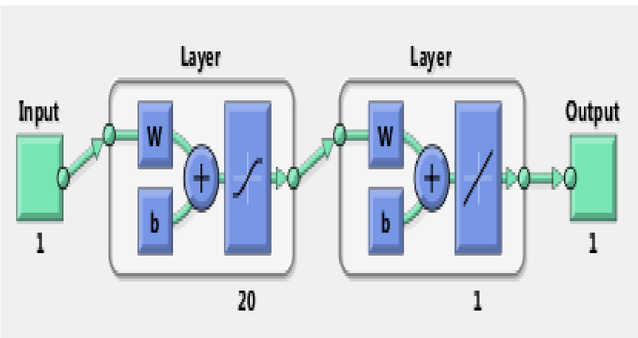


Fig. 3. Architecture of the ANN.

A multilayer perceptron (MLP) neural network was used, consisting of one input layer, one hidden layer and one output layer (Fig. 3.) as it showed a better generalisation capability. A tangent sigmoid function has been used as the activation function for the hidden layer due to its non-linear and saturation properties for inputs of large absolute values. A linear transfer function has been used for the output layer. The Levenberg-Marquardt (LM) algorithm, which is similar to the Newton method, is used for the back-propagation error in the supervised learning of the ANN. The root mean squared error (RMSE) was used as the performance index in this study [10, 11].

Measurement

Measurements by the eddy current method were carried out using two types of devices, the first to detect the signature of ferromagnetic steels with and without crack in impedance plane, the second to quantify (measure) these cracks.

Signature of ferromagnetic steels in impedance plane

To detect the characteristic signature in the complex plane, we used a Nortec 500 series eddy current cracks finder from the Olympus firm, with a sensor consisting of a single coil, emitter and receiver with a frequency of 100 kHz to 500 kHz. (Fig. 4).

Fig. 4. Nortec 500 eddy current flaw detectors.

We present in Fig. 5 the signatures registered with two samples ferromagnetic and one sample non-ferromagnetic without cracks. This is a graphical representation of the complex probe impedance where the abscissa (X value) represents the resistance and the ordinate (Y value) represents the inductive reactance.

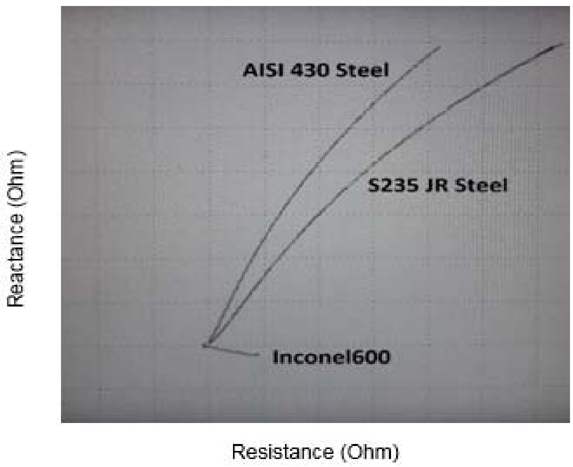


Fig. 5. Impedance plane without crack.

We observe that the increasing of the material permeability has a direct influence on the coil magnetic field causing an increase in the coil Inductive Reactance (XL), and the characteristic signatures in the complex plane of these materials are similar to those of the curves existing in the literature [12, 13].

For locating the cracks in the plane of the inspected part, a scan of the workpiece surface by the Eddy current sensor is necessary.

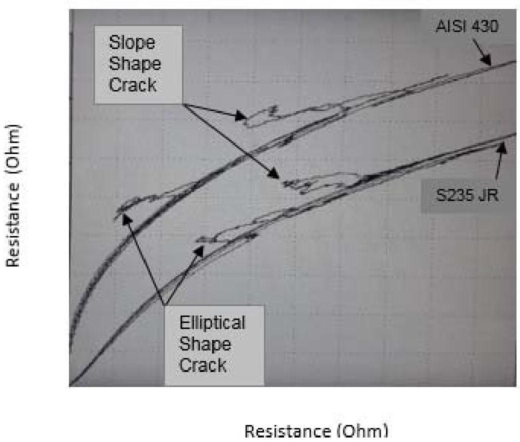
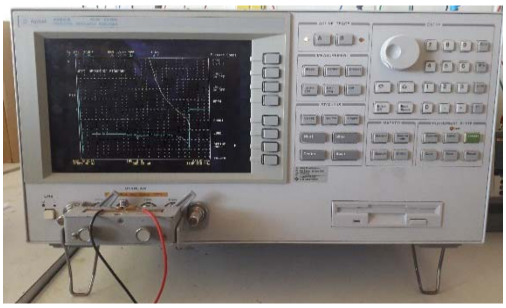
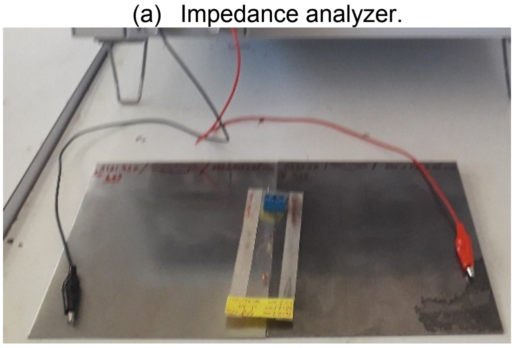


Fig. 6. Impedance plane with crack.

The signals recorded in the case of steel ferromagnetic stainless AISI 430 and steel ferromagnetic S235JR, containing Slope shape crack and Elliptical shape crack are given in (Fig. 6).



(a) Impedance analyzer.



(b) Inductive sensor & ferromagnetic plates with thin cracks.

Fig. 7. Equipment used

Quantification of the signal

A series of experimental studies was carried out to examine the capabilities of the fine crack detection and quantification technique on ferromagnetic materials. The test setup for measuring Eddy currents signals was composed of a dual function inductive sensor, an impedance analyzer, and two specimen plates containing cracks, as shown in (Fig. 7).

The sensor (Fig.7.b) is connected to Agilent 4294A impedance analyzer (Fig. 7.a) which provides a supply current and measures the impedance at its terminals. The maximum output current is 20 mA and it varies depending on the measurement frequency from 40 Hz to 110 MHz.

To perform the experiments, two thin cracks are artificially realized in the center of each plate using the electro-erosion process. The shape and the dimensions of cracks are shown in (Fig. 2).

If we place the eddy current sensor in a marked spot of the sample, we can then measure the electrical impedance of that coil (influenced by material properties at that position), and if we measure this impedance in the presence of a crack at the same position, we get the trend or evolution of that impedance at that position.

To start we measure the impedance for a plate without crack (Z_0), then after we measure this impedance for a plate with crack (Z). The probe impedance is calculated for lift-off of 0.15 mm above the plate surface for different coil locations, starting from x = -10 mm till x = 10 mm at every 1 mm along the crack direction. The settings of the impedance analyser (feeding current, frequency) are the same as those used in simulation and remain unchanged for all measurements and until the end of the tests

Results & discussion

In table we reported the details about the numerical method used.

Table 2. Parameters used in numerical analysis.

The number of total elements	50656
The number of total nodes	25405
Computer	*hp* EliteBook 840
Processor	Intel(R) Core (TM) i5-4300U CPU @ 1,90GHz 2,50 GHz
Installed memory (RAM)	4 Go (3,90 Go Usable)
Operating system (bits)	64

In Fig. 8. is reported the used mesh for the modelling of the geometry. In the field of electromagnetism, the triangular element is used for 90% of cases. The calculated values obtained using this mesh are always the closer ones to the measurements.

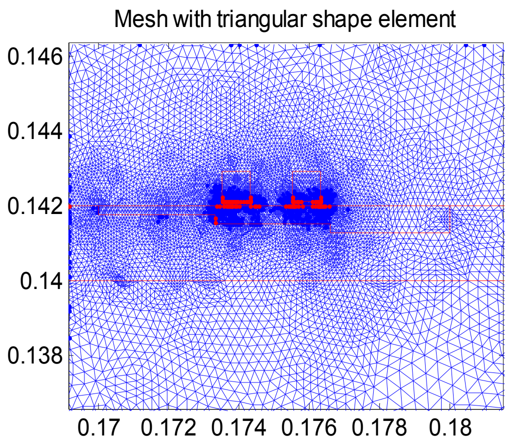
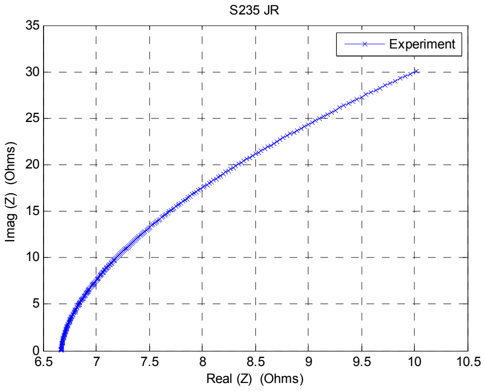


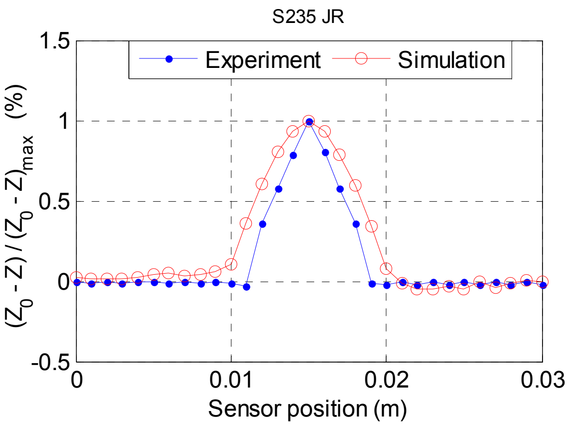
Fig. 8. Meshes for the plate with crack and the probe coil.

The results of measurement and simulation for S235JR steel and AISI430 stainless steel are plotted in Fig. 9 (b, c) and Fig. 10 (b, c). Signals were repeatedly measured 30 times at each specimen, with 1mm of displacement pitch.

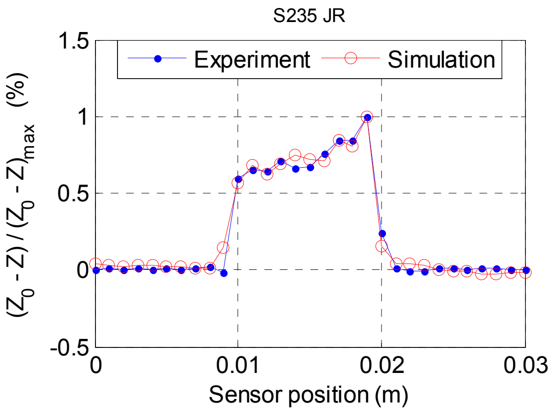
Fig. 9(a) and Fig. 10(a) show the impedance plane of materials without cracks for various frequency and for a sensor fixed position in experiment case. The simulation results show that the measurement is appropriated since these results well agreed with results obtained in Fig. 5.



(a) Impedance plan.

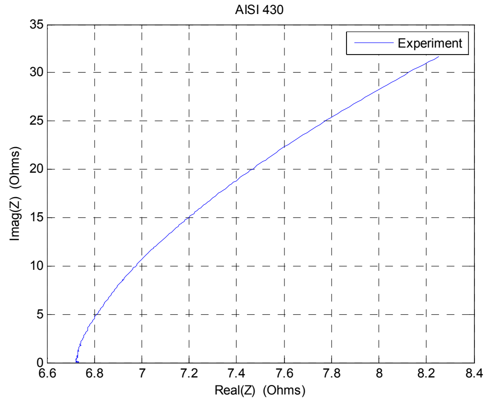


(b) Absolute impedance vs sensor position (Elliptical shape crack).

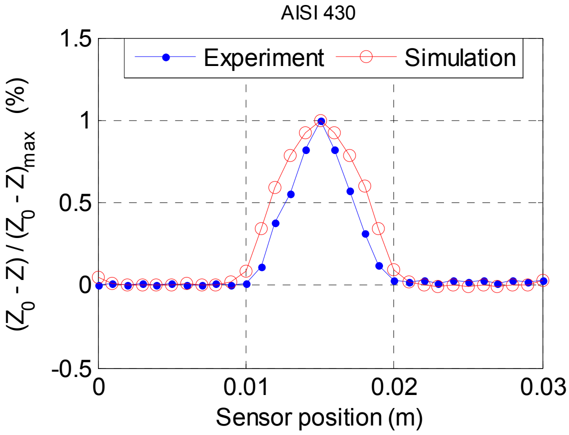


(c) Absolute impedance vs sensor position (Slope shape crack)

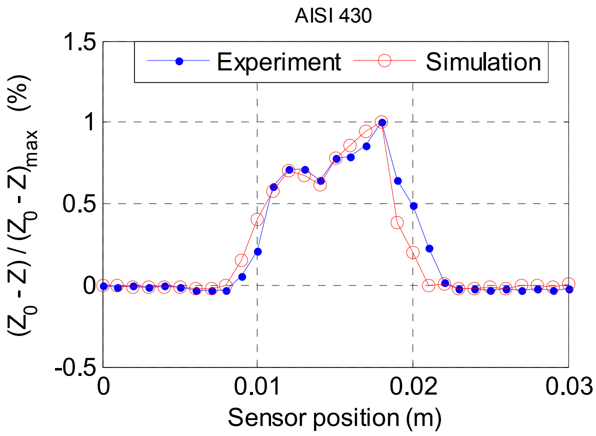
Fig. 9. Comparison of measurement and analysis for S235 JR.



(a) Impedance plan.



(b) Absolute impedance vs sensor position (Elliptical shape crack).



(c) Absolute impedance vs sensor position (Slope shape crack)

Fig. 10. Comparison of measurement and analysis for AISI 430.

We can see in the Fig. 9 (b, c) and 10 (b, c) that the amplitude of the signal increases with the depth of the defects in all peaks sections, and that the distribution of absolute impedance (Z_0 - Z) versus the position of the coil with respect to the defect are always of the same shape of those measured.

Knowing that the sensor displacement was done manually, the offset of the charts is due to the lack of precision during the displacement

If we make a comparison with a previous article [4], we find that the ΔZ signals are inversed, which can tell us if any material presents the magnetic character or not.

Results of the Network Validation

The measured signals in the first part were then processed to characterize these cracks. The neural network input ANN is constituted of thirty values of impedances. The results are shown in Fig. 11; for different shapes of cracks

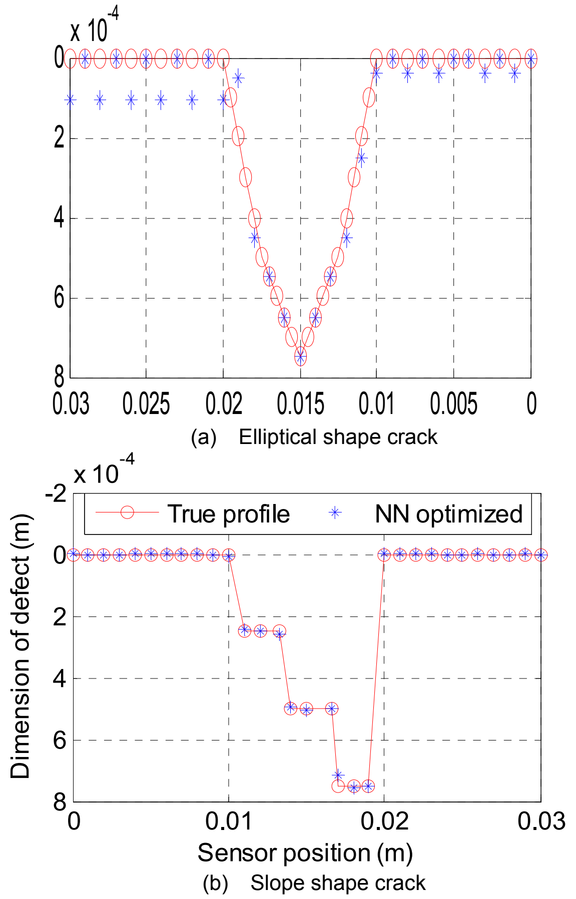


Fig. 11. Crack reconstruction.

The results show that the used network can predict the length and the depth of a crack cluster with a very good accuracy. Note that the learning base was built with experimental and simulation data and of course the results give the same for both cases.

Conclusion

Finite element modeling and results of numerical analysis for eddy current testing of ferromagnetic materials with a thin crack were described in this paper. For two cases, 1) elliptical shape crack, 2) slope shape crack, the comparison of numerical analysis and measurement were discussed. The change in Eddy currents signal were determined according to shape and dimensions of cracks. The results verified the accuracy of the modeling and the analysis method.

Both in measurement and simulation, the impedance changes from the sensor position show that the detection of thin cracks in the ferromagnetic materials is possible through detection of the Eddy current testing signal.

ANN based pattern recognition was applied to estimate the depth and width of the cracks. The ANN classifier was trained using diffrents values of impedances extracted from the Eddy current signals; the trained ANN classifier can successfully estimate the size of cracks with little error.

Overall, these results demonstrated that the proposed damage detection and quantification method using inductive sensors and an ANN classifier is able to diagnose defects in steels ferromagnetic.

***Authors**: dr. Hamid Mehaddene, Department of Electrotechnics, Mouloud Mammeri University of Tizi-Ouzou, BP 17RP 15000, Algeria, E-mail: mehaddenehamid@yahoo.com; prof. dr. Hassane Mohellebi, Department of Electrotechnics, Mouloud Mammeri University of Tizi-Ouzou, BP 17RP 15000, ALGERIA, E-mail:mohellebi@yahoo.fr; dr. Azouaou BERKACHE, Department of Electrotechnics, Mouloud Mammeri University of Tizi-Ouzou, BP 17RP 15000, Algeria, E-mail: azouaoubrk@yahoo.fr. prof. dr.Gérard Berthiau, Institut de Recherche en Energie Electrique de Nantes Atlantiaque (EA4642), 37 boulevard de l'université, BP 406, 44602, Saint Nazaire, Cedex, France, gerard.berthiau@univ-nantes.fr.*

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