Modeling of Corrosion Degradation for PCCP for Condition Monitoring Simulation Using Equivalent Circuit and Artificial Neural Networks (A Simulation Study in GMRA)

Youssef Hamad Shakmak and Saleh Hussein Awami

***Abstract*—There are many methods for inspecting corrosion interaction in objects. Some of these methods are known as the Non-Destructive Test (NDT) which uses a successful approach to monitor materials without harming the objects. In this paper, corrosion degradation is modeled and simulated by using equivalent electrical circuit. The components of the designed equivalent circuit contain resistances and coils related to the condition of the wire used in the Pre-stressed Concrete Cylinder Pipe (PCCP). The change of the resistance value, self and mutual inductance due to the certain wire loop is related to the change of the wire diameter which changes due to the corrosion. These changed factors change the pattern and the value of the exciter current. The fault resulted by simulated model is inspected using Artificial Neural Networks (ANN) through monitoring of the exciter current changes. PCCP is modeled as equivalent electrical circuit based on Dave's model which was developed in Queen University. Different techniques of calculations of the model components were used in the work which gives better results and different view than the one given by Dave.**

The simulation of proposed approach of this work gave a good solution to the corrosion degradation that related to the number of broken wires in PCCP. That can be modeled and can be detected by using ANN system for monitoring of the exciter current. The system is able to detect the severity of the fault by finding the approximate number of broken wires and their location in the tube. In this work, MATLAB as a technical scientific language were used to build the simulated system and to monitor it using a proper designed ANN system. The study shows that a simple method for modeling the data of corrosion the wires of PCCP and the possibility of monitoring these changing by monitoring the change of the exciter parameters values changes. The method shown in this study makes it possible to simulate the PCCP for different condition ranging from perfect case to sever defected cases. Many patterns were generated by simulating the model at different conditions of the pipe, then recognized as perfect case (no defect or free corrosion) or defected case (corrosion or broken wires).

Pipe parameters of the type of Embedded Cylinder Pipe (ECP) are used for large diameter PCCP for condition monitoring simulation which was designed by the Great Man-Made Rive Project (GMRP).

***Index Terms*—PCCP inspection; PCCP modeling and simulation; NDT; ANN; PCCP condition monitoring, eddy current, GMRA.**

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N. Nower is with the Institute of Information Technology, University of Dhaka, Dhaka, Bangladesh (e-mail: naushin@iit.du.ac.bd).

A. Raja Chowdhury is with the Department of Computer Science and Engineering, University of Dhaka, Dhaka, Bangladesh (e-mail: farhan717@cse.univdhaka.edu).

F. A. is with the National Institute of Standards and Technology, Boulder, CO 80305 USA (e-mail: author@ boulder.nist.gov).

S. B. Jr., was with Rice University, Houston, TX 77005 USA. He is now with the Department of Physics, Colorado State University, Fort Collins, CO 80523 USA (e-mail: author@lamar. colostate.edu).

T. C. is with the Electrical Engineering Department, University of Colorado, Boulder, CO 80309 USA, on leave from the National Research Institute for Metals, Tsukuba, Japan (e-mail: author@nrim.go.jp).

I. Introduction

There are four major underground basins in the deep of sahara desert of Libya, these being the kufra basin, the Sirt basin, the Morzuk basin and the Hamada basin, the first three of which contain combined reserves of 35,000 cubic kilo-meters of water. The reserves offer almost unlimited amounts of water for Libyan people. The Great Man-made River Project consists of five phases, with more than 4,000 km (2485 miles) of 4 meters (158-inch) diameter and section length of 7.52 meters pre-stressing Concrete Cylinder Pipe in order to convey pure water from the aquifer in the south to the Libyan costal belt which improves Libyan's agriculture , Fig. 1 [1], the phase I ,the first water line, is represented as the Sarir to Sirt and Tazerbo to Benghazi system (SSTB system – conveying water from Sarir and Tazerbo to Sirt and Benghazi), the phase II , the second water line, is represented as the Western Jamahiriya System (WJS) bringing water from Fezzan to Triopli, the phase III is represented as the kufra link which develops well-fields at Kufra and conveys water to increase the capacity of phase I, the phase IV is represented as the Ajdabia to Tobruk conveyance pipeline, the phase V is represented as the Sirt to Triopli connecting conveyance pipeline link , Al Gardabiya/Assdada system, the first river (including Al sarir/Sirt system and Tazerbo / Benghazi system) and the second river (including Al Hasawna/Al Jefra plain system) by conveying a quantity of fresh water in either direction, and thus the meeting of the two rivers is realized [1].

In October 1983, the Great Man-Made River Authority (GMRA) was created and invested with the responsibility of taking water from the desert of Libya, and conveying it to the most of Libyan's cities by using PCCP conveyance [1], [2].

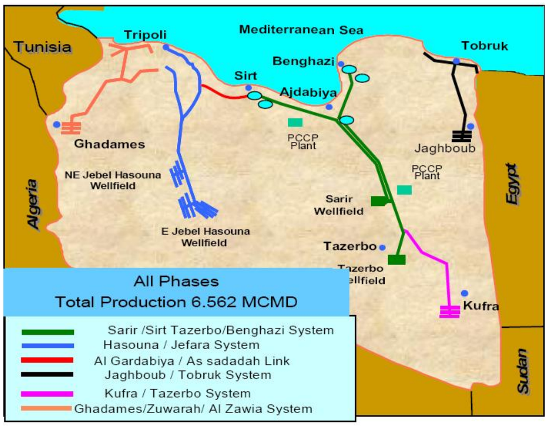

Fig. 1. Five phase of the Great Man-Made River Project.

II. PCCP Materials Components

The pre-stressed concrete cylinder pipe is made of five basic components which are:

- A watertight steel cylinder is encased within the concrete core with thickness of 1.9 millimeters.
- The inner concrete and the outer concrete which are the concrete core. In this work, the single wrapped with high tensile is modeled and simulated.
- Wounded steel pre-stressing wires which provide compressive stressed on the concrete core.
- External mortar coating.

The pipe diameter is large as four meters long. In this work, all pipe geometries are used as parameters/constants in the model simulation. The cross section and elements of Embedded Cylinder Pipe (ECP) is shown in Figure 2.

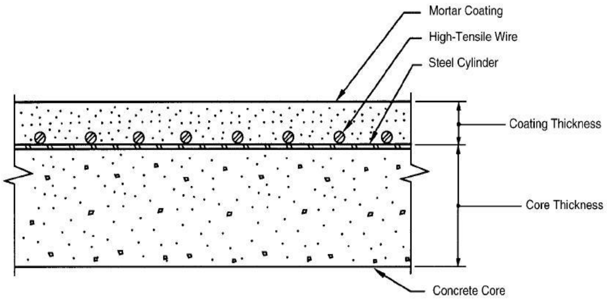

Fig. 2. The cross section and elements of Embedded Cylinder Pipe (ECP) [3]

III. Problem Identification

The pre-stressed concrete cylinder pipe is constructed with an expected life time of 50 years. Also, there are other factors which reduce the expected life time and help to increase the corrosion interactive as follows:

- Pipe storage, transportation and installation.
- Saline ground environment (Aggressive Area).
- First pipe test by exposing the pipe with high water flow pressure.

GMRA conducted a rehabilitation program and implemented different technologies to assess the condition of pipeline sections as follows:

- Remote field eddy current transformer/coupling (RFEC/TC).
- P-wave inspection.
- Acoustic emission inspection.
- Close Interval Potential Survey (CIPS) using Cathodic Protection System (CPS) data.

All of these assessment methods need to be combined because of sharing the same information about pipe condition monitoring. The collected data of each above non-destructive methods is different but it should have the same results of pipe status. Unfortunately, it is difficult to analysis the practical collected data in some method like CIPS survey to gather information about the number of broken wires and its location(s). The more study is needed in order to analysis these collected data to reach the desired solution. Both technologies the RFEC/TC inspection and the P-wave inspection are able to detect the number of broken wires and its location(s). Both of these technology are using the different technique of using the two coils (transmit and receiving) because of the distance between two coils. So the results obtained from these technologies are different in the mean time they are using the same electromagnetic inspection method to inspect the pipe. Using too many inspection methods will lead to different results of Pipe inspection. A computer simulation is highly required to better understand of pipe condition monitoring which will improve the PCCP inspection technique. In addition, it has now proven that some of the PCCP placed without Cathodic Protection system was corroded by the saline environment for sooner than anticipated. The corroded pipe is recognized by detecting the number of broken pre-stressing wires.

IV. Demanded Solution

A computer modeling simulation is needed to provide a great help for making a decision of replacement, maintenance, or keeping the pipe in-service. ***In this work***, a computer simulation is used to simulate and represent a sound condition pipe (free of corrosion and wire breaks) and defected condition pipe (showing of corrosion and wire breaks) using an Equivalent Electrical Circuit Model (Dave's model) and Designing of Artificial Neural Networks (ANN) as NDT system to monitor PCCP based on simulation result. The solution should including the follows:

- Determining the number of broken wires and its location(s).
- Determining the severity of pre-stressing wires (Corrosion Rate).
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V. PCCP Model and Simulating Technique

As stated above the Dave's model [3] is used as equivalent electrical circuit of PCCP. The obtained results were depicted and indicated both the perfect case of concrete pipe and the defected case of concrete pipe that it has shown one broken wire and its location along a concrete pipe. In this work, the large diameter pipe in GMRA is modeled and simulated by using Dave's model but using different parameters and different calculations technique of pipe geometry. The perfect pipe and the defect pipe cases are recognized by using the eddy induced currents that measured on Exciter coil as a receiving coil tool. Figure 3

[1] and Figure 4 show the PCCP material components and the equivalent circuit for N-turn loops which representing the N- turns of pre-stressing wires.

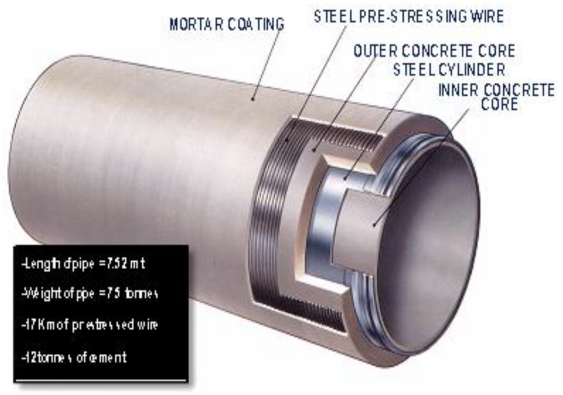

Fig. 3. PCCP material components

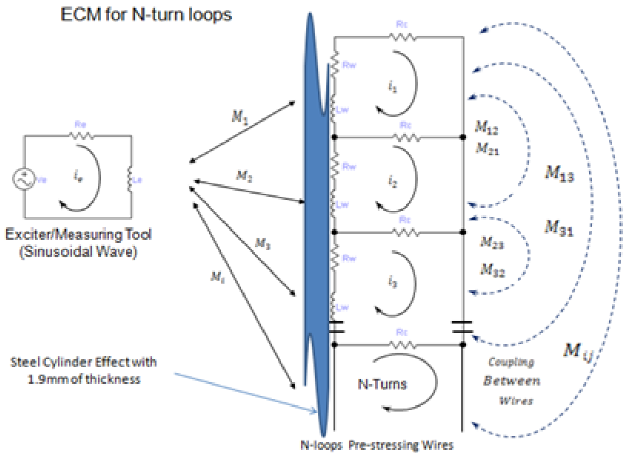

Fig. 4. Equivalent circuit model for PCCP

This model can be simulated by using one-turn loop, two-turn loops or three-turn loops and so on till N-turn loops depending on the selected case of simulation. This approach is used to guarantee a better understanding of pipe system behavior. The number of different combination that can be obtained using different number of wire loops can be computed with the relation as showed in Table I by using the following equations:

TABLE I: PARTIAL COMBINATION, COMPLETE COMBINATION VS. NUMBER OF WIRE LOOPS

(l)	1	2	3	4	5	.....
N_{PS}	1	3	6	10	15	.....
N_{CS}	1	3	7	15	31	.....

$$N_{PS} = l \cdot \left(\frac{l+1}{2} \right) \quad (1)$$

$$N_{CS} = 2^{(l)} - 1 \quad (2)$$

With:

(l) is number of loops.

N_{CS} is the complete defect combination for the simulation.

N_{PS} is the partial defect combination for the simulation.

Some considerations were taken in account to build a sound PCCP model as follows:

- The exciter coil and pre-stressing wire coil are treated as filamentary coils according to references [4] and [5] respectively.
- In this work, simulate the exciter scan movement in order to get better understand of Electromagnetic (EM) wave traveling through the pipe and in order to implement and comparing it with actual inspection.
- In this work, the exciter coil must be used as the sensor for the resulted electrical and magnetic fields produced by pipe's wires.
- Dave's model is used because of comparison of the actual inspection to the model.

In this work, different calculations were implemented as treading the R-matrix as symmetrical matrix in both cases the perfect case and the defect case. Dave's model represented the pipe by using symmetrical matrix when simulating the perfect case and unsymmetrical matrix when simulating the damaged cases.

The system that represents the interaction between exciter coil and the equivalent circuit components can be represented mathematically as matrix equation given below:

$$[V]_{nxm} = [R]_{nxm} \cdot [I]_{nx1} \quad (3)$$

where: "V" is the voltage in each loop of the system.
"I" is the current in each loop.
"R" is the impedance matrix of the system.

R-matrix is the impedance matrix describes the pipe characteristics of the pipe using this equivalent circuit for the case of 3 loops system. The impedance matrix is given below by using Kirchoff's Voltage Law:

$$\begin{bmatrix} (R_e + j\omega L_e) & -j\omega M_1 & -j\omega M_2 & -j\omega M_3 \\ -j\omega M_1 & (R_w + 2R_c + j\omega L_w) & -(R_c + j\omega M_{12}) & -j\omega M_{13} \\ -j\omega M_2 & -(R_c + j\omega M_{21}) & (R_w + 2R_c + j\omega L_w) & -(R_c + j\omega M_{23}) \\ -j\omega M_3 & -j\omega M_{31} & -(R_c + j\omega M_{32}) & (R_w + 2R_c + j\omega L_w) \end{bmatrix} \quad (4)$$

where:

i_e is the exciter current.

V_e is the exciter AC voltage source.

R_e is the exciter resistance.

L_e is the exciter self-inductance.

M_1 is Mutual inductance between the exciter and the wire loop one.

i_1 is the current induced in the wire loop one.

R_w is the prestressing wire resistance.

L_w is the prestressing wire sel-inductance.

R_c is steel cylinder to prestressing wire loop path concrete resistance.

M_2 is Mutual inductance between the exciter and the wire loop two.

i_2 is the current induced in the wire loop two.

M_{12}, M_{21} are mutual inductance between wire loop one and wire loop two.

M_2 is Mutual inductance between the exciter and the wire loop three.

i_3 is the current induced in the wire loop three.

M_{13}, M_{31} are mutual inductance between wire loop one and wire loop three.

M_{23}, M_{32} are mutual inductance between wire loop two and wire loop three.

The componenets of R-matrix that related to the status of the wire are R_w, L_w, M_1, and so on , these components change their values with the change of the wire condition. The resistance of the wire is given by [6]:

$$R_W = \frac{\rho_W L_W}{A_W} = \frac{2a_w N_w}{\sigma_w \left(\frac{C_w}{2}\right)^2} \tag{5}$$

With: a_w = Pre-stressing Wire Radius (Meters)

C_w = Pre-stressing Wire Diameter (Meters)

σ_w = Material Connectivity $(\Omega m)^{-1}$

ρ_W = Material Resistivity

A_w = Cross-section area of Pre-stressing Wire $(m)^2$

N_w = Turns of Pre-stressing Wire

Change of the resistance of the wire is due to change of the wire diameter, corrosion change the material characteristics and reduce the perfect material wire diameter using this idea then,

$$cc_w = \left(\frac{C_w}{4a_w}\right)^2 \tag{6}$$

By using this inductance of the coil wire can be computed using the formula below [6]:

$$L_w = 2\pi a_w N_w{}^2 \left[\frac{(1+cc_w/6)\log_e(8/cc_w) -}{2(0.84834+0.2041cc_w)}\right] 10^{-7} \tag{7}$$

where,

a_w = Pre-stressing Wire Radius (meters)

C_w = Pre-stressing Wire Diameter (meters)

N_w = Turns of Pre-stressing Wire

L_w = Pre-stressing Wire Self-Inductance (Henries)

Due to the relation between the mutual and self inductance the mutual can be computed using the self inductance by the relation.

It is clear that all the resistances, self inductances and mutual inductances depend on the wire radius. The change of the wire radius of any loop will produce changes at the components the R impedance matrix that related to the loop. If the corrosion changes the resistance to the half value, this can be used to compute the change in self and mutual inductance related to this change. This means that if resistance of the wire is change by some ration this will help to find the diameter that produces this resistance which helps to compute the change in the complex parts of impedance.

If it is supposed that m_1 is the defect value factor which can be multiply by the resistance value to give multiple of R-matrix. The change of R the impedance resistance will be computed by formula below:

$$R_{wm} = m_1 \cdot R_w \tag{8}$$

By using some of physical relation then the diameter can be computed as follows [6]:

$$c_{wc} = \sqrt{2\left(\frac{R_L}{R_{wm}}\right)} \tag{9}$$

Where,

$$R_L = \frac{2a_w}{\sigma_w} \tag{10}$$

This changed value affects the induced current as follows:

$$cc_{wm} = \left(\frac{C_{wc}}{4a_w}\right)^2 \tag{11}$$

$$L_{wm} = 2\pi a_w N_w{}^2 \left[\frac{(1+cc_{wm}/6)\log_e(8/cc_{wm}) -}{2(0.84834+0.2041cc_{wm})}\right] 10^{-7} \tag{12}$$

And so on. All of these formulas derivatives and used from Grover's book [6].

The above reduced mathematical expression show how the change of R-matrix values can be computed and changed due to m_1 factor, where m_1 can be any number. In this simulation work is taken as one values of the set

$\{\frac{1}{8}\ ;\ \frac{1}{4}\ ;\ \frac{1}{2}\ ;\ 1\ ;\ 2\ ;\ 4\ ;\ 8\ \}$. $m_1 = 1$ is the perfect case and the others are the change which result due to corrosion.

VI. Model Solution

In General form, for the multi-turn loops we have got: Solving the system as by using Kirchhoff's Voltage Law:

$$[I]_{nx1} = [R]^{-1}_{nxn} \cdot [V]_{nxm} \tag{13}$$

With:

$I = nx1$: Column Matrix Containing Unknown Induced Currents.

$V = nxm$: Matrix Containing Sinusoidal Wave to Produce EM Signal.

$R = nxn$: Coefficients Matrix Containing the Physical Properties of PCCP variables.

and from the computed solution,

$$i_e = f(M_i, M_{ij}, R_w, L_w, R_c, L_e, R_e) \cdot V_e \tag{14}$$

From the solution in equation (4) the exciter coil's induced current is sensitive to any change that may occurs in pre-stressing wire loops which is represented as components of equivalent circuit model.

VII. Modeling of the Defects

Defects were modeled by changing the default value (R_w) of pre-stressing wire's resistance. This change will effect on pre-stressing wire physical properties including the pre-stressing wire resistance and its self inductance as well as mutual inductances between each pre-stressing wires and mutual inductances between exciter coil and desired location(s) of defected pre-stressing wires. Defected of PCCP is simulated in three cases, the first case represents the perfect case with no broken wires and free corrosion, the second case represents the values less than the default value of the pre-stressing wire and the third case represents the values larger than the default value of pre-stressing wire. Defected cases are represented as defect values of pre-stressing wire loops. By using this technique of modeling the defects in PCCP will lead to recognize and determine the severity of corrosion activity in defected wires. Table II shows defects value, where the defect value is m_1 and m is the defect factor index as follows:

TABLE II: DEFECT MODELING VS. DEFECT FACTOR INDEX (CORROSION RATE)

m	$-\infty \rightarrow$	-3	-2	-1	0	1	2	3	$\infty \rightarrow$
m_1 (2^m)	$-\infty \rightarrow$	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{1}{2}$	1 Perfect	2	4	8	$\infty \rightarrow$

* m can be any real number

In this paper, difference exciter current real part is considered and computed in order to simulate the different cases of defected PCCP. Difference exciter current real part was extracted from a full solenoid wave to present both the perfect case and defected case of PCCP. Difference exciter current real part is shown different patterns of defects that can be recognized easily by using the technique was followed in this work. The computed difference values are obtained from:

$$i_{ed} = i_e - (i_e)_{no\_defect} \quad (15)$$

$$= (i_e)_{measured} - (i_e)_{refernce} \quad (16)$$

Difference exciter current real part shows the different between the perfect case of pipe without any defect which gives zero value, otherwise gives different values and different patterns of pipe with defect. Grover book physical mathematical formulas [6] are used for self inductance, mutual inductance and resistances calculations for both pre-stressing wire coil and exciter coil which are both considered as circular coils and thin filaments coils.

VIII. MODEL SIMULATION AND RESULTS VISUALIZATIONS

In order to simulate the model, first the solenoid wave is applied inside the pipe by using the producer wave tool which represents the equivalent circuit of exciter coil. Then, a solenoid wave will travels inside the pipe throughout pre-stressing wires media. A coupling between these pre-stressing wires will help this signal to travel outer pipe wall (in-direct wave travelling) as well as inner pipe wall (direct wave travelling). The received signal can be measured at any location inside the pipe which it affects both in-direct travelling signal and direct travelling signal. Exciter coil parameters are applied as inputs to produce the solenoid wave signal as well as a signal received tool. A received signal is analyzed and interpreted to reflect the PCCP condition monitor. The difference exciter current real part is extracted from a full-wave signal for visualizing and studding the different patterns of PCCP status. Figure 5 visualized the obtained result by simulating a large diameter pipe (7.52 meters) with the exciter at fixed location at loop one inside the pipe.

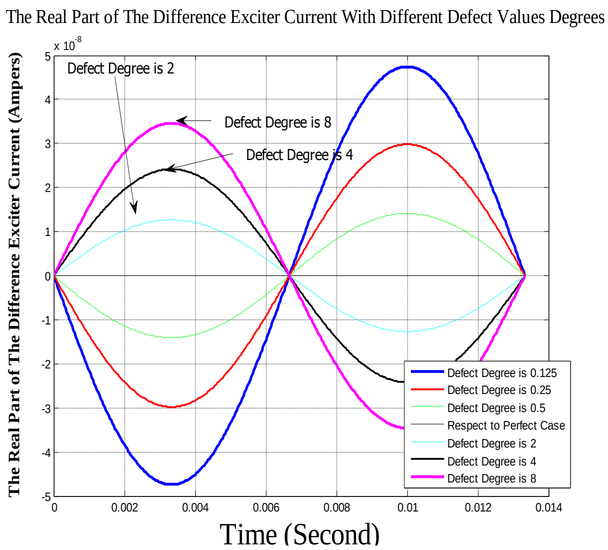

Fig. 5. 478-wire loops: the real part of the difference exciter current with different defect values degrees with exciter at loop 1 with frequency of 75Hz.

The obtained results are similar in shape but different in maximum values of signal. This behavior of different signals of measured difference exciter current can be distinguished by using an expert system as Artificial Neural Networks. Using this technique will give the ability of determine the intensity of the fault of PCCP which represents how degrees of the corrosion activity in pre-stressing wires. Figure 3 and Figure 4 show that the number of pre-stressing wires and exciter coil location will affect on the received signal in exciter coil.

The difference exciter current is visualized against two factors. These factors are defect factor values m_1 and defect factor index m, the obtained data is depicted as linear and nonlinear relationships respectively. Figure 6 shows these relationships. The exciter movement scan is simulated, which travels from one location to another through the pipe.

This technique will give ability to compare the results which obtained from simulation process to the results which will obtain from the actually inspection in the real world.

The case of 5-wire loops is simulated by using exciter movement scan technique which travels in parallel through PCCP crossing the first wire loops, the second wire loop, the third wire loop, the fourth wire loop and the fifth wire loop in order to simulate the real world process inspection of pipe. The difference exciter current is depicted against the number of wire loops which is 5-wire loops case as shown in Figure 7 considering that:

- The upper part of the figure is changed coordinate.

- The lower part of the figure the coordinate scale is fixed for all patterns.
  - The Figure 7 shows that:
  - (a) The change of pattern when the number of defects increased each time by one.
  - (b) Exciter induced current difference is increased by increasing the number of broken wires.

The obtained data of this technique is compared to the actually inspection results which depicted by using the results of RFEC/TC inspection method. RFEC/TC theory depend on two coils, transmittal coil (Exciter) to produce EM signal and receiving coil(s)/detector(s) to read signal. Any obtained data from simulation process between 10^{-6} and 10^{-8} is considered as closer to the actually results using measured induced current amplitude as shown in Figure 8 [7],[8].

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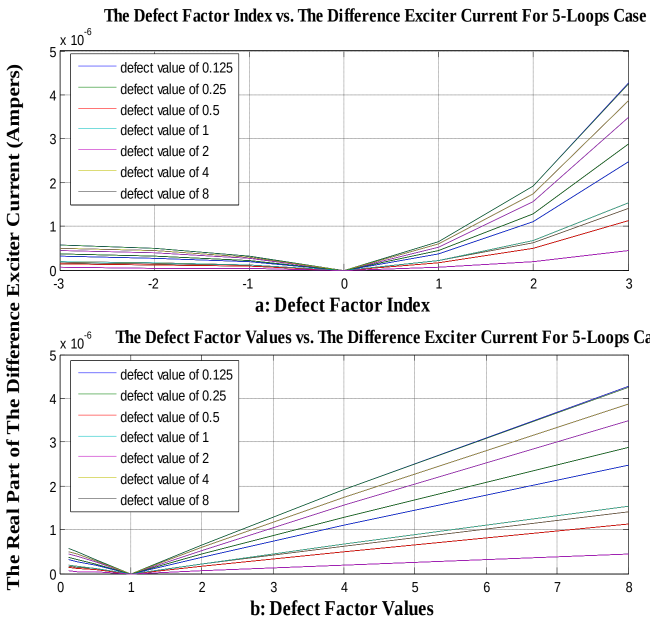

Fig. 6. Linear and nonlinear relationship for the difference exciter current

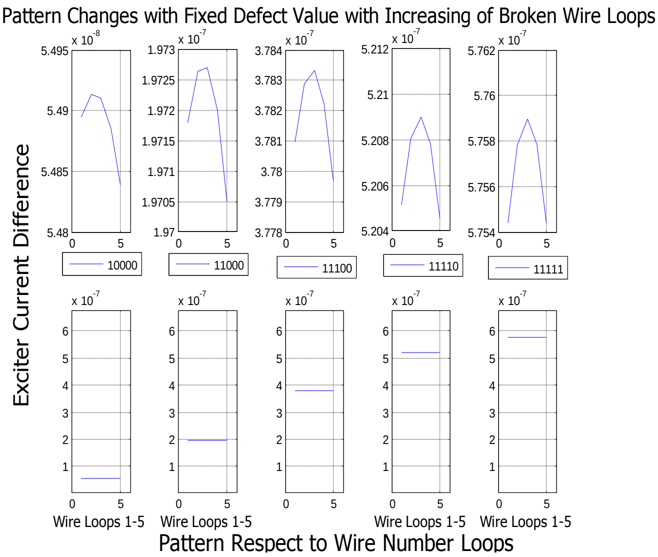

Fig. 7. Pattern changes with fixed defect value for 5-loops case with increased defect at each loop with movement exciter scan with 75Hz

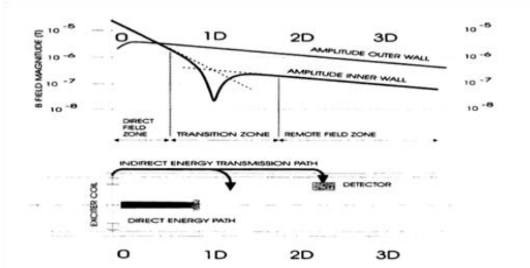

Fig. 8. Shows the B field magnitude profile inside and outside the pipe

IX. ANN Simulation and Its Structure

In this paper, the 5-wire loops case is simulated by using non-normalized and normalized data which produced by simulating the equivalent circuit model in order to solve the system for induced currents of exciter coil. Real part induced current difference is used as inputs into ANN. It is found that the normalized data which between one and zero is suitable for ANN in training phase. The Figure 9 shows the suitable network structure of three layers for 5-wire loops simulation that used resilient back propagation algorithm as learning algorithm in order to learn the network on the other patterns and wire defects that excluded from training phase to be recognized in test phase.

X. ANN Training Phase Result

In the Training Phase of ANN for both Cases of partial defect combination and complete defect combination is 100% Correct and result is showed in Table III and in Figure 10.

TABLE III: Training Phase of 5-Wire Loops Case

Case (Defect Data)	**No. Of Patterns**	**Resulted Training Parameters**			
		Time	***No. of epochs***	***Computed error***	***Gradient***
Partial Combination	90	0:00:01	123	1.05×10^{-10}	1.61×10^{-9}
Complete Combination	186	0:05:00	26936	1.2×10^{-10}	1.75×10^{-8}

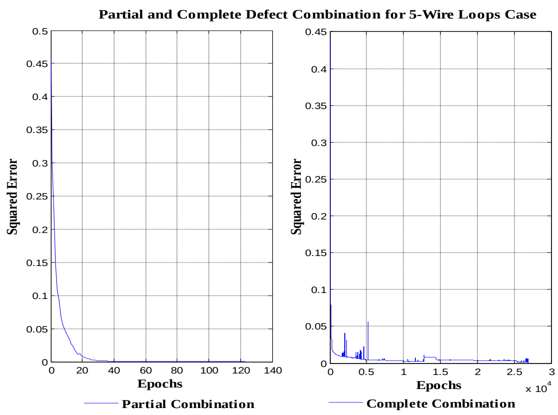

Fig. 10. Training phase of 5-wire loops case

XI. ANN Test Phase Result

In the Test Phase, random of 153 patterns are tested and give testing data correct as shown in Table IV.

TABLE IV: TEST PHASE : COMPLETE COMBINATION INCREASING RANDOMLY WITH PATTERN NUMBERS

Training Phase	Number of patterns	Tests Percentages for random of fixed 153 patterns (%)			Average (%)
		Test 1	*Test 2*	*Test 3*	
Training 1	93	76.4706	75.8170	77.1242	76.4706
Training 2	103	82.3529	82.3529	83.6601	82.7887
Training 3	113	71.8954	71.8954	72.5490	72.1133
Training 4	123	83.6601	92.1569	88.8889	88.2353
Training 5	133	79.0850	87.5817	85.6209	84.0959
Training 6	143	87.5817	81.6993	84.9673	84.7495
Training 7	153	81.0458	92.1569	88.2353	87.1460
Training 8	163	92.1569	95.4248	93.4641	93.6819
Training 9	173	86.2745	83.0065	84.3137	84.5316
Training 10	183	87.5817	88.8889	88.2353	88.2353

The total average in the test phase is 84.2048 %

XII. Results Discussion

In this paper, the case of 5-wire loops is simulated in both the partial combination case and the complete combination case as shown in Table I. The partial combination case produces 15 different patterns for just one degree of corrosion. Six different values of corrosion degrees are simulated to be 90 different patterns in partial case as shown in Table II and Table III. The same process is applied to complete combination case which contains 31 different patterns just in one degree of corrosion and 186 different patterns in six different degrees of corrosion as shown in Table II and Table III. In partial combination case, some patterns were excluded from training phase this will help to test ANN structure by using the complete combination patterns which contains the excluded patterns from partial combination. The technique of this work should be used for patterns recognition.

XIII. Conclusion and Future Works

A conclusion section is not required. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions. By using the technique that was shown in this paper the successful approach of using Exciter Coil as a measured tool, it will be much easier to distinguish the number of broken wires and its severity of corrosion in PCCP.

This technical approach need to be applied in a practical life of water industry in order to compare the actual results to theoretical results that were obtained in this work.

The advantage of this work is that the movement of the exciter scan which is simulated by putting the exciter in different location along with sequence of the loops of pipe, that will gives the ability to compare the theoretical results with the actual results easily.

This idea of monitoring is based on that the induced current in the exciter. Due to the electrical characteristics of pipe's wire loops, this induced current carry information about the status of the pipe. This technical approach proves the idea of the current pattern of exciter changes with faults that occurs in the pipe. These distinguished patterns of the exciter current are fed to a designed ANN to classify them and identify the number of wire loops, which are faulty. The suggested future works are as follows:

- The model can be modified to include more features to become more realistic by adding other components to ECM of the pipe.
- The designed ANN can be done in stages, first stage is analyze the faults up to simple faults, that contain single fault then find the locations and severity of the faults in next stage which is classification stage.
- The faulty pipes found in previous works in GMRA can be used to build a real database, which can be used in real environment using the idea of this work.
- Using other factor such as amplitude, phase, impedance and other that can be found from the simulated data will increase the ability of this suggested system.
- Using Geographic Information System (GIS) software to build database for all inspection methods, this can be accomplished by collecting survey data (including pipeline maps), CIPS data, acoustic emission data and electromagnetic (RFEC/TC and P-Wave) data.

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Dr. Y. H. Shakmak received B.S.c in Physics and Chemistry from Science Faculty in Benghazi University in 1979, Then he got his M.S.c in Computer Control and Signal Processing from Kogakuin Daigaku in Japan 1988 , P.h.D degree received in 2002 in Signal Processing from U.K.M in Malaysia. His research interests include Modeling and Simulation, Signal Processing, Numerical Mathematical Analysis and Soft Computing and Artificial Neural Networks. Contact email is yamashaa@yahoo.com.

S. H. Awami received the B.S. from the Department of Computer Sciences; University of Benghazi formally named Garyounis University, Benghazi-Libya, in 1996. He received his M.S. degrees from the Computer Sciences Department, The Academy of Postgraduate Studies Benghazi Branch, Libya, in April 2010. Since 2000, he has been with the Al Nahr Engineering Limited (ANE) formally named Brown and Root North Africa Limited (BRNA), Department of Management Information System (MIS). His research interests include computer networks analysis and design, network security, Artificial Neural Networks (ANN), and Soft Computing. Mr. Awami has certificated from Microsoft and novel corporate in network computers. He has trained in computer networks and e-mail system courses in United Kingdom (UK), Egypt, and Libya. His practical experience in computer networks was growing since he was responsible to upgrade BRNA/ANE infrastructures in various locations in Libya. Contact email is salehawami@yahoo.co.uk.