Modelling and Simulation of Large Diameter PCCP in GMRA Using Equivalent Circuit Technique (Fault Inspection Using Artificial Neural Networks)

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Abstract **-** *This paper presents a simulation technique to simulate a Pre-stressed Concrete Cylinder Pipe (PCCP), for monitoring and inspection pipe using a non-destructive test (NDT) method in Great Man-Made River Project (GMRP). The paper presents an equivalent circuit model (ECM) technique to model the electrochemical corrosion interactive and failing in the individual large pipe diameter of four meters by using Dave's model physical simulation. Data obtained from an equivalent circuit model is computed by using different technique and different computations using a computer simulation package (MATLAB Language). The computer simulation is a powerful tool, which provides a better understanding of problem which can be simulated at different conditions of pipe condition. The use of such a tool has the potential to improve the understanding of PCCP condition monitoring (CM).*

ECM simulation technique increases the confidence level of accurate test results which will reflect on the pipe condition that is used in NDT techniques. One of the main objectives of this paper is to introduce a model of such type of PCCP to produce data that represent the pipe status by monitoring the changes in the exciter current (measured tool and suggested method). When it is compared with the state with no defect (free corrosion and no broken wires), a neural network were designed and trained with simulated data. The obtained results shows that it is possible to use exciter induced current measured for this monitoring purpose, the obtained results will find the defect locations better in the pipe as well as the severity of the defect.

Keywords: PCCP Inspection; PCCP Modeling; NDT; ANN; PCCP Condition Monitoring.

1 Introduction

The Great Man-Made River project is the one of the largest water transport project ever undertaken in the world, with more than 4000km (2485 miles) of mainly four meters (158-inch) diameter pre-stressed concrete cylinder pipe in operation [1][2]. The ground earth in Libya is highly saline and has corrosive to the PCCP this will effect the 50 years life time of the pipe. PCCP has been severing corroded experiencing failures in some sections between 1999 and 2000; Great Man-Made River Authority (GMRA) conducted a rehabilitation program and implemented different technologies to assess the condition of pipeline sections [1]. Some of these technologies are Remote Field Eddy Current Transformer/Coupling (RFEC/TC), P-wave Inspection, Acoustic Emission Inspection, and Close Interval Potential Survey (CIPS) using Cathodic Protection System data .Different inspection methods lead to different results on the same conveyance pipeline, so a computer modeling simulation is needed to provide help for making a decision of replacement, maintenance, or keeping the pipe in-service. In addition, it has now proven beyond reasonable doubt that some of the PCCP placed without corrosion protection was damaged by the environment sooner than anticipated. In such cases, the pre-stressed wires which protect that concrete core is corroded the pipe fails due to corrosion of sufficient numbers of their pre-stressed wires.
In this paper, a computer simulation is used to simulate and represent a good condition of pipe (free of corrosion and wire breaks) and defected condition of pipe (showing corrosion and wire breaks) using an Equivalent Electrical Circuit Model and Designing of Artificial Neural networks as NDT system to monitor PCCP based on simulation results.

2 Electrical circuit model and simulating technique

Dave's model [3] is used as a successful model for small pipe diameter because of the successful comparison between the equivalent circuit and the actual results from PCCP inspection survey that was based on RFEC/TC inspection using two coils, one for transmitting signal (Exciter Coil), the others for receiving the signal (Detector Coil) [4]. In this work, the large diameter pipe is modeled and simulated using Dave's model but with large diameter pipe parameters (4 meters) that was used in GMRA project. For all pipe geometry and using just one coil as transmitting coil and measuring coil in the same time. Figure 1 [1] and Figure 2 show the PCCP material components and the equivalent circuit for N-turn loops which representing the N-turns of pre-stressing wires.

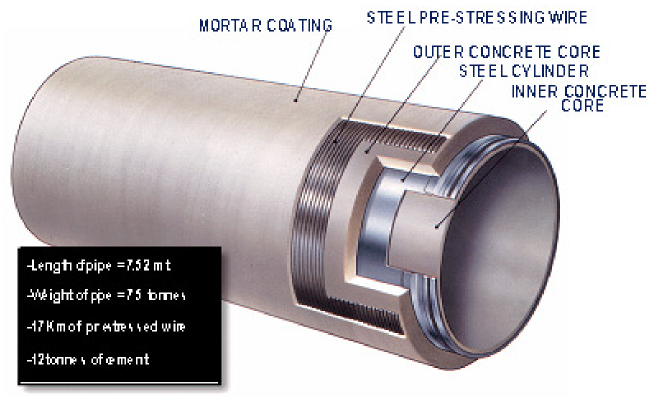

Figure 1: PCCP Material Components

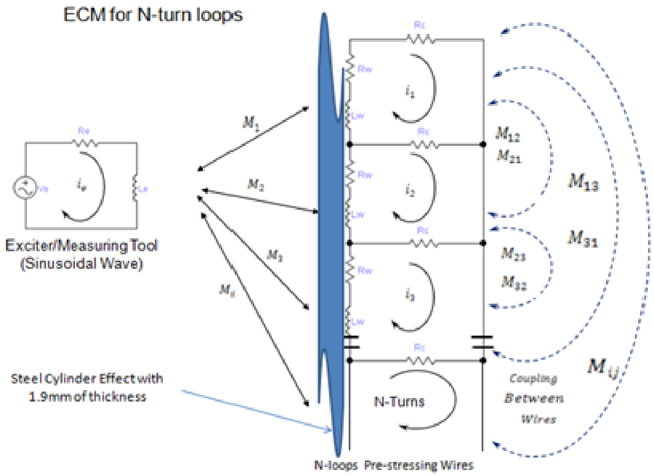

Figure 2: Equivalent Circuit Model for PCCP

The electrical circuit simulation based on simulating one wire loop, two wires loops, and so forth till N-turn loops. This technique is used to guarantee a better understanding of pipe system behaviour. 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 1 by using the following equations:

Table 1: Total Number of Simulation vs. Number of Simulated Combination

(l)	1	2	3	4	5	…..
N_{lt}	1	6	21	60	243	…..
N_s	1	6	18	40	75	…..
N_{ps}	1	3	6	10	15	…..
N_{cs}	1	3	7	15	31	…..

$$N_{lt} = \sum_{l=1}^{lt}\left(l \cdot \left(\sum_{n=1}^{l}\binom{l}{n}\right)\right) \qquad (1)$$

$$N_s = l^2 \cdot \left(\frac{l+1}{2}\right) \qquad (2)$$

$$N_{cs} = 2^{(l)} - 1 \qquad (3)$$

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
N_s is total elements of reading values from the partial simulation.
N_{lt} is the total number of combinations.

Some considerations were taken in account to build a sound PCCP model as follows: (1) The exciter coil and pre-stressing wire coil are treated as filamentary coils. (2) Simulate the exciter scan movement in order to get better understand of Electromagnetic (EM) wave travelling through the pipe and in order to implement and comparing it with actual inspection. (3) The exciter coil must be used as the sensor for the resulted electrical and magnetic fields produced by pipe's wires. (4) Dave's model is used because of comparison of the actual inspection to the model.

3 Model basic idea

A model works on analysis of EM signal, which is produced by exciter coil tool inside the pipe. This EM signal travels throughout the pipe and through pre-stressing wires along pipeline. Any changes or damages in the pre-stressing wires will be reflected in the exciter coil current. A received signal in exciter/receiver coil which is the measured EM signal can be analyzed to provide information about pipe status. Once effect of electromagnetic signal received by receiver as measured by the induced current. Numerical techniques based on a full-wave analysis can be used to extract the information carried by the measured exciter current. Equivalent circuit model is simulated to understand the behavior of valid (free corrosion and broken wires) and damaged pipes. The relation between the damage and pattern extracted from measured exciter current. This approach is developed in this work for simulate a large PCCP diameter in order to find a method for finding the location and number of broken wires based on designed simulation study.

4 Model solution

In order to model one-turn loop the system derivatives and the computed solution found relation as follows:

$$i_e = f(M_1, R_w, L_w, R_c, L_e, R_e).V_e \qquad (4)$$

From the solution in equation (4) the exciter coil's induced current is changeable according to change of any components of equivalent circuit model in the loop that represent the pre-stressing wire in PCCP.
In General form, for the multi-turn loops we have got:

Solving the system as:

$$[I]_{nx1} = [R]^{-1}{}_{nxn} . [V]_{nxm} \qquad (5)$$

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,

$$i_e = f\left(M_i, M_{ij}, R_w, L_w, R_c, L_e, R_e\right). V_e \quad (6)$$

5 Model components computation

Electromagnetic coupling between elements of the model should be calculated by using specific mathematical formulas for physical interaction between them. A matrix that reflect the pipe physical properties. This matrix is used to simulate the damages in the pipe by changing the pre-stressing wire loop components in desired locations of the matrix. This mathematical formulas used for calculations is given in Grover [5] and its used for the exciter coil and the pre-stressing wire which are considered as circular coils, and thin wire filaments.

6 Modeling of the defects

Defects can be simulated by setting the wire resistance, R_w, to different values at desired location(s), in order to detect the broken wires and the severity of corroded wires, Corrosion Rate, in the large diameter PCCP. Table 2 shows defects values where m_1 is defect value and m is defect factor index as follows:

Table 2: Defect Modelling by 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

All PCCP physical electrical properties such a pre-stressing wire resistance, pre-stressing self-inductance, mutual-inductance between wire to wire and exciter to wire are damaged due to the defect in loops so that the calculation of R matrix elements are different from case to case. The obtained result gives the valid system of pipe without any defect gives zero value and other gives difference patterns. The computed difference values are obtained from:

$$i_{ed} = \; i_e - (\,i_e)_{no\ defect} \quad (7)$$

$$= (\,i_e)_{measured} - (\,i_e)_{refernce} \quad (8)$$

All measured components were calculated as difference exciter current real part, difference exciter current imaginary part, difference exciter current amplitude, difference exciter current phase, difference exciter current impedance real part, difference exciter current impedance imaginary part, difference exciter current impedance amplitude, difference exciter current impedance phase.

7 Visualization of obtained data and its characteristics

In this paper, the difference exciter current real part is visualized and used as inputs into Artificial Neural Networks (ANN) in order to assess the pipe condition. Figure 3 visualized the obtained result by simulating a large diameter pipe with the exciter at fixed location at loop one inside the pipe. By using this technique, the severity of the corrosion in pre-stressing wires can be distinguished.

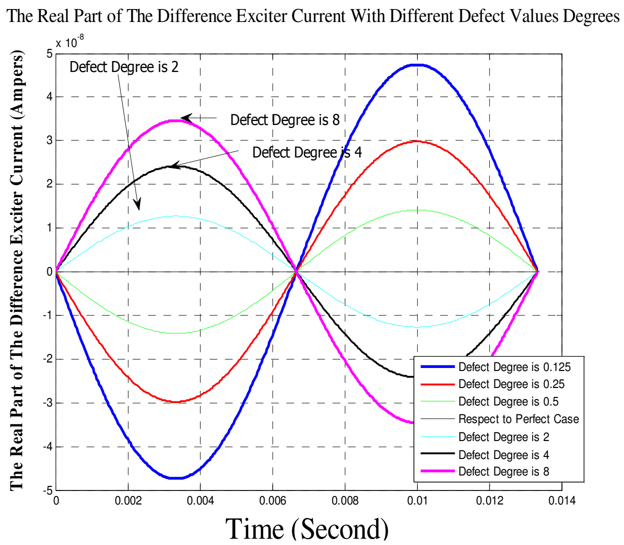

Figure 3: 478-wire Loops: The Real Part of The Difference Exciter Current With Different Defect Values Degrees with Exciter at loop 1 with frequency of 75Hz.

The obtained data visualized by two relationships between the difference exciter current and defect factor values m_1 and defect factor index m as linear and nonlinear relationships respectively while the exciter movement scan travelling from one location to another through the pipe. Figure 4 shows these relationships.

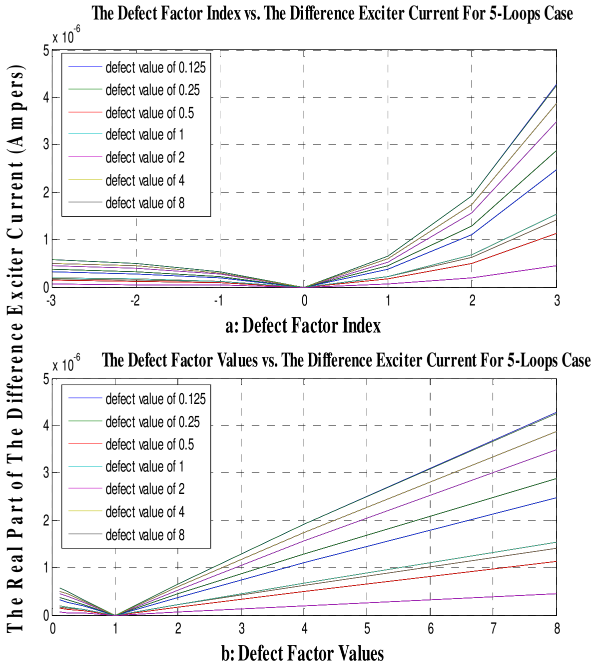

Figure 4: Linear and nonlinear Relationship for The Difference Exciter Current

The case of five loops are simulated and some of the characteristics are shown in Figures 5 considering that :

(1) The upper part of figures are changed coordinate.

(2) The lower part of figures the coordinate scale are fixed for all patterns.

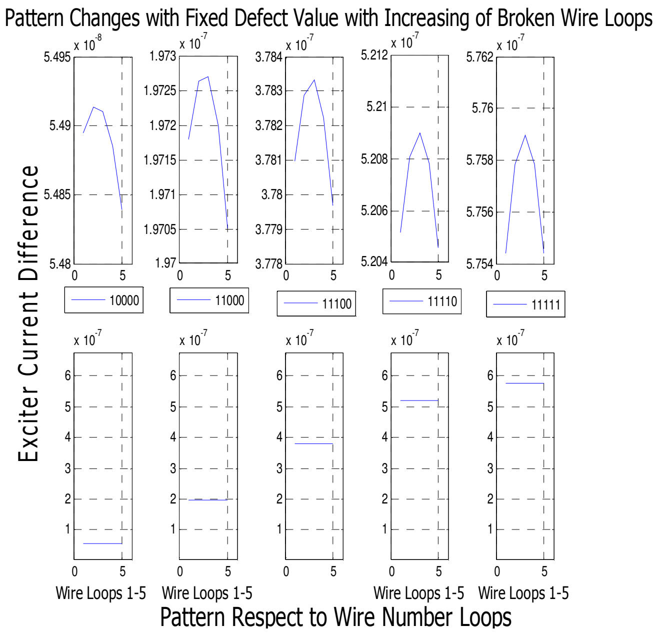

Figure 5: Pattern changes with Fixed Defect Value for 5-Loops Case with Increased Defect at Each Loop with movement exciter scan with 75Hz

The Figure 5 is showing 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.

Measured data by using exciter deference current can be compared with measured induced current amplitude on the inner and outer pipe’s wall of the actual survey by using RFEC/TC inspection method using transmittal coil (exciter) and receiving coil (detector) as shown in Figure 6 [6][7].

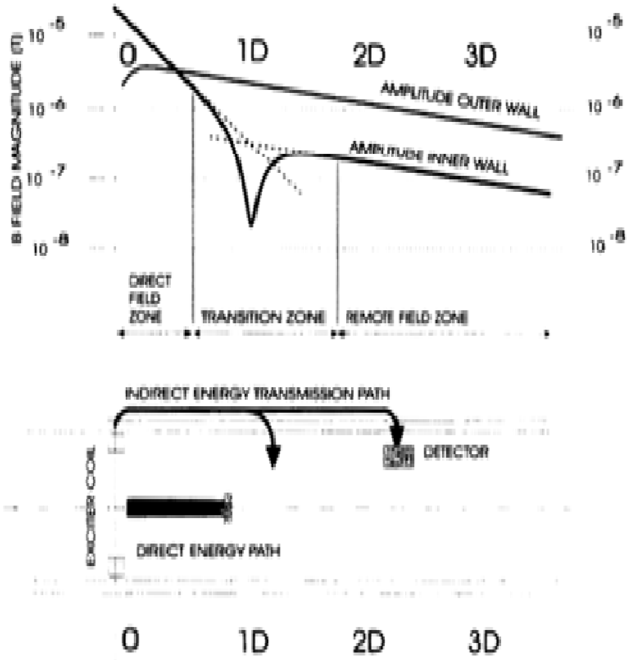

Figure 6: shows the B field magnitude profile inside and outside the pipe

8 ANN simulation and its structure

In this paper, the 5-wire loops system is simulated to study the different patterns that extracted from the obtained data and rearranged to be suitable for ANN inputs to model the system. These patterns need to be optimized by normalizing each input pattern between zero and one. The characteristics of these patterns have kept the same behavior after normalization stage. The Figure 7 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.

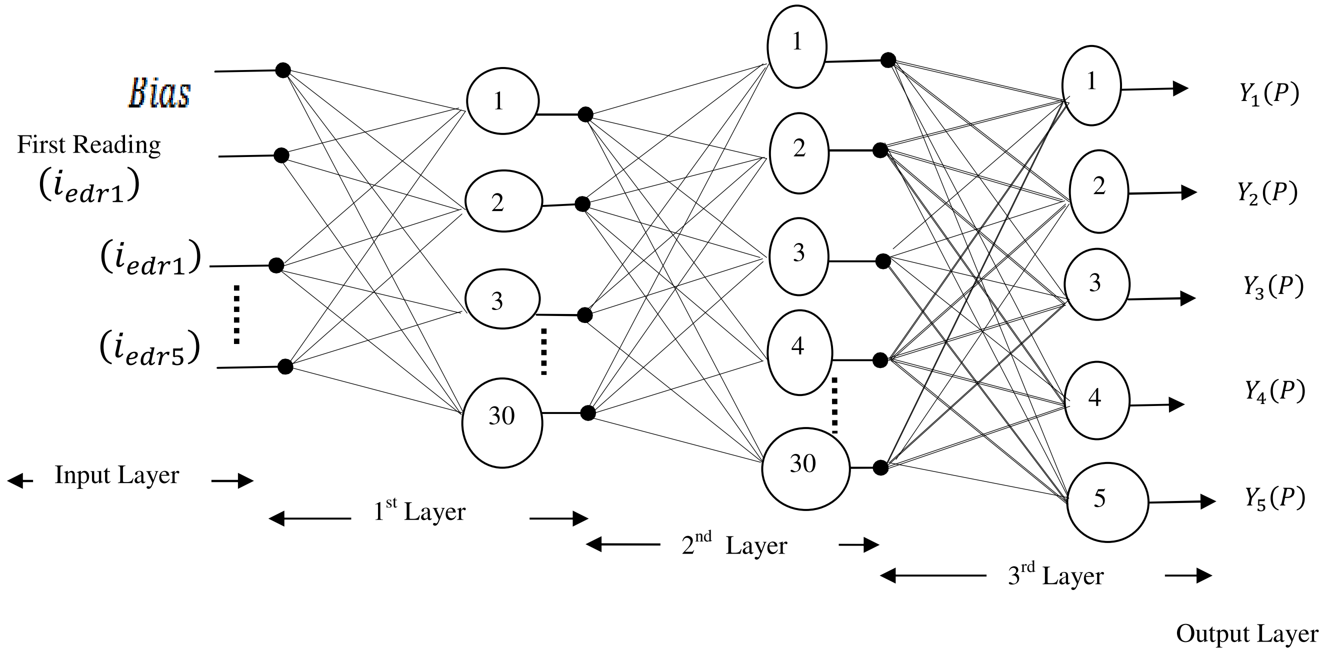

Figure 7: ANN Structure (7-30-30-5) 5-Wire loops

9 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 3 and in Figure 8.

Table 3: 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	$1.05\ x\ 10^{-10}$	$1.61\ x\ 10^{-9}$
Complete Combination	186	0:05:00	26936	$1.2\ x\ 10^{-10}$	$1.75\ x\ 10^{-8}$

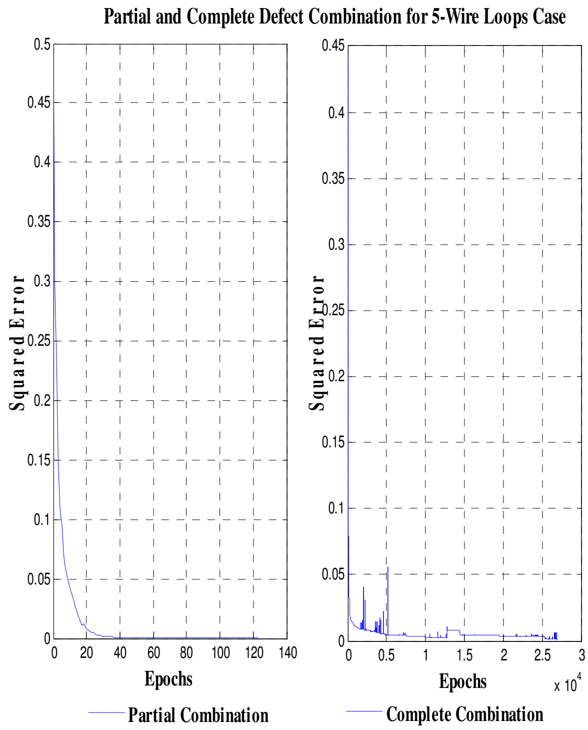

Figure 8: Training phase of 5-wire loops case

10 ANN test phase result

In the Test Phase, random of 153 patterns are tested and give testing data correct as shown in Table 4.

Table 4 : 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 %

11 Conclusion

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.

12 acknowledgment

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