FAULT DIAGNOSIS OF PLANAR ANTENNA ARRAYS USING NEURAL NETWORKS

D. Vakula and N. V. S. N. Sarma

Department of ECE
National Institute of Technology
Warangal 506004, India

Abstract—A systematic method for the diagnosis of planar antenna arrays from far field radiation pattern using neural networks is presented. Two types of neural networks, Radial basis function (RBF) and Probabilistic neural network (PNN) are considered for the performance comparison. Deviation pattern is used as input to the neural network to determine the location of the faulty element and error in excitation.

1. INTRODUCTION

In many real time applications, it is required to have high performance antenna array systems. In order to achieve this, the system must be monitored continuously. If any one or more elements in the array are not functioning properly due to failure of drive electronics, the antenna system will not give the required radiation pattern because of the change in magnitude and phase of current fed to the antenna elements.

A few articles are available on the diagnosis of planar antenna arrays. Lee et al. [1] presented a system using built in transmission line signal injector embedded at radiating aperture to isolate current magnitude faults. But it is too expensive to use the signal injecting circuit at the design stage apart from increasing the overall system weight and size. Bucci et al. [2] reported diagnosis of on-off faults in planar array from noisy far field radiation pattern using global optimization technique. Rodriguez et al. have used genetic algorithm to detect the faulty elements in small size arrays [3]. But the Genetic algorithm has to be run several times to yield high accuracy for large

---

Corresponding author: D. Vakula (dameravakula@yahoo.co.in).

sized arrays. Bucci et al. discussed the diagnosis of only phase faults of planar arrays [4]. Fault diagnosis of linear arrays to find the location, error in excitation is presented [5, 6].

In the present paper, a method is devised to detect both phase and magnitude of current in the faulty elements apart from its location. The change in magnitude and phase of the current in an antenna element are known as current magnitude faults and current phase faults respectively. These two faults collectively are called as error in excitation.

The presence of any aforementioned faults results in deviation in radiation pattern of the array. This motivates to devise a method to diagnose faults. The proposed method detects the faults based on the change in the radiation pattern. Far field radiation pattern can be measured without removing the array from its working site and without a serious interruption of its normal operating conditions. For satellite borne antennas and large earth based antennas, it is convenient to detect faults by measurement of far field radiation pattern. Artificial Neural Network (ANN) approach is adopted to identify the faults in the planar array due to its built in flexibility, less computing time and robustness to noise. Initially the ANN is trained with some of the possible faulty patterns and is tested with remaining faulty patterns with predefined measurement errors. This method can be used for large earth based antennas like atmospheric weather radar, astronomy radar and satellite antenna arrays.

2. THEORY

In order to find the radiation pattern of faulty array first of all it is required to derive the antenna array factor for the planar array, from which deviation pattern is derived. The deviation pattern is the difference between faulty and fault free patterns.

Here two cases are considered.

a) Antenna array with single faulty element and

b) Array with two faulty elements

Array factor for general planar antenna array without faults: A planar array, which consists of $2N_x + 1$ rows of elements and each row has $2N_y + 1$ elements arranged in a rectangular grid as shown in Fig. 1 is considered. The spacing between rows is d_x and between elements in a row is d_y. (m, n)th element is the element whose positional coordinates are $\xi_m = md_x$ and $\eta_n = nd_y$. The current in (m, n)th element is designated as I_{mn}. The array factor can be written
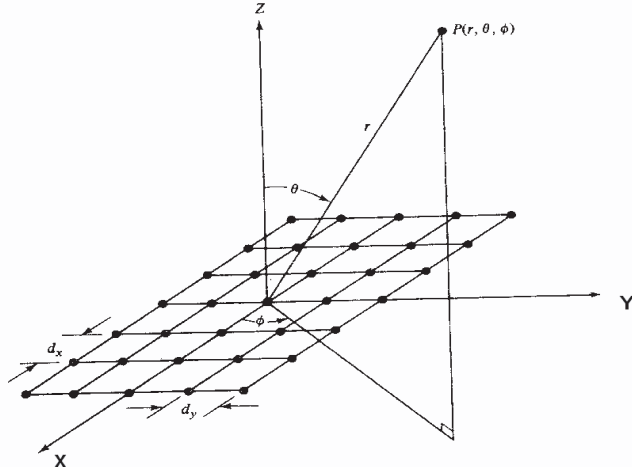
Figure 1. Planar antenna array arranged in rectangular grid.

as [7]

$$A\left(\theta,\phi\right) = \sum_{m=-N_x}^{N_x} \sum_{n=-N_y}^{N_y} \left(\frac{I_{mn}}{I_{00}}\right) e^{jk\sin\theta(md_x\cos\phi + nd_y\sin\phi)} \quad (1)$$

If $I_{mn} = 1$, for uniform excitation, the array factor is modified as

$$A\left(\theta,\phi\right) = \sum_{m=-N_x}^{N_x} \sum_{n=-N_y}^{N_y} e^{jk\sin\theta(md_x\cos\phi + nd_y\sin\phi)} \quad (2)$$

where

$k = \frac{2\pi}{\lambda}$ is propagation constant,

ϕ is angle of observation from X-axis,

θ is angle of observation from array normal (Z-axis).

The radiation pattern can be plotted along the planes $\phi = 0°$ and $\phi = 90°$. Along $\phi = 0°$ plane the array factor reduces to

$$A\left(\theta,0\right) = N_y \sum_{m=-N_x}^{N_x} e^{jkmd_x\sin\theta} \quad (3)$$

And along $\phi = 90°$ plane the array factor can be written as

$$A\left(\theta,90\right) = N_x \sum_{n=-N_y}^{N_y} e^{jknd_y\sin\theta} \quad (4)$$

2.1. Derivation for Magnitude and Phase of Deviation Pattern of an Array with Single Faulty Element

If (r, s)th element in the array is faulty, then current magnitude and phase error in faulty element are represented as a_{rs} and $\delta\phi_{rs}$ respectively.

Array factor can be obtained from Equation (2)

$$A_1(\theta, \phi) = \sum_{\substack{m=-N_x \\ m \neq r}}^{N_x} \sum_{\substack{n=-N_y \\ n \neq s}}^{N_y} e^{jk \sin\theta(md_x \cos\phi + nd_y \sin\phi)}$$

$$+ a_{rs} e^{j(k \sin\theta(r\cos\phi + s\sin\phi) + \delta\phi_{rs})} \tag{5}$$

Deviation pattern is given by

$$\left.\begin{aligned}
A_d(\theta, \phi) &= A(\theta, \phi) - A_1(\theta, \phi) \\
&= e^{jk \sin\theta(r\cos\phi + s\sin\phi)} - a_{rs} e^{j(k \sin\theta(r\cos\phi + s\sin\phi) + \delta\phi_{rs})} \\
&= [\cos\varphi_{rs} - a_{rs}\cos(\varphi_{rs} + \delta\phi_{rs}) + j(\sin\varphi_{rs} - a_{rs}\sin(\varphi_{rs} + \delta\phi_{rs}))] \\
&\qquad\qquad\qquad \text{where} \quad \varphi_{rs} = k\sin\theta(r\cos\phi + s\sin\phi) \\
&= B_{rs}(\theta, \phi) \angle \xi_{rs}(\theta, \phi)
\end{aligned}\right\} \tag{6}$$

Magnitude of deviation pattern is

$$B_{rs}(\theta, \phi) = \left[1 + a_{rs}^2 - 2a_{rs}\cos\delta\phi_{rs}\right]^{1/2} \tag{7a}$$

Phase of deviation pattern is

$$\xi_{rs}(\theta, \phi) = \sin^{-1}\left[\frac{\sin\varphi_{rs} - a_{rs}\sin(\varphi_{rs} + \delta\phi_{rs})}{B_{rs}(\theta, \phi)}\right] \tag{7b}$$

The phase of the deviation pattern along the normal to the array can be obtained by substituting $\theta = 0$ in (7b)

$$\xi_{rs}(0, \phi) = \sin^{-1}\left[\frac{-a_{rs}\sin\delta\phi_{rs}}{B_{rs}(0, \phi)}\right] \tag{8}$$

From the Equation (7a), it is evident that magnitude of deviation pattern is independent of angle of observation and location of faulty element and depends on the error in excitation. Further it is clearly understood from Equation (8) that the phase of deviation pattern at zero angle of observation is independent of location of faulty element. The derived Equations (7a) and (8) are used in calculating the magnitude and phase errors of current in faulty element. Phase of deviation pattern along $\phi = 0°$ plane is used to know location of row of faulty element. Similarly, from phase of deviation pattern along $\phi = 90°$ plane, column location of faulty element is determined.

2.2. Derivation for Magnitude and Phase of the Deviation Pattern of an Array with Two Faulty Elements

Let the faulty elements locations be (r, s) and (t, w). The magnitude of excitation in (r, s)th, (t, s)th elements are a_{rs}, a_{tw} and phase errors are $\delta\phi_{rs}$, $\delta\phi_{tw}$ respectively. The array factor of array with two faulty elements is given by

$$A_2(\theta, \phi) = \sum_{\substack{m=-N_x \\ m \neq r \\ m \neq t}}^{N_x} \sum_{\substack{n=-N_y \\ n \neq s \\ n \neq w}}^{N_y} e^{jk\sin\theta(md_x\cos\phi + nd_y\sin\phi)}$$
$$+ a_{rs}e^{j(k\sin\theta(rd_x\cos\phi + sd_y\sin\phi) + \delta\phi_{rs})} + a_{tw}e^{j(k\sin\theta(td_x\cos\phi + wd_y\sin\phi) + \delta\phi_{tw})}$$

$$(9)$$

The deviation pattern $A_d(\theta)$ for this array is given by

$$
\begin{aligned}
A_d(\theta, \phi) &= A(\theta, \phi) - A_2(\theta, \phi) \\
&= e^{jk\sin\theta(rd_x\cos\phi + sd_y\sin\phi)} + e^{jk\sin\theta(td_x\cos\phi + wd_y\sin\phi)} \\
&\quad - a_{rs}e^{j(k\sin\theta(rd_x\cos\phi + sd_y\sin\phi) + \delta\phi_{rs})} \\
&\quad - a_{tw}e^{j(k\sin\theta(td_x\cos\phi + wd_y\sin\phi) + \delta\phi_{tw})} \\
&= \begin{bmatrix} \cos\varphi_{rs} + j\sin\varphi_{rs} + \cos\varphi_{tw} + j\sin\varphi_{tw} \\ -a_{rs}\cos(\varphi_{rs} + \delta\phi_{rs}) - ja_{rs}\sin(\varphi_{rs} + \delta\phi_{rs}) \\ -a_{tw}\cos(\varphi_{tw} + \delta\phi_{tw}) - ja_{tw}\sin(\varphi_{tw} + \delta\phi_{tw}) \end{bmatrix} \quad (10)
\end{aligned}
$$

where

$$\varphi_{rs} = k\sin\theta(r\cos\phi + s\sin\phi)$$
$$\varphi_{tw} = k\sin\theta(t\cos\phi + w\sin\phi)$$
$$A_d(\theta, \phi) = B_2(\theta, \phi) \angle \xi_2(\theta, \phi) \qquad (11)$$

where

$$B_2(\theta, \phi) = \begin{bmatrix} 2 + a_{rs}^2 + a_{tw}^2 - 2a_{rs}\cos\delta\phi_{rs} - 2a_{tw}\cos\delta\phi_{tw} \\ +2\cos(\varphi_{rs} - \varphi_{tw}) - 2a_{tw}\cos(\varphi_{rs} - \varphi_{tw} - \delta\phi_{tw}) \\ -2a_{rs}\cos(\varphi_{tw} - \varphi_{rs} - \delta\phi_{rs}) + 2a_{rs}a_{tw}\cos(\delta\phi_{rs} - \delta\phi_{tw}) \end{bmatrix}^{1/2} \quad (12)$$

is the magnitude of deviation pattern for the two faulty elements case and

$$\xi_2(\theta, \phi) = \sin^{-1}\left[\frac{\sin\varphi_{rs} + \sin\varphi_{tw} - a_{rs}\sin(\varphi_{rs} + \delta\phi_{rs}) - a_{tw}\sin(\varphi_{tw} + \delta\phi_{tw})}{B_2(\theta, \phi)}\right] \quad (13)$$

is the phase of the deviation pattern.

From Equation (12), it is understood that magnitude of the deviation pattern is same if distance between two faulty elements is same.

The magnitude and phase of deviation pattern for this case at zero angle of observation are given by

$$B_2\left(0,\phi\right) \;=\; \left[4 + a_{rs}^2 + a_{tw}^2 - 4a_{rs}\cos\delta\phi_{rs} - 4a_{tw}\cos\delta\phi_{tw}\right.$$
$$\left.+ 2a_{rs}a_{tw}\cos\left(\delta\phi_{rs} - \delta\phi_{tw}\right)\right]^{1/2} \tag{14}$$

$$\xi_2(0,\phi) \;=\; \sin^{-1}\left[\frac{-a_{rs}\sin\delta\phi_{rs} - a_{tw}\sin\delta\phi_{tw}}{B_2(0,\phi)}\right] \tag{15}$$

From Equations (14) and (15), it is apparent that both the quantities are independent of location of faulty elements. The Equations (12), (14) and (15) are used to find error in excitation of two faulty elements. The row in which faulty elements are located are determined from Equations (13) and (14) along $\phi = 0°$ plane. Further, locations of columns of faulty elements are found along the $\phi = 90°$ plane. Finally to account for the noise and measurement errors a random variable is introduced. By measuring amplitude of far field pattern, using this method error in excitation and location of faulty elements with duplicates (on either side of center element) can be determined. Phase of radiation pattern is used to determine the exact location of faulty element out of the two possible elements. In cases where phase of radiation pattern is not available, fault diagnosis can still be performed with amplitude of deviation pattern.

3. RESULTS AND DISCUSSION

The proposed method has been applied to detect faults for two arrays: one is array with 5×5 elements and other one is with 8×8 elements. The spacing between elements is taken as $\lambda/2$ and all the elements are isotropic, excited with current of magnitude 1 Amp.

As the deviation pattern plays an important role in diagnosing the faults in antenna arrays, it requires large numbers of samples to describe the deviation pattern correctly. This dictates a large number of input nodes for the neural network. Hence large neural network is hard to implement and needs a lot of time for training, the number of input nodes to ANN must be minimized. An appropriate method is used to minimize the numbers of input nodes in a given ANN to improve the efficiency. All possible faulty patterns for single and two faulty elements in the array are divided into two sets: training set and test set. The selection of an adequate set of patterns to train a
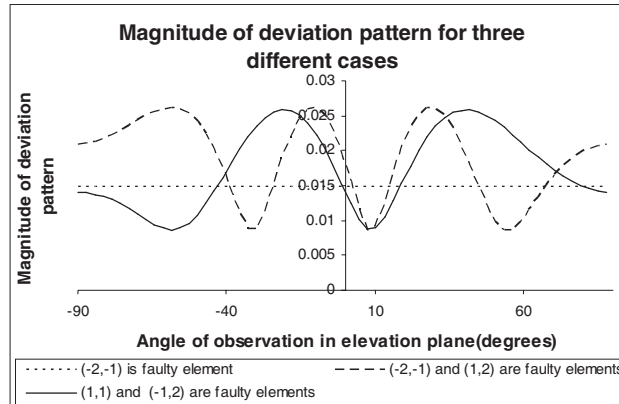
Figure 2. Magnitude of deviation pattern for the array with 5×5 elements. (a) Error in excitation in $(-2, -1)$ element is (mag = 0.7, phase = $-15°$). (b) Error in excitation in $(-2, -1)$ element is (mag = 1.2, phase = $10°$) & (1, 2) element is (mag = 0.9, phase = $20°$). (c) Error in excitation in (1, 1) element is (mag = 0.8, phase = $10°$) & $(-1, 2)$ element is (mag = 0.9, phase = $20°$).

Figure 3. Phase of deviation pattern for the array with 5×5 elements. (a) Error in excitation in $(-2, -1)$ element is (mag = 0.7, phase = $-15°$). (b) Error in excitation in $(-2, -1)$ element is (mag = 1.2, phase = $10°$) & (1, 2) element is (mag = 0.9, phase = $20°$). (c) Error in excitation in (1, 1) element is (mag = 0.8, phase = $10°$) & $(-1, 2)$ element is (mag = 0.9, phase = $20°$).
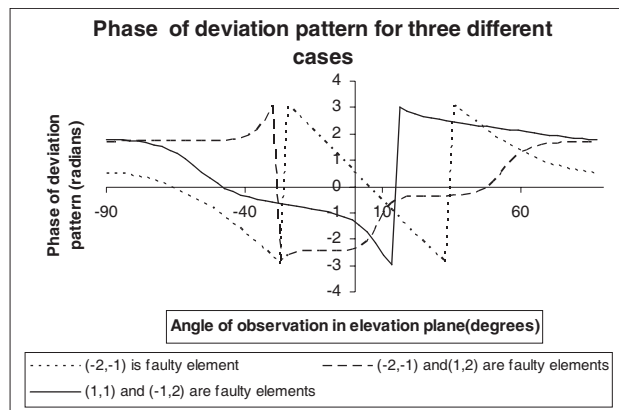
Table 1. Parameters of the array.

Serial No	Parameter	Value	Value
1	*No. of isotropic elements*	(5 × 5) 25	(8 × 8) 64
2	*Distance between successive elements*	λ/2	λ/2
3	*Excitation*	1 Amp	1 Amp
4	*No. of samples of radiation pattern between angles − 90º to 90º*	32	32
5	*Error in current magnitude considered*	60%, 70%, 80%, 90%, 110%, 120%, 130%, 140% of 1 Amp	60%, 70%, 80%, 90%, 110%, 120%, 130%, 140% of 1 Amp
6	*Error in phase*	− 20, − 15, − 10, − 5, 5, 10, 15, 20 degrees	− 20, − 15, − 10, − 5, 5, 10, 15, 20 degrees
7	*No. of possible faulty patterns for one faulty element*	25×8×8	64×8×8 combinations
8	*No. of possible faulty patterns for two faulty elements*	300 × 64 × 64	2016 × 64 × 64 combinations
9	*% Measurement error considered* (±)	0,3,6	0,3,6

neural network is very important. The neural network has to be trained with a set of input output data pairs. The training will be stopped if any one of the following conditions is satisfied: maximum number of epochs, maximum time and minimum performance error. The test set is chosen randomly to test the ANN by introducing 3 possible errors: no measurement error, ±3% and ±6% measurement errors. Table 1 lists details of array. Using the parameters listed in Table 1 the deviation pattern is determined. Figs. 2 and 3 show the magnitude and phase of deviation pattern of an array with 5×5 elements for specific faults. It is observed from Fig. 2 that magnitude of deviation pattern is constant with angle of observation for single faulty element array. Deviation pattern is sampled uniformly at 32 points between angles −90° and 90° which are used as inputs to the neural network for training.

From Fig. 4 and Fig. 5, it is observed that magnitude and phase of deviation pattern are equal at zero angle of observation. The network is found to be robust to take care up to ±6% measurement error in deviation pattern initially. The robustness of network is also verified with ±6% error in fault free pattern alone or faulty pattern alone or
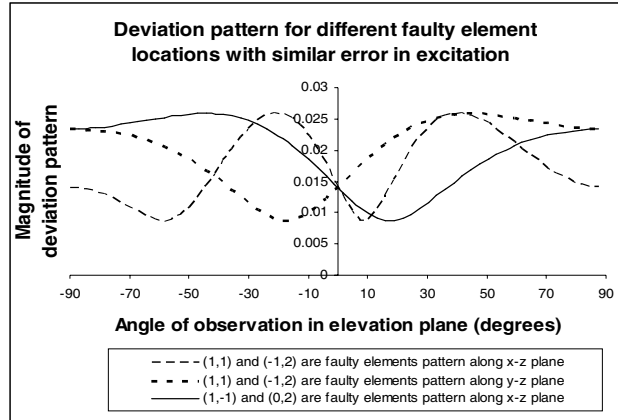
Figure 4. Magnitude of deviation pattern for 5×5 element array. (a) Error in excitation in $(1, 1)$ element is (mag $= 0.8$, phase $= 10°$) & $(-1, 2)$ element is (mag $= 0.9$, phase $= 20°$) along $\phi = 0°$ plane. (b) Error in excitation in $(1, 1)$ element is (mag $= 0.8$, phase $= 10°$) & $(-1, 2)$ element is (mag $= 0.9$, phase $= 20°$) along $\phi = 90°$ plane. (c) Error in excitation in $(1, -1)$ element is (mag $= 0.8$, phase $= 10°$) & $(0, 2)$ element is (mag $= 0.9$, phase $= 20°$) $\phi = 0°$ plane.

Figure 5. Phase of deviation pattern for 5×5 element array. (a) Error in excitation in $(1, 1)$ element is (mag $= 0.8$, phase $= 10°$) & $(-1, 2)$ element is (mag $= 0.9$, phase $= 20°$) along $\phi = 0°$ plane. (b) Error in excitation in $(1, 1)$ element is (mag $= 0.8$, phase $= 10°$) & $(-1, 2)$ element is (mag $= 0.9$, phase $= 20°$) along $\phi = 90°$ plane. (c) Error in excitation in $(1, -1)$ element is (mag $= 0.8$, phase $= 10°$) & $(0, 2)$ element is (mag $= 0.9$, phase $= 20°$) $\phi = 0°$ plane.
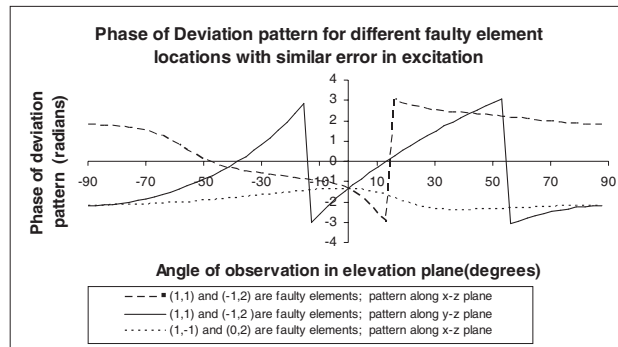
Table 2. Test results for 5×5 element array when a single faulty element exists for PNN network with $\pm 6\%$ measurement error.

Actual failures			Results from the method		
Location of faulty elements	Magnitude of current (Amp)	Phase of current (Degrees)	Location of faulty elements	Magnitude of current (Amp)	Phase of current (Degrees)
r	a_r	$\delta\phi_r$	r	a_r	$\delta\phi_r$
(1, 1)	0.6	− 10	(1, 1)	0.6	− 10
(− 2, 0)	1.2	− 15	(− 2, 0)	1.2	− 15
(−1, − 2)	0.7	− 5	(− 1, − 2)	0.7	− 5
(−1, 1)	0.9	10	(− 1, 1)	0.9	10
(0, 0)	1.1	15	(0, 0)	1.1	15

Table 3. Test results for 5×5 element array when two faulty elements exists for PNN network with $\pm 6\%$ measurement error.

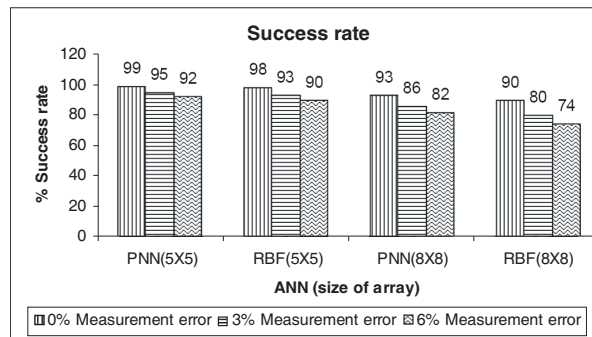| Actual failures						Results from the method					
Location of faulty elements		Magnitude of current (Amp)		Phase of current (degrees)		Location of faulty elements		Magnitude of current (Amp)		Phase of current (degrees)	
r	s	a_r	a_s	$\delta\phi_r$	$\delta\phi_s$	r	s	a_r	a_s	$\delta\phi_r$	$\delta\phi_s$
(1,−1)	(1,2)	1.2	0.8	−10	5	(1,−1)	(1,2)	1.2	0.8	−10	5
(0,1)	(2,−1)	0.6	0.7	10	5	(0,1)	(2,−1)	0.6	0.7	10	5
(−2,1)	(0,1)	1.1	1.2	−20	−10	(−2,1)	(0,1)	1.1	1.2	−20	−10
(0,0)	(−1,−1)	0.8	0.9	10	−5	(0,0)	(−1,−1)	0.8	0.9	10	−5
(2,1)	(−2,−1)	1.2	1.3	−10	15	(2,1)	(−2,−1)	1.2	1.3	−10	15

Figure 6. Success rate of fault diagnosis for 5×5, 8×8 elements array using PNN and RBF networks.

together. The network showed high success rate.

The performance of RBF and PNN networks in the form of success rate for 5×5 and 8×8 elements array is compared in Fig. 6. Test results of 5×5 elements array using PNN network with $\pm 6\%$ measurement error are tabulated in Tables 2 and 3. Test results demonstrate high performances of the suggested method.

4. CONCLUSIONS

RBF and PNN based neural network models are applied to diagnose error in excitation of faulty elements and their location in an antenna array. The proposed method allows the user to train the neural network off-line for any number of elements, spacing and excitation. It is established that, once the network is trained, it can detect location and current magnitude & phase of faulty element in the antenna array. A high success rate demonstrates the validity of the proposed technique.

REFERENCES

1. Lee, K. M., R. S. Chu, and S. C. Liu, "A built-in performance monitoring/fault isolation and correction (PM/FIC) system for active phased array antennas," *IEEE AP-International Symposium 1993, AP-Digest*, 206–209, Mi, USA, Jun. 28–Jul. 2, 1993.
2. Bucci, O. M., A. Capozzoli, and G. D'Elia, "Diagnosis of array faults from far field amplitude — Only data," *IEEE Transactions on Antennas and Propagation*, Vol. 48, No. 5, 647–652, May 2000.
3. Rodriguez, J. A., F. Ares, H. Palacios, and J. Vassal'lo, "Finding defective elements in planar arrays using genetic algorithms," *Progress In Electromagnetic Research*, PIER 29, 25–37, 2000.
4. Bucci, O. M., A. Capozzoli, and G. D'Elia, "A method for the diagnosis of phase faults in array antennas from amplitude only field data," *IEEE International Conference-2000*, 2238–2241, 2000.
5. Sarma, N. V. S. N. and D. Vakula, "Single fault detection of an array using neural networks," *Antenna Measurement Techniques Association Meeting & Symposium (AMTA-2004)*, 337–339, held at Stone Mountain GA, USA, during October 17–22, 2004.
6. Vakula, D. and N. V. S. N. Sarma, "A generalized method to diagnose faults in antenna arrays using neural networks," *Antenna Measurement Techniques Association Meeting & Symposium*

(AMTA-2006), 290–292, held at Austin, Texas, USA, during Oct. 22–27, 2006.

7. Elliot, R. S., *Antenna Theory & Design*, revised edition, Wiley India Pvt Ltd, 2006.