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Research Article

Linear Antenna Array Failure Correction with Mutual Coupling Effects using Element Position of the Array Elements

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Abstract

A new technique for the restoration of the field pattern in a linear array constructed using parallel dipole antennas is carried out by altering the spacing between the array elements. In an N-element optimized linear antenna array, the differential evolution (DE) algorithm is used to correct a specific number of failed elements with the objective of achieving the specified side lobe level (SLL) and maximum reflection coefficient (RC). The mutual coupling effects of the pattern are taken into consideration here. The necessary simulations are performed using Matlab software which depicts the effectiveness of this technique in establishing the corrected far field radiation pattern approaching the desired radiation pattern. To prove its effectiveness, two examples are tested in this process. The simulation findings are verified using the FEKO electromagnetic simulation software.

Keywords: Antenna array, differential evolution algorithm, failure correction, side lobe level, reflection coefficient

1. Introduction

When any evenly spaced linear array [1-2] is excited uniformly, one of the key benefits of antenna arrays over individual elements is high directivity. However, this will lead to high SLLs. This level will be more when there is a working failure of the elements in the array. This will seem very profounded in analog beam forming, which will ultimately end up in the substitution of new elements in place of the failed ones. Here, bringing back to the original pattern consumes more time. However, this is not the case with digital beam forming, as necessity of replacing the failed antennas does not exist. Instead, the excitations of the remaining un-failed elements can be altered so that the re-established radiation pattern looks in par with the original un-failed pattern. A review of the literature reveals that this replacement option is suitable for a wide range of functions, including satellite, radar, and military applications. There is no one approach, or set of procedures, that has emerged as the best for generating a corrected pattern that is identical to the intended original pattern.

Till date, many researchers presented different techniques for this failure correction using amplitude excitations of the antenna elements [3-10]. Genetic algorithm [3-4] is one of the primitive algorithms that is quite often seen in failure corrections. A technique for re-establishing the pattern with digital beamforming in linear arrays, which are symmetrical in construction is detailed in [5]. Techniques for antenna array failure correction using differential search, firefly, and an improved bat algorithm are described in the literature [6-8]. Paper [9] describes how to recover the original pattern with low SLLs and nulls in the desired direction using a greedy sparse constrained optimization approach. Literature [10] describes a comparison of the PSO and BFO algorithms for reducing SLL and null steering in failure corrections.

As Mutual Coupling (MC) consisting of self and mutual impedance parameters plays an important and devastating part in the radiation pattern of arrays, much about it has been discussed by researchers in [11-13]. Methods for correction of pattern in the presence of the MC using excitation amplitudes are detailed in [14-17]. Array failure correction methods using Quantum PSO, Firefly algorithm and Bat algorithm for low SLL are available in the articles [14-16]. Shaped beam patterns are synthesized and failure correction is also included in a linear antenna array [17].

However, the methods/techniques used in the past to recover the original pattern just by altering the amplitude excitations are found to be costly and they also introduce more complexity in the feed networks. Literature reports [18] a method to re-establish the pattern by altering the position of the individual elements in linear arrays without MC. Corrections by adjusting the length and spacing related to failed components are detailed in [19].

We describe a new method for recovering the original pattern in the presence of failures in a linear antenna array that takes into account the mutual coupling effect in this study. This technique is used to adjust the space between array members. Furthermore, unlike other contemporary techniques, the complexity of the feed network is lowered by omitting the non-uniform amplitude introduction part [3-10, 14-17]. The induced Electro-Motive Force (EMF) approach, which incorporates the presence of mutual coupling in the array, is used to compute current in both failed and unfailed antenna elements. Matlab is employed here for the purpose of simulations and for evaluation of performance of the optimization process generated by well-known DE algorithm [20-26].

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Synthesis processes involved in equally/unequally distributed antenna arrays using DE algorithms are discussed by various researchers in [18, 20-26]. Moreover, DE algorithm is successfully used in antenna array failure correction techniques [6, 18].

In addition to the above, the simulation results are validated using the FEKO software [27].

2. Major Contribution of the Proposed Work

In general, the specific amplitude excitations of their individual elements are required for the synthesis of antenna array failure correction. Because non-uniform amplitude excitations are used, the feed complexity increases. However, in the suggested array, linear antenna array failure correction is accomplished by the use of array element position for a multi-objective problem. The suggested approach differs from [3–10, 14-17] in that the authors here used just element spacing as a design variable to create the corrected radiation pattern with the specified specifications. Furthermore, this method differs from [3–10, 18] in that the authors here considered actual antennas with mutual coupling. The main benefit of the suggested technique is that it avoids challenges associated with the creation of excitations and their feed networks. It is highly useful to produce the corrected radiation pattern by supplying an appropriate location of the array elements. It does not necessitate the use of any extra attenuators or phase shifters. As a result, the overall design will be simple because the feed network complexities are decreased due to the absence of excitations. As a result, the costs can be reduced. Furthermore, the coupling effect is minimized by decreasing the reflection coefficient of the antenna elements with the corrected pattern. Here, the simulation findings are also validated using FEKO electromagnetic software.

3. Problem Formulation

We consider here two examples of parallel dipole antennas in linear arrays. As seen in Figure 1, the array's dipole components are oriented parallel to the *Z*-axis and along the *X*-axis.

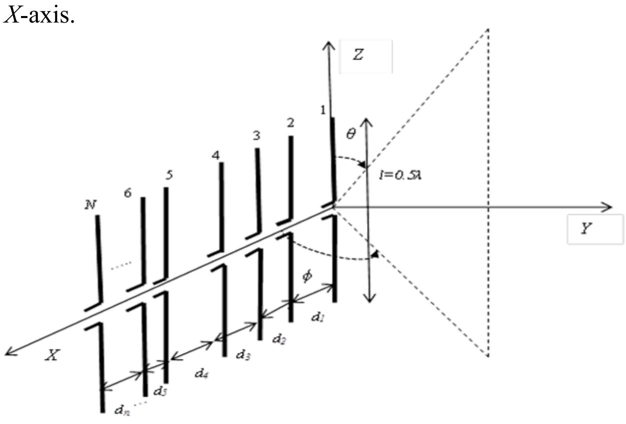

Fig. 1. A linear array antenna's geometry.

The original pattern and other parameters involved in generation of the original pattern are restored by altering the element spacing in the presence of the corrupted elements. Altering the spacing of antenna elements modifies the position of all the elements because of which, currents in all the elements are modified in presence of mutual coupling. The term 'Failure' of an antenna elements refers to the voltage across it being equal to zero. But this is not the case with the current as currents exits because of the mutual coupling effects.

Radiation pattern is computed in the horizontal (*X-Y)* plane. The currents in all the elements are obtained mathematically using the following equation.

$$[I] = [Z]^{-1}[V] \quad (1)$$

In the above equation, $[V]$ refers to the voltage vector that is given to the dipole elements. This is generated for the antenna elements involved in the corrected patterns. Its value is kept to zero for the corrupted/failed components. *[Z]* is the matrix holding the self- and mutual impedance values, and *[I]* is the vector of complex current excitations for all antenna elements. The induced EMF approach was used to get these impedances. Here, the distribution of currents is assumed to be sinusoidal on the dipoles.

The following equation (2) represents the radiation pattern $RP(\theta,\varphi)$ of a linear array that includes the mutual coupling effects.

$$RP(\theta,\varphi) = [\sum_{n=1}^{N} I_n \, exp^{jkd_n \sin(\theta)\cos(\varphi)} \quad].ELEP(\theta) \quad (2)$$

In the above equation, the termI_n represents the current excitations of the n^{th}dipole that is placed in *X*-axis. *N* refers to the total elements inclusive of both the failed and un-failed antennas. k=2π/λ=wave number, λ=wavelength, θ= angle between *Z*-axis and the far field point is the polar angle, ϕ =azimuth angle from *X*-axis (0^o to 180^o), d_n = distance between the origin to centre of n-th dipole antenna. *ELEP(θ)* represents the individual pattern of the dipole element. Equation (3) represents the element pattern equation for θ=90^o in horizontal plane:

$$\boldsymbol{ELEP(\theta)} = \frac{\cos\left(\frac{kl_n\cos(\theta)}{2}\right)-\cos\left(\frac{kl_n}{2}\right)}{\sin(\theta)} \quad (3)$$

The length of n-th antenna is denoted by l_n.

In addition, the lowering of the n-th dipole element's RC when re-establishing the pattern is taken into account.

The active impedance [10] of all the dipoles, Z_n^A is given by:

$$Z_n^A = |V_n/I_n| \quad (4)$$

The voltage across and current through the dipole n are V_n and I_n, respectively. Now the maximum active impedance $\left(Z_{n,max}^A()\right)$ among all the elements is computed.

The feed network's characteristics impedance (Z_o) is considered to be 50Ω and the maximum *RC* (RC_{max}) at the input of n-th element [1] is written as:

$$RC\left[\frac{|Z_n^A|o_{max}}{|Z_n^A|o_{max}}\right]_{max} \quad (5)$$

The appropriate design of fitness function is very much essential as it should successfully continue the search for any algorithm. There are many factors which are used for evaluation of fitness function such as gain, beamwidth and SLL, etc. In this problem, re-establishment of the pattern in the broadside direction is done with desired SLL and RC_{max} of the antenna elements. The objective is now to find the spacing between the dipoles using DE algorithm that will reduce the cost/fitness function shown in equation (6).

$$fitness = \sum_{i=1}^{2} Vt_i \times F_i^2 \quad (6)$$

Where

$$\boldsymbol{F_1} = \begin{cases} \boldsymbol{SLL_{ob} - SLL_{de}, if \rightarrow SLL_{ob} > SLL_{de}} \\ \boldsymbol{0, if \rightarrow SLL_{ob} \leq SLL_{de}} \end{cases} \quad (7)$$

$$F_2 = \begin{cases} RC \\ ob^{0,if\rightarrow RC_{ob}^{max^{max}_{de}}} \{ \\ max^{max}_{de} \\ ob^{de_{max}}_{max} \end{cases} \quad (8)$$

Vt_1 and Vt_2 are the corresponding weight factor that are given to each term in equation (6). They control the overall optimization process.

SLL and RC^{max} are the value of SLL and RC_{max} respectively. Suffix *ob* refers to the obtained value and *de* refers to the desired value.

4. Differential Evolution Algorithm

DE uses certain number of *D*-dimensional vectors, which are considered as the population for each and every generation [20-26]. It can again be defined as a variant form of Genetic Algorithm, by replacing the cross over operator using a differential operator for producing an offspring in the subsequent generation. It searches for a global optimum location in the allotted space. The algorithm itself is divided into four stages and these stages are explained below:

(i) Initialization

The vectors are randomly populated and each one is referred to as a chromosome, which itself is a potential solution. The vectors are represented by the $\vec{X}_{i,G}$ where i=0, 1, 2…*NP*-1, where *NP* refers to the total number of vectors in a particular generation *G* in *D* dimensions. The population at the start of the first generation should include the full space specified within the maximum and minimum bounds. At any generation, the population's *i-th* vector is determined by:

$$\vec{X}_{i,G} = [x_{1,i,G}, x_{2,i,G}, x_{3,i,G}, x_{4,i,G}, \ldots . x_{D,i,G}] \quad (9)$$

(ii) Evaluate the fitness

Fitness of each vector at present generation is evaluated.

(iii) Mutation

The next stage refers to mutation, which is generation of a mutant vector is given by equation (10). Different most popular mutation strategies are given in [20-23]. Here, we used '*DE/current-to-best/1*' which is detailed below:

$$\vec{V}_{i,G} = \vec{X}_{i,G} + F(\vec{X}_{best,G} - \vec{X}_{i,G}) + F(\vec{X}_{r1,G} - \vec{X}_{r2,G}) \quad (10)$$

Where $r1, r2, r3 \in$ [1, NP] and $r1 \neq r2 \neq r3 \neq i$, and $F\in$ [0, 2] is a constant factor that monitors and takes necessary action on the rise in differential variance from $(\vec{X}_{r1,G} - \vec{X}_{r2,G})$.

At generation *G*, $\vec{X}_{best,G}$ is found to be the best vector with the best fitness value in the appropriate population.

(iv) ***Crossover***

The cross over stage comes after the mutation stage, where a trial individual is obtained using crossover operator.

$$\vec{U}_{ji,G} = \vec{V}_{ji,G}, if \rightarrow r(j) \leq C_R \quad \text{or} \, j = r(i) \quad (11)$$

else $\vec{X}_{ji,G}$

j=1, 2, 3, 4, 5, 6…....,*D*.

$C_R \in$ [0, 1] is a constant, and $r(j)$ is a uniform random number between 0 and 1.

(v) ***Selection***

When comparing $\vec{U}_{i,G}$'s fitness value to $\vec{X}_{i,G}$, and if $\vec{U}_{i,G}$'s fitness is less than or equal to that of $\vec{X}_{i,G}$, then $\vec{X}_{i,G}$ will be set to $\vec{U}_{i,G}$ and it enters the next population group.

This algorithm's stages *(ii)-(v)* are repeated until max generation is attained or a stop condition is notified.

4. Simulated Results

For the simulation purposes, two examples are taken into consideration, with 16 elements in Example1 and 26 elements in Example2. The original patterns for the above mentioned two examples with all the elements in perfect condition (no failures) are generated by altering the excitation amplitudes of the corresponding dipole elements, as can be found in literature [3-10, 14-17]. Here, the inter element spacing and the length of the antenna components are fixed at 0.5λ. The radius of the elements is set at 0.003λ.

For the purpose of experimenting with failures, the following elements are chosen randomly. Third element, eighth element and fourteenth elements are considered to be faulty with all their voltages assumed to be zero for Example1. Similarly, fifth element, ninth element, fifteenth element and twenty-fourth elements are assumed to be faulty for Example2. By setting the voltages of the related failed dipole components to zero, the voltage excitations are employed to create the far-field pattern of this failed array.

Once the above setting is over, the process of re-establishment of the original pattern is done. Here, the patterns are newly generated by only altering the inter-element spacing (*d*) of the antenna elements using DE. Here, DE is run for 200 iterations. The overall population for both the examples is taken to be 40. Un-failed elements are excited by unit voltages.

For DE, step size F_weight of 0.7 and cross over probability constant of 0.9 are chosen for simulation purposes.

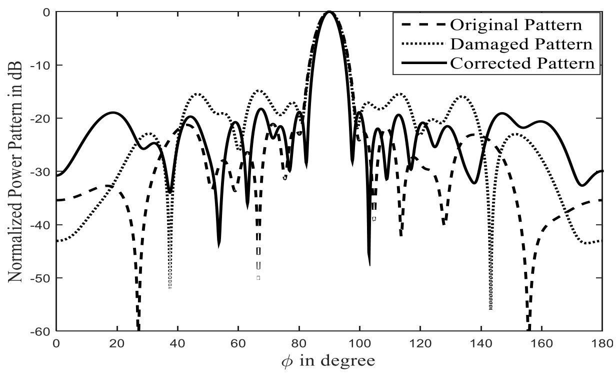

Fig. 2. Example1's normalized power pattern in dB.

Figure 2 shows the obtained original, damaged as well as the corrected power patterns for Example1.

It is assumed that $Vt_1 = Vt_2 = 1$ (*SLL* and *RCmax* are treated equally) for original and corrected patterns in both the above-mentioned examples. The distance between antenna elements may be adjusted between 0.1λ and 1.1λ values. Table 1 shows the results. It also gives an indication of the effectiveness of the technique used.

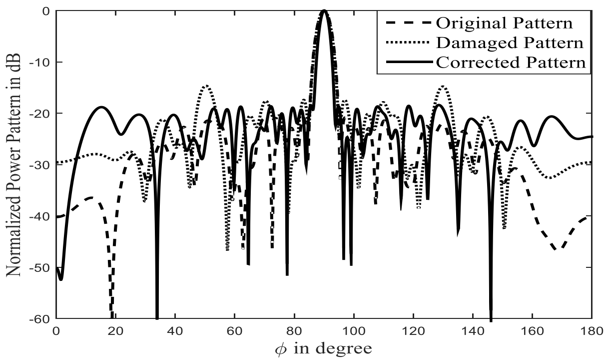

Fig. 3. Example2's normalized power pattern in decibels.

For Example2, Figure 3 depicts the acquired original, damaged, and restored power pattern.

A computer is used to calculate the computation time. This PC's specifications are as follows: Intel(R) Core (TM) i5 CPU, 3.50 GHz clock frequency, and 4 Gigabyte RAM. For Example1, the computing time for the corrected pattern is found to be 2343.695980 seconds, while for Example2, it is found to be 5979.667714 seconds. Figure 4 and Figure 5 indicate the value of voltage amplitudes for original patterns of the exampleswhich have a minimum and maximum bound of 0 and 1. The distance (in λ) between the origin and the center of the dipole elements for the re-established pattern is shown in Tables 2 and 3.

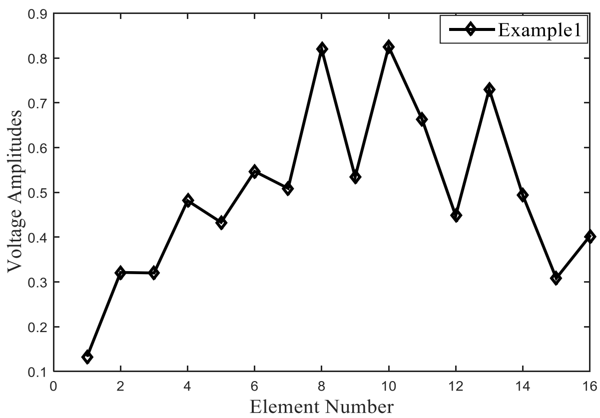

Fig. 4. Original pattern voltage amplitudes.

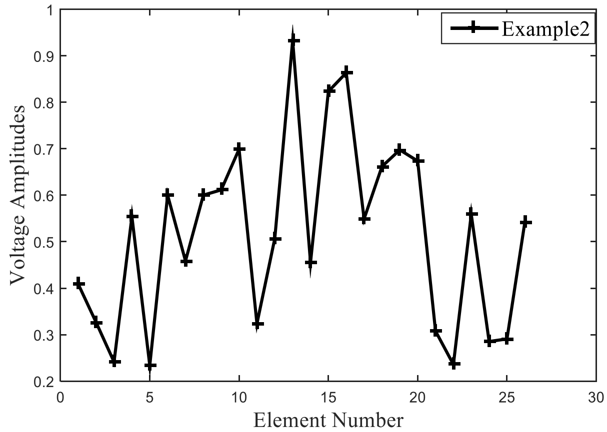

Fig. 5. Original pattern voltage amplitudes.

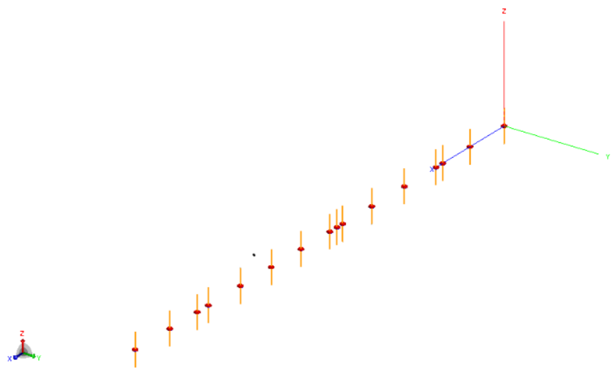

Fig. 6. Geometry of Constructed dipole antenna array on FEKO for Example 1.

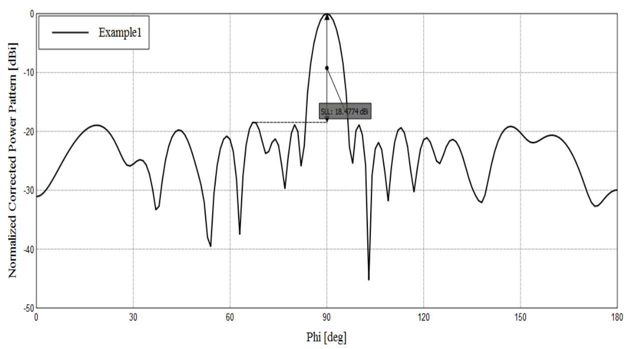

Fig. 7. Corrected pettern for Example1 obtained from FEKO.

Table 1. Desired and achieved outcomes

Parameters of design	Desired values	Original Pattern		Damaged Pattern		Corrected Pattern	
		Example1	Example2	Example1	Example2	Example1	Example2
SLL (dB)	-20	-20.0282	-20.8395	-14.8328	-14.6727	-18.250	-18.4053
Maximum RC	0.18	0.1633	0.1762	0.1901	0.2019	0.1737	0.1814

Table 2. The array's spacing (Example1)

Number of Elements	Spacing (in λ)	Number of Elements	Spacing (in λ)
1	0.0000	9	3.8539
2	0.7570	10	4.4926

3	1.3604	11	5.1484
4	1.5062	12	5.8332
5	2.2068	13	6.5414
6	2.9284	14	6.7884
7	3.5700	15	7.3951
8	3.6950	16	8.1590

Table 3. The array's spacing (Example2).

Number of Elements	Spacing (in λ)	Number of Elements	Spacing (in λ)
1	0.0000	14	8.6952
2	0.7512	15	9.3289
3	1.6757	16	9.9343
4	2.4624	17	10.5884
5	3.2824	18	11.2768
6	3.8887	19	11.8464
7	4.6417	20	12.7619
8	5.2847	21	13.3391
9	5.9107	22	14.2004
10	6.0630	23	14.9849
11	6.7374	24	15.6025
12	7.4087	25	16.4163
13	8.0436	26	17.1621

FEKO Evaluation:

Steps required for FEKO analysis are given below:

● Building antenna array geometry and surroundings geometry

● Combine the array with the surrounding geometry to form a mesh.

● Types of solutions are requested and solution parameters are set.

● Read in and interpretation of results

Further information related to the above steps are available in [27].

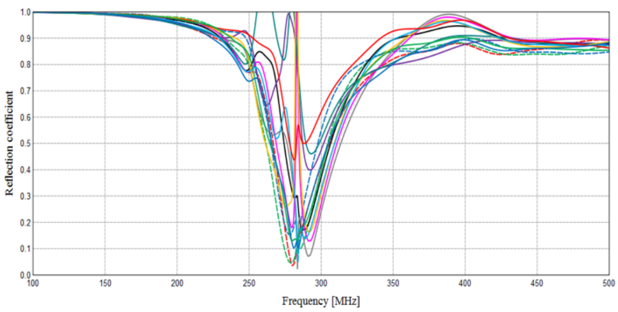

Fig. 8. *RC* obtained from FEKO for Example1.

Geometry of the dipole arrays on FEKO are build-up by taking the value of the antenna length = 0.5λ (same as used in MATLAB simulation) and the spacing between the antenna elements are taken from Table 2 and Table 3 for both the examples. For confirming the findings, non-faulty elements are excited at unit voltage, whereas defective elements are excited at zero voltage. Figure 6 shows the geometry of 16 element dipole array on FEKO. 100 to 500MHz frequency range is considered during FEKO analysis.

About 300 MHz operating frequency is taken to generate the corrected pattern and RC. Figures 7 and 9 show the normalized corrected pattern in dB obtained for both the examples. Figures 8 and 10 display the *RC* plot between 100 and 500 MHz. Figure 11 demonstrates how the fitness value converges as the number of iterations increases. It shows precisely the fitness values that are obtained for the both the examples.

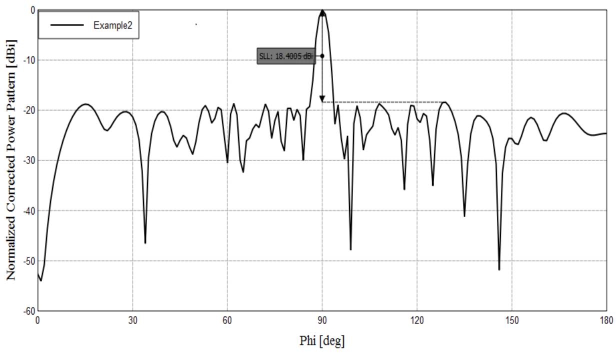

Fig. 9. Corrected pattern obtained from FEKO for Example2.

The proposed method is different in following ways from the above literature [3-10, 14-17, and 19]. In earlier literature, linear antenna array failure correction requires the specific amplitude excitations of the non-defective antenna elements. However, applied methods using amplitude of radiating elements are quite complex for obtaining the corrected power pattern. The need for this scheme is to avoid the problems dealing with the generation of amplitude excitations and their feed networks. Furthermore, removing the non-uniform excitation introduction element of the feed network, which is distinct from other contemporary techniques [3-10, 14-17], is one option to lower the complexity of the feed network. This study is also distinct from the others [3-10] in that it considers actual antennas with mutual coupling. It is quite useful to restore the original pattern in the presence of failed elements by providing adequate element spacing of the antenna components. Also, the obtained SLL (dB) results of -18.250 dB and -18.405 dB are better than the simulation findings of -16.8002 and -18.34 [19], while the FEKO values of -18.4774dB and -18.4005dB are better than the simulation results of -16.62dB and -17.812 dB [19].

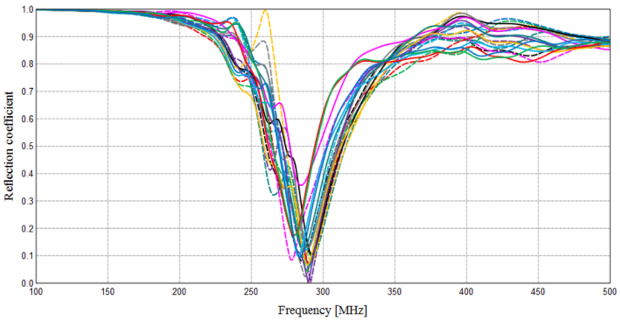

Fig. 10. *RC* obtained from FEKO for Example2.

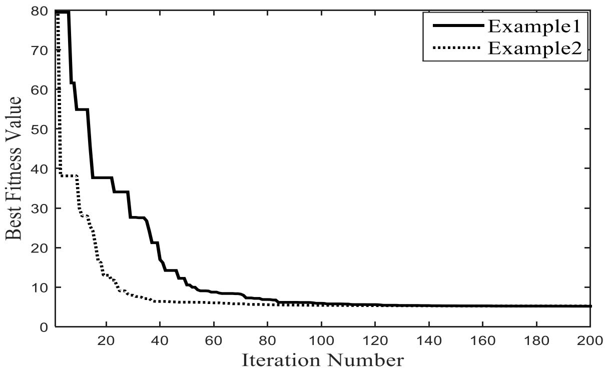

Fig. 11. Convergence curves for corrected pattern.

The validity of the proposed approach for reconstructing the original pattern was tested using the two sets of antenna components. The produced pattern has a lower error between the values of the parameters of the corrected patterns from simulations and FEKO analysis. In addition, the impedance matching is well satisfied.

5. Conclusion

This paper presented a new technique that relied on altering the position of the elements in linear antenna arrays failed with certain number of elements. In this study, antennas having mutual coupling effects are employed instead of isotropic sources. Furthermore, this approach is proven to be superior to previous procedures in which the excitation amplitudes are modified for the linear array correction process. This strategy may be used to reduce the feed complexity in hardware circuits. Because no additional attenuators or phase shifters are necessary in this technology, it is also cost effective. Two examples are presented in this paper to substantiate the results obtained by this process. The results that are obtained show the effectiveness of this method. This also worked well for different set of antenna elements and with different number of failures. In addition to it, RC also undergone a reduction to the specified value. It may also be used to reconfigure the radiation patterns of various array configurations, and it can take into account ground plane effects.

References

1. C. A. Balanis, Antenna Theory: Analysis and Design, 2nd Edition, John Wiley and Sons (Asia), Singapore, 2003.
2. L.C. Godara, Handbook of Antennas in Wireless Communications, CRC, Boca Raton, FL, 2002.
3. B. K. Yeo, andY.Lu,Array failure correction with a genetic algorithm, IEEE Transactions on Antennas and Propagation, 47 (1999), 823-828.
4. J.A.Rodriquez, F.Ares, E. Moreno, and G.Franceschetti, Genetic algorithm procedure for linear array failure correction, Electronics Letters, 36 (2000),196-198.
5. S. U.Klhan, I.M.Qureshi, B. Shoaib, and A.Naveed, Recovery of failed element signal with a digitally beamforming using linear symmetrical array antenna, Journal of Information Science and Engineering, 32(2016), 611-624.
6. K.Guney, A. Durmus, andS. Basbug, Antenna array synthesis and failure correction using differential search algorithm, International Journal of Antennas and Propagation, 2014 (2014), 1-8.
7. N. S.Grewal, M. Rattan, and M. S. Patterh, A linear antenna array failure correction using firefly algorithm, Progress in Electromagnetics Research M, 27(2012), 241–254.
8. N. S. Grewal, M. Rattan, and M. S. Patterh, A linear antenna array failure correction using improved bat algorithm, International Journal of RF and Microwave Computer Aided Eng 2017, DOI: 10.1002/mmce.21119.
9. S. U. Khan, M. K. A. Rahim, M. A. Baba and N. A. Murad, “Correction of failure in linear antenna arrays with greedy sparseness constrained optimization technique”, Vol, 12, no, 12, pp. 1-18, 2017.
10. O. P. Acharya and A. Patnaik, “Antenna Array Failure Correction”, *IEEE Antennas & Propagation Magazin*, Vol, 59, No.6, pp. 106-115, 2017.
11. J. H. Lee, andY. L. Chen, Performance analysis of antenna array beamformers with mutual coupling effects, Progress in Electromagnetics Research B, 33(2011),291-315.
12. G.K.Mahanti, S.Das, A.Chakrabarty, J.C. Bregains, and F.Ares,Design of reconfigurable array antennas with minimum variation of active impedances, IEEE Antennas and Wireless Propagation Letters, 5(2006),541-544.
13. M.Thevenot, C.Menudier, A. E.Sayed Ahmad, Z. E.Nashef, F.Fezai, Y.Abdallah, E.Arnaud, T F.orres, and T.Monediere, Synthesis of antenna arrays and parasitic antenna arrays with mutual couplings, International Journal of Antennas and Propagation, 2012(2012), 1-22.
14. R.Muralidharan, A.Vallavaraj, G.K. Mahanti, and H.Patidar, QPSO for failure correction of linear array of mutually coupled parallel dipole antennas with desired side lobe level and return loss, Journal of King Saud University –Engineering Science, 29 (2017), 112-117.
15. R. Muralidharan, A. Vallavaraj, and G.K. Mahanti, Firefly algorithm for failure correction of linear array of dipole antennas in presence of ground plane with mutual coupling effects, ACES journal, 30 (2015), 1122-1128.
16. N. S. Grewal, M. Rattan, and M. S. Patterh, A linear mutually coupled parallel dipole antenna array failure correction using bat algorithm, ProgressIn Electromagnetics Research M, 54 (2017),9-18.
17. H. Patidar, G.K. Mahanti and R Muralidharan, “Synthesis and Failure Correction of Flattop and Cosecant Squared Beam Patterns in Linear Antenna Arrays”, Journal of Telecommunication and Information Technology, Vol, 4, pp. 25-30, 2017.
18. S. KMandal, S. Patra, S.Salam, K.Mandal, G.K. Mahanti, and N.N.Pathak, Failure correction of linear antenna arrays with optimized element position using differential evolution, 2016 IEEE Annual India Conference (INDICON),Bangalore, India.
19. H. Patidar and G.K. Mahanti, “Failure Correction of Linear Antenna Array by Changing Length and Spacing of Failed Elements” Progress in Electromagnetics Research M, Vol. 61, 75–84, 2017.

20. R. Storn, and K.Price, Differential evolution a simple and efficient heuristic for global optimization over continuous spaces, J. Global Optimization, 11(1997),341-359.
21. P.Rocca, A.Massa, and G. Oliveri, Differential Evolution as Applied to Electromagnetics, IEEE Antennas and Propagation Magazine, 53(2011), 38-49.
22. V. P.Kenneth,M. S. Rainer, andA. L.Jouni, Differential evolution: a practical approach to global optimization, Springer, 2005.
23. V.Feoktistov, Differential Evolution: In Search of Solutions, Springer, 2006.
24. D. G.Kurup, M.Himdi, and A. Rydberg, Synthesis of uniform amplitude unequally spaced antenna arrays using the differential evolution algorithm, IEEE Transactions on Antennas and Propagation 51(2003), 2210-2217.
25. C. Lin, andA., Qing Synthesis of unequally spaced antenna arrays by using differential evolution, IEEE Transactions on Antennas and Propagation, 58(2010), 2553-2561.
26. Amara Prakasa Rao & N.V.S.N Sarma, Synthesis of Reconfigurable Antenna Array Using Differential Evolution Algorithm, IETE Journal of Research, DOI:10.1080/03772063.2017.1284614, 2017.
27. FEKO Suite 6.1., EM software and systems. Retrieved from (www.feko.info), 2011.